<table>
<thead>
<tr>
<th>Instrument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard X-ray Telescope (HXT)</td>
<td>Fourier-synthesis type collimator (64 elements)</td>
</tr>
<tr>
<td>Energy bands</td>
<td>15–24–35–57–100 keV (4 bands)</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>~ 5 arc sec</td>
</tr>
<tr>
<td>Field of view</td>
<td>Full solar disk</td>
</tr>
<tr>
<td>Effective area</td>
<td>~ 70 cm²</td>
</tr>
<tr>
<td>Time resolution</td>
<td>0.5 s</td>
</tr>
<tr>
<td>Soft X-ray Telescope (SXT)</td>
<td>Modified Wolter type I grazing incident mirror + CCD with coaligned optical telescope</td>
</tr>
<tr>
<td>Wavelength range (X-ray) (optical)</td>
<td>3–60 Å (selectable with filters)</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>~ 2.5 arc sec</td>
</tr>
<tr>
<td>Field of view</td>
<td>Full solar disk</td>
</tr>
<tr>
<td>Time resolution</td>
<td>up to 0.5 s</td>
</tr>
<tr>
<td>Wide Band Spectrometer (WBS)</td>
<td>Gas proportional counter (soft X-rays; 2–30 keV)</td>
</tr>
<tr>
<td></td>
<td>NaI scintillation counter (hard X-rays; 20–400 keV)</td>
</tr>
<tr>
<td></td>
<td>BGO scintillation counter (gamma-rays; 0.2–100 MeV)</td>
</tr>
<tr>
<td></td>
<td>(count-rate data) 0.125, 0.25, or 0.5 s</td>
</tr>
<tr>
<td></td>
<td>(pulse-height spectrum data) 1, 2, or 4 s</td>
</tr>
<tr>
<td>Bragg Crystal Spectrometer (BCS)</td>
<td>Bent crystal spectrometers</td>
</tr>
<tr>
<td>Spectral lines and resolutions</td>
<td>S xvi (5.0385 Å) 5.0160–5.1143 Å with 3.232 mÅ resolution</td>
</tr>
<tr>
<td></td>
<td>Ca xix (3.1769 Å) 3.1631–3.1912 Å with 0.918 mÅ resolution</td>
</tr>
<tr>
<td></td>
<td>Fe xxv (1.8509 Å) 1.8298–1.8942 Å with 0.710 mÅ resolution</td>
</tr>
<tr>
<td></td>
<td>Fe xxvi (1.7780 Å) 1.7636–1.8044 Å with 0.565 mÅ resolution</td>
</tr>
<tr>
<td>Time resolution</td>
<td>up to 0.125 s</td>
</tr>
</tbody>
</table>

The angular resolution of the optical system of SXT is on the order of 2 arc sec across the solar disk, slightly better than that determined by the CCD pixel size (2.4 arc sec). Two filter wheels and a shutter device are placed in front of the CCD detector to choose energy band and exposure time properly. Filter and exposure selection as well as data acquisition are controlled by a dedicated microprocessor, following the commands dispatched by the main data processor on board the spacecraft. When the Sun is quiet, whole-Sun images are taken together with up to four bright active regions which are monitored at a moderate rate. When a flare occurs, the observation will be concentrated on the brightest region by taking ‘partial-frame’ images with up to 0.5 s time resolution.

2.3. Wide Band Spectrometer (WBS)

The WBS (Yoshimori et al., 1991) consists of four types of detectors: the Soft X-ray Spectrometer (SXS), the Hard X-ray Spectrometer (HXS), the Gamma-Ray Spec-
trometer (GRS), and the Radiation Belt Monitor (RBM). The SXS, HXS, and GRS detectors observe the Sun, while RBM views perpendicular to the solar direction in order to monitor the radiation-belt environment of the spacecraft.

The SXS, a gas proportional counter filled with xenon, detects soft X-rays in the 2–30 keV band. Count-rate data are taken in two channels every 0.25 s and in a 128-channel pulse-height spectrum every 2 s. The HXS, a NaI(Tl) scintillation counter, detects 20–400 keV X-rays. Two-channel counting rates are taken every 0.125 s and 32-channel pulse-height spectrum every second. The GRS consists of two identical bismuth germanate (BGO) scintillators and detects 0.2–100 MeV gamma-rays, each producing six-channel count-rate data every 0.25 or 0.5 s and also a 128-channel pulse-height spectrum data every 4 s.

The RBM consists of a silicon diode detector and a NaI scintillator. The silicon detector measures counting rates of charged particles above about 20 keV every 0.25 s, while the NaI detector records counting rates in two channels every 0.25 s and 32-channel pulse-height data every second. In addition to solar flare observations, HXS and the NaI/bursts detector of RBM are used to detect cosmic gamma-ray burst during quiet periods of the Sun and during spacecraft night.

2.4. Bragg Crystal Spectrometer (BCS)

The BCS (Culhane et al., 1991) consists of four bent-crystal spectrometers with position-sensitive proportional counters. The wavelength bands covering S xv, Ca xix, Fe xxv, and Fe xxvi lines are chosen to get information about the temperature and motion of hot plasmas produced in solar flares. Each energy band has up to 256 spectral bins. The BCS is equipped with its own queue memory (384 kbytes) to store the initial-phase data with high time resolution (up to 0.125 s). The data accumulation of BCS is controlled by a dedicated microprocessor to accommodate the maximum possible number of data with suitable time resolution during a flare. Data temporarily stored in the queue memory are read out at a fixed rate by the main data processor.

3. The Spacecraft

3.1. General

The SOLAR-A is to be launched in August 1991 from the Kagoshima Space Center at latitude 31 N, longitude 131 E, by an M-3S-II launcher, into a nearly circular orbit of about 600 km altitude, 31 deg inclination, and 97 min period.

The spacecraft, schematically shown in Figure 1, has dimensions of approximately 100 x 100 x 200 cm with two external solar panels (150 x 200 cm each) outside, and weighs about 400 kg. The spacecraft body is made up of seven panels, i.e., one center panel and six surrounding panels. The center panel and two side panels form an H-shaped structure, the mechanical backbone of the spacecraft. The center panel holds the two large telescopes (SXT and HXT), as well as BCS, and plays the role of optical bench for them. The top panel facing the Sun holds the WBS detectors and also has
aperture windows for SXT, HXT, and BCS. Most of the electronics units are attached to the four side panels and the bottom panel.

Two solar cell panels are to supply about 570 W during spacecraft day. Excess power in daytime is stored into NiCd batteries for the power required during night. By this arrangement, about 220 W of power during day and 180 W during night are available.

The major parameters of the spacecraft are summarized in Table III.

3.2. ATTITUDE CONTROL

Since the SOLAR-A spacecraft is to take high spatial resolution images as well as spectra, precise control of the attitude is crucially essential. Thus it is stabilized in all three axes and its Z-axis (cf. Figure 1) is pointed at the center of the Sun with a stability of the order of 1 arc sec s\(^{-1}\) and several arc sec min\(^{-1}\). The Y-axis is directed toward celestial north.

The attitude control system uses momentum wheels, magnetic torquers, and control-moment gyros as the actuators. As the attitude sensors, two Sun sensors and a star tracker, as well as geomagnetic sensors, are available for determining the spacecraft pointing relative to the direction of the Sun and to the ecliptic plane, respectively, while an inertial reference unit comprising four gyros detects changes of attitude with time. As a whole, the attitude system, using elaborate control programs with microprocessors, keeps the three axes well inside the requirements specified in Table III. The accuracy of Z-axis determination is estimated to be about 1 arc sec, disregarding bias error due
### TABLE III

Major parameters of SOLAR-A

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>~100 cm (L), 100 cm (W), 200 cm (H)</td>
</tr>
<tr>
<td>Weight</td>
<td>~400 kg</td>
</tr>
<tr>
<td>Power</td>
<td>~570 W (maximum; supply from solar cells)</td>
</tr>
<tr>
<td>Data recorder</td>
<td>10 Mbytes (magnetic bubble memory)</td>
</tr>
<tr>
<td>Data rate</td>
<td>32, 4, or 1 kbps</td>
</tr>
<tr>
<td>Telemetry rate</td>
<td>32, 4, or 1 kbps (real-time data)</td>
</tr>
<tr>
<td></td>
<td>262 kbps (reproduced data from the data recorder)</td>
</tr>
<tr>
<td>Orbit</td>
<td></td>
</tr>
<tr>
<td>Altitude</td>
<td>~600 km (nearly circular)</td>
</tr>
<tr>
<td>Inclination</td>
<td>~31 deg</td>
</tr>
<tr>
<td>Period</td>
<td>~97 min</td>
</tr>
<tr>
<td>Attitude control (requirement)</td>
<td></td>
</tr>
<tr>
<td>Absolute pointing</td>
<td>a few arc min</td>
</tr>
<tr>
<td>Stability</td>
<td>around X/Y-axes (origin of image)</td>
</tr>
<tr>
<td></td>
<td>&lt;36 arc sec hr$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>&lt;7 arc sec min$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>&lt;1.2 arc sec s$^{-1}$</td>
</tr>
<tr>
<td>Z-axis pointing determination</td>
<td>≤1 arc sec</td>
</tr>
<tr>
<td>Offset pointing</td>
<td>capable, up to 45 arc min from the Sun center</td>
</tr>
<tr>
<td>Ground stations</td>
<td></td>
</tr>
<tr>
<td>Commanding and downlink</td>
<td>Kagoshima Space Center (131 E, 31 N)</td>
</tr>
<tr>
<td>Downlink only</td>
<td>NASA stations at Goldstone, Madrid, and Canberra</td>
</tr>
</tbody>
</table>

...to misalignment of the fine Sun sensor. Note that the two imaging telescopes have their own aspect sensors.

### 3.3. ONBOARD DATA PROCESSING

The scientific instruments of SOLAR-A, especially SXT, require sophisticated control of flight operations to exploit their capabilities within the constraints of the telemetry data rate and the capacity of the data recorder (cf. Table III). This is achieved by the 'data processor' (DP) unit.

The DP consists of dual redundant microcomputer systems. Further, the most essential parts of the DP functionality can also be achieved by hardwired logic if both of the microcomputer systems should fail to operate.

The fundamental functions of DP are as follows:

1. Data gathering from all the instruments.
2. Data processing and editing into the telemetry stream.
3. Data recording to and data dump from the data recorder, including complicated control of the data recorder (cf. Section 4.3).
4. Automated control of observing mode, the data rate, and the operation of the scientific instruments, especially SXT. The mode and rate are switched by DP depending on conditions such as occurrence of flares, spacecraft sunrise/sunset, etc.
The data can be telemetered to the ground in real time, with data rates of 32, 4, or 1 kbps, depending on the observation conditions. Since contacts with downlink stations are limited, the data are also stored in an on-board recorder, and dumped during ground-station contacts. The recorder is a magnetic bubble data recorder with 10-Mbyte capacity. Unfortunately this capacity is not sufficient for recording data continuously at the high rate (32 kbps) for a full orbital period, so that sophisticated control algorithms are required. Such operations-related items, together with data processing and editing, will be further discussed in Section 4.

3.4. Command System

An uplink commanding system controls the operation of all the instruments on the spacecraft. Commands from the ground are to be sent only from the Kagoshima Space Center, during contacts of about 10 min duration each for 5 orbits day\(^{-1}\). Each command is distributed by the telemetry command control unit to the instrument specified by the instrument code included in the command.

In addition, the control unit can coordinate sequences of commands. First, it can store up to 128 sets of `organized commands' (OG's), each being a set of up to 32 commands. An OG can be launched by an `OG start command' from the ground. Also several OG's can be automatically triggered to start at the times of interruption messages issued by specific on-board instruments. Such interruptions include sunrise/sunset (from a Sun sensor), occurrence of a flare (from DP), and emergencies in the power control system or the attitude control system. Second, a series of OG's can be dispatched sequentially with specified time intervals. Such a command series is called an `operation program (OP)', and is controlled by a program which contains a sequence of 128 OG addresses and intervals stored in the program memory. The operation program is initiated by an `OP start command' and can last for up to about 10 days, so that the operator can easily program several days' spacecraft operation beforehand.

3.5. Telemetry

Data acquired with the instruments on board SOLAR-A can be telemetered to three Deep Space Network stations at Goldstone, Madrid, and Canberra, as well as to the Kagoshima Space Center station. Two telemetry channels are used, one at S-band (2.2 GHz) and the other at X-band (8.4 GHz). At Kagoshima, the two channels are received simultaneously; the S-band channel transmits `real-time data', while the X-band transmits `reproduced data' from the bubble data recorder at 262 kbps. The 10-Mbyte data stored in the data recorder can be sent in about 5 min well within the 10-min contact duration. On the other hand, at the other stations only reproduced data are transmitted via the S-band and no real-time data are available.

Real-time data downlinked at Kagoshima are sent to ISAS at Sagamihara, near Tokyo, via a real-time data link. Reproduced data are also sent to ISAS within 30 min from downlink. Data taken at the Deep Space Network stations are brought first to the Jet Propulsion Laboratory and then transferred to ISAS through a NASA Communication (NASCOM) line in less than a few days. For archiving and scientific analysis
all of the data are finally stored and maintained in a database system at ISAS. For more information the reader should refer to the article by Morrison *et al.* (1991).

4. Operations

Since the primary objective of SOLAR-A is to understand the high-energy aspects of solar flares, it is of crucial importance to observe as many flares as possible. Major flares are given higher priority, because such flares emit a wide range of radiations from soft X-rays to gamma-ray lines and thus make comprehensive studies possible. At the same time, the mission objectives include understanding of preflare conditions of active regions and also non-flare phenomena such as coronal holes, interconnecting loops, X-ray bright points, etc. The SOLAR-A instruments, especially the Soft X-ray Telescope (SXT), have good capabilities for making such preflare and non-flare observations. In the following we will discuss how the SOLAR-A program has been organized to accomplish these two different (and sometimes mutually contradictory) types of observations in an automated but flexible manner.

4.1. Observing modes

The spacecraft has four observing modes (‘flare’, ‘quiet’, ‘night’, and ‘BCS-out’ modes) and three telemetry data rates (‘high’ 32 kbps, ‘medium’ 4 kbps, and ‘low’ 1 kbps). The flare and quiet modes run either at high or medium bit rate. The night mode, used in spacecraft night, runs at low rate. The BCS-out mode at high rate, used specifically for sweeping out the BCS queue memory, is initiated when the spacecraft enters night or just after the flare mode ceases.

Each mode has its own telemetry data format, i.e., the telemetry assignment differs from one mode to another, as shown in Table IV. There is only one significant difference between the quiet mode and the flare mode; the four scientific instruments (HXT, SXT, WBS, and BCS) share the telemetry in flare mode, while HXT yields most of its telemetry assignment to SXT in quiet mode.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Flare mode 32 or 4 kbps</th>
<th>Quiet mode 32 or 4 kbps</th>
<th>BCS-out mode 32 kbps</th>
<th>Night mode 1 kbps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic data$^a$</td>
<td>32 bytes</td>
<td>32 bytes</td>
<td>32 bytes</td>
<td>32 bytes$^b$</td>
</tr>
<tr>
<td>HXT</td>
<td>16</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SXT</td>
<td>64</td>
<td>64 + 16$^c$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>WBS</td>
<td>8</td>
<td>8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BCS</td>
<td>8</td>
<td>8</td>
<td>64</td>
<td>-</td>
</tr>
</tbody>
</table>

$^a$ Contains the spacecraft system information, status and housekeeping data, and some basic monitoring data from the scientific instruments.

$^b$ Remaining 96 bytes are used for recording cosmic gamma-ray bursts.

$^c$ Two sections.
In quiet mode the two SXT telemetry sections (64 + 16 bytes) are assigned to obtain 'full frame' images (whole-Sun images) together with what we call 'partial frame' images (images with areas small compared to the whole CCD field of view) in parallel, i.e., one of the two is used for whole-Sun images and the other for partial-frame images. If the 16-byte section is used for whole-Sun images, the image cadence is typically once every 10 min at high data rate (assuming 2 × 2 on-chip summation mode; see Tsuneta et al. (1991) for more details). This time resolution can be improved by a factor of 4 by assigning the 64-byte section to whole-Sun images, resulting in a reduced area size and/or reduced time resolution for partial-frame images. In flare mode, on the other hand, only partial-frame images are telemetered, with no whole-Sun images. The time resolution is 2 s if the area size is 64 × 64 pixels (about 2 × 2 arc min) at high data rate.

The 'basic' section of the telemetry data format is not affected by the observing mode. This contains the spacecraft system information (clocks, command answerback, observing mode/data rate, attitude, power supplies, etc.), status and housekeeping data for all of the instruments, and also some basic monitoring data from the scientific instruments. With regard to HXT, data from the lowest-energy band (15–24 keV) are always recorded in this section, so that we can expect to obtain preflare hard X-ray images even before the flare mode is initiated by a flare. Note that at higher energies usually no hard X-rays with intensity high enough to be image-synthesized are emitted without the occurrence of a flare.

The observing modes also affect the control of the instruments. For example, the SXT control in flare mode is completely independent of that in quiet mode (for details see the separate papers in this issue).

4.2. AUTOMATED MODE CONTROL

The logic of the DP software that controls the observing modes is schematically shown in Figures 2 and 3.

At the beginning of each spacecraft day the operating mode is 'quiet' and the data rate is predetermined at 'high' or 'medium'. In this mode SXT takes whole-Sun images to monitor the global structure of the corona together with partial-frame images of active regions to monitor their development. The data taken with HXT are restricted to the lowest energy band.

When DP recognizes flare occurrence by an abrupt increase of counting rate in one of the three sensors (HXS, SXS, and BCS; selectable) above a 'flare threshold', it turns on the flare flag and initiates flare mode at high rate within the next two seconds, provided that there is no simultaneous increase in the RBM counting rates which monitor the particle background environment. In this mode the whole HXT data are sent to the telemetry, while for SXT image-processing software picks out the brightest region and edits partial-frame images for telemetry.

This mode continues unconditionally during a preset 'flare minimum duration'. After this period elapses, two thresholds are applied once every 64 s to determine the mode and data rate. If the counting rates exceed the 'great flare threshold' (case C of Figure 3), the flare mode continues at high rate. If the flare flag turns off due to lower counting
rates than the ‘flare end threshold’ (case A of Figure 3), the mode is changed to quiet. Otherwise (case B of Figure 3), the flare mode continues but the data rate is changed to medium. This allows recording any long-enduring flare until its end.

When flare mode ends, the observing mode usually returns to quiet. However, if so specified in advance, data stored in the BCS queue memory are swept out (BCS-out mode) before the quiet mode is initiated. When the spacecraft enters into the shadow of the Earth, the mode is changed into night mode, in which data taken with HXS and RBM are recorded to monitor occurrence of cosmic gamma-ray bursts and the particle environment of the spacecraft. The BCS-out mode can be initiated before night mode if its queue memory stores flare data.

Besides this automated operation, it is possible to control the observing mode manually either by directly specifying the mode or by indirectly setting/resetting flags. Such a manual control is initiated and terminated either by commands from the ground (when the spacecraft is within the reach of the Kagoshima Space Center) or by the operation program (see Section 3.4). This manual mode control function will be used, for example, for calibrating the instruments.
Fig. 3. Three flare thresholds and the control of the flare mode. The flare and flare-end thresholds are used for setting and resetting the flare flag, respectively. The flare mode starts at high data rate. After a specified time elapses, the mode and data rate depend on the flare sensor counting rates. The ‘great flare threshold’ allows classification of flares into two classes, and determines the data priority against overwrite on the data recorder (see text).

4.3. CONTROL OF DATA STORAGE TO THE BUBBLE DATA RECORDER

Because flare occurrence cannot be scheduled, an on-board data recorder is essential. However, the data can consume the bubble data recorder (BDR) capacity of 10 Mbytes in some 40 min at high rate, so that overwriting is inevitable. This causes a serious problem because one orbit day lasts for more than 60 min. This problem would become more serious in cases when some of the downlink stations were not available.

To avoid loss of important data by overwriting with less important data, the DP software is so designed as to compare the importance between the data which DP is going to write and the data which is already stored, and, if necessary, to protect the stored data by skipping.

The priority levels usually used are as follows:

‘great flare’ data > ‘normal flare’ data > quiet or night mode data.

Here ‘great flares’ are flares whose peak counting rates exceed the ‘great flare threshold’. This is the same logic as adopted in the HINOTORI mission which resulted in successful observations of many major flares (Kondo, 1983). It is to be noted, however, that in the case of SOLAR-A this overwrite control is executed by the DP software so
that it is more flexible and more powerful. The logic can protect not only flare data but also any associated preflare data. The priority levels are changeable. Further, the observer can unconditionally protect the data taken in a certain period of time by declaring a 'campaign observation'. This campaign observation function will be used to protect, for example, SXT whole-Sun images taken at a regular interval, say once in a few orbits, used for example for a 'synoptic movie' in a given filter. This function will be also useful when the SOLAR-A team makes a short-term, simultaneous observation with certain observatories in which the loss of data by overwriting would be undesirable.

5. Scientific Topics

The SOLAR-A mission is a unique space solar observatory accommodating a coordinated set of instruments. The instruments are individually advanced over their predecessors, but there is no doubt that their combination together will make scientific return more fruitful.

For example, the HXT imaging of hard X-ray sources with high time resolution in the four energy bands up to 100 keV will give us information about rapid processes occurring in the impulsive phase of a flare, as well as fainter thin-target sources showing the location of the storage of accelerated particles. Coaligned flare images taken simultaneously with SXT will be of crucial importance to locate the hard X-ray sources on the flaring loop structure seen in soft X-ray images. High-resolution images in the two energy ranges will give much-improved physical interpretations of the energy release and particle acceleration processes in solar flares. In this respect, we note that the two imagers have wide fields of view that cover the whole Sun, which guarantees simultaneous observations for most flares. Similarly the use of BCS together with SXT will allow us to discern the successive brightenings of neighboring points from the true motion of the X-ray emitting plasma.

Another advantage of SOLAR-A is that fainter objects such as loop structures in the quiet corona are expected to be observable with SXT due to its high sensitivity and wide dynamic range. The preflare evolution of active regions is an interesting objective to be examined in detail. Such non-flare objectives may include globally-distributed X-ray bright points, possibly related to the internal dynamo activity of the Sun. Another example would be the morphology of faint coronal loops that we expect to reveal the magnetic connectivity of the outer atmosphere of the Sun and the solar wind.

In the following, we briefly mention possible scientific objectives of SOLAR-A, and give comments from these viewpoints. Since a thorough survey and discussion of the objectives of SOLAR-A are beyond the scope of this introductory overview, we simply make a candidate list and give a very brief discussion of a single topic as an example.

A list of objectives may include:

(A) Flare-related phenomena

(1) Evolution of active regions, especially their preflare states, in terms of the coronal loop structures that show their magnetic connectivity and its changes.
(2) Flare onset: what happens immediately before and at the very beginning of the impulsive phase?
(3) High-temperature loops and arcades: when and how are they formed and where do the mass and energy come from?
(4) Electron accelerations: where and when exactly?
(5) Ion accelerations and gamma-ray line flares: where and when?
(6) Dynamic behavior of the footpoints of the flaring loops: mass ejection and/or evaporation from the chromosphere.
(7) Flare ejecta, shocks, and plasmoids: are they observable in X-rays?
(8) Relation between the sources of hard X-ray, soft X-ray, optical, and radio emissions.
(9) White-light flares (observable with the SXT aspect sensor).

(B) Dynamical phenomena not necessarily related to flares
(1) Surges and Brueckner's jets in X-rays.
(2) Disappearances of quiescent filaments and related phenomena (in some cases, accompanying low-energy two-ribbon flares).
(3) Coronal mass ejections and related phenomena.

(C) Other forms of activity
(1) X-ray bright points and their solar-cycle variations.
(2) Micro- and nano-flares.
(3) Formation and evolution of active-region loops.

(D) Global coronal structure, and others
(1) Formation and evolution of quiet coronal loops, if possible.
(2) Behavior of coronal holes.
(3) Solar oscillations (observable with the SXT aspect sensor).
(4) Other kinds of simple photospheric imaging.

Here we pick only one example from this list, namely, the problem of what is happening immediately before the 'flare onset'.

HINOTORI and SMM indicated (a) that evidence exists for the presence of a very important stage, in which violent uprising motions with 300–400 km s \(^{-1}\) were found in Fe \text{xxv} or Ca \text{xi} lines immediately before the flare onset (Tanaka \textit{et al}., 1983; Antonucci, 1983); (b) that an X-ray source brightens up and is confined at the top of a loop-like structure, already with high temperature when it first appears in X-rays (Tsuneta \textit{et al}., 1984), without rapid expansion or rapid cooling, requiring special mechanisms of confinement and insulation; and (c) that gamma-ray line emissions appear simultaneously with hard X-ray impulsive bursts (Forrest and Chupp, 1983; Nakajima \textit{et al}., 1983), requiring almost instantaneous ion acceleration if the impulsive phase is taken to indicate the flare onset. Observations (a) and (b) suggest the possibility that a very important dynamical phase, occurring immediately before the impulsive
phase and possibly carrying mass and energy from below, has escaped our attention thus far (Uchida and Shibata, 1988). If this turns out to be the case by observations with SOLAR-A, it would change our understanding of flares drastically. Note that, in this case, even observation (c) does not necessarily mean any instantaneous acceleration of ions. Instead it would mean the simultaneous release of both electrons and ions accelerated in a dynamical phase before the impulsive phase. The clarification of the processes occurring in this period would be vital for our understanding of flares.

This example shows that an obvious contribution which SOLAR-A can make will be to give a precise answer to the questions regarding where, when, and how mass and energy actually enters a flaring coronal loop. Whether magnetic reconnection really occurs or not can also be examined by SOLAR-A because it can give us the magnetic connectivities and their changes in the flaring locations in terms of coronal loop structures in the preflare and flaring states.

6. Concluding Remarks

There will be no other satellite project totally dedicated to solar flare observations during the current maximum period. Only the SOLAR-A mission will provide systematic data covering the broad energy range from soft X-rays to gamma-rays. The coordinated set of instruments on board this mission will provide precious and well-organized data to investigate solar flares and related high-energy phenomena in the corona. The instruments make substantial improvements over those flown earlier on spacecraft such as HINOTORI and SMM.

Although observations in X- and gamma-rays are well established to be very important in the study of solar flares, they still provide only partial information about the flare phenomenon. Solar flares have many aspects, and collaborative observations with ground-based optical and radio telescopes will be extremely important in clarifying the physics of flares and of other active phenomena. In addition, theoretical investigations that can help to synthesize a coherent picture from these complex data will be indispensable. The SOLAR-A will take part in these coordinations and contribute to the investigation of such thorny problems.

We believe that the fruitful scientific return from SOLAR-A will unfold still newer aspects of our understanding of flares and that these new aspects will lead us to develop a more advanced space observatory which, we hope, will be flown as SOLAR-B at some time in the future.

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SOLAR-A mission would not have existed. Two important persons passed away during the preparatory stage of this mission. We express our thanks to the late Prof. Katsuo Tanaka, who first proposed the SOLAR-A mission as a successor of HINOTORI, and the late Prof. Keizo Kai, who worked hard until the end as Principal Investigator for HXT. Hugh Hudson and Bob Bentley are acknowledged for their assistance in preparing this manuscript.

References


THE HARD X-RAY TELESCOPE (HXT) FOR THE SOLAR-A MISSION*

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Abstract. The Hard X-ray Telescope (HXT) is a Fourier-synthesis imager; a set of spatially-modulated photon count data are taken from 64 independent subcollimators and are Fourier-transformed into an image by using procedures such as the maximum entropy method (MEM) or CLEAN. The HXT takes images of solar flares simultaneously in four energy bands, nominally 15 (or 19)-24, 24-35, 35-57, and 57-100 keV, with an ultimate angular resolution as fine as ~ 5 arc sec and a time resolution 0.5 s. Each subcollimator has a field of view wider than the solar disk. The total effective area of the collimator/detector system reaches ~ 70 cm², about one order of magnitude larger than that of the HINOTORI hard X-ray imager. Thanks to these improvements, HXT will for the first time enable us to take images of flares at photon energies above ~ 30 keV. These higher-energy images will be compared with lower-energy ones, giving clues to the understanding of nonthermal processes in solar flares, i.e., the acceleration and confinement of energetic electrons. It is of particular importance to specify the acceleration site with regard to the magnetic field configuration in a flaring region, which will be achieved by collaborative observations between HXT and the Soft X-ray Telescope on board the same mission.

1. Introduction

The SOLAR-A mission is the second satellite of the Institute of Space and Astronautical Science, Japan (ISAS) dedicated to the study of solar flares. The first solar-flare mission, HINOTORI, was launched during the previous maximum in February 1981. At that time the Solar Maximum Mission (SMM) had been in operation for about one year with almost the same scientific objectives as HINOTORI. Each of the two missions conducted a wide variety of observations in the X- and γ-ray ranges (including EUV and visible-light observations in the case of SMM), and diagnosed high-energy particles and high-temperature plasmas involved in flares. In particular, the two missions made the first hard X-ray imaging observations of flares (Van Beek et al., 1980; Makishima, 1982).

Hard X-rays are produced by collisions of high-energy electrons with ions (bremsstrahlung) and their propagation is almost unaffected by the solar atmosphere above the photosphere. Accordingly, images taken in this range provide direct information on the generation, transfer, and confinement of high-energy electrons. In fact, the two earlier experiments revealed that hard X-ray imaging observations were very promis-

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* After the launch the name of SOLAR-A has been changed to YOHKOH.


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ing, as expected. At the same time, the experiments should be regarded as preliminary ones; the two imagers had only one or two energy bands in the hard X-ray range, all below $\sim 30$ keV, and the angular and temporal resolutions were not sufficient. Thus, it is evident that an advanced hard X-ray imager will play a very important role to settle the puzzles of solar flares (e.g., Dennis, 1988). The Hard X-ray Telescope (HXT) for the SOLAR-A mission is such an instrument.

In the following, we will give an overview of HXT and its scientific objectives in Section 2. These objectives and the expected properties of the sources lead to X-ray optical design and the image synthesis principle (Section 3). Section 4 gives an outline of the HXT instrument. A few remarks will be made in Section 5 with regard to the performance of the flight instrument.

2. HXT Overview

The HXT is a Fourier-synthesis imager of 64 elements; each subcollimator measures a spatially-modulated incident photon count. A set of photon count data from the 64 subcollimators are telemetered to the ground and synthesized there into an image through, at least in principle, the Fourier transform.

Instrumentally HXT consists of three major sections (Figure 1).

The collimator (HXT-C) is the X-ray optics part of the instrument. Simply it is a metering tube ($417$ mm $\times$ $376$ mm $\times$ $1400$ mm) with X-ray grid plates at both ends. Each grid plate is an assembly of 64 subcollimator grids made of tungsten $0.5$ mm thick. At the center of the X-ray optics is installed the aspect system (HXA) optics, which include lenses with appropriate filters on the front grid plate and fiducial marks on the rear plate, thus providing white-light images of the Sun which yield the axis direction information of the X-ray optics with respect to the solar disk. The HXT-C weighs $\sim 13.5$ kg.

The detector assembly (HXT-S; S denotes sensors) is a package of 64 detector modules ($465$ mm $\times$ $392$ mm $\times$ $223$ mm, weight $\sim 17.1$ kg); each module consists of a NaI(Tl) scintillation crystal ($25$ mm square) and a photomultiplier tube, with dynode bleeder string and pre-amplifier assembled as a unit. Eight high-voltage power supply units are attached to HXT-S. The HXT-S also has two one-dimensional CCD's at the center for detecting HXA visible-light signals.

The electronics unit (HXT-E) is $374$ mm $\times$ $246$ mm $\times$ $220$ mm in size and $\sim 10.8$ kg in weight. It processes hard X-ray signals from HXT-S; first it converts pulse-height analogue signals into digital signals and then it counts the incident photon number after discriminating the photon energy into four energy bands. Here, signals from the individual subcollimators are processed separately and simultaneously. Finally HXT-E sends the photon count data to the data processor (DP; Ogawara et al., 1991) of the spacecraft once every $0.5$ s. The HXA signals are also digitized and processed in HXT-E. In addition HXT-E plays the role of power/mode controller of the whole HXT instrument.

The main characteristics of HXT are summarized and compared with its two pre-
SOLAR-A HXT

Fig. 1. Schematic drawing of the HXT instrument. HXT consists of three major sections: the collimator (HXT-C), the detector assembly (HXT-S), and the electronics unit (HXT-E). The aspect system (HXA) is installed along the central axis of HXT-C and HXT-S.
TABLE I
Main characteristics of HXT (comparison with its predecessors)

<table>
<thead>
<tr>
<th></th>
<th>HXT (SOLAR-A)</th>
<th>HINOTORI imager</th>
<th>HXIS (SMM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collimator type</td>
<td>Multi-el. bigrid MC</td>
<td>Rotating bigrid MC</td>
<td>Multi-el. IC</td>
</tr>
<tr>
<td>No. of elements</td>
<td>64 SC's</td>
<td>2 (orthogonal)</td>
<td>(F)304; (C)128</td>
</tr>
<tr>
<td>Size of elements</td>
<td>23 mm □</td>
<td>120 mm Ø</td>
<td>7.5 mm Ø</td>
</tr>
<tr>
<td>Image acquisition</td>
<td>2D Fourier synthesis</td>
<td>1D scans → 2D image</td>
<td>1 el./1 pixel</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>~5°</td>
<td>~10°</td>
<td>8° (32&quot;)</td>
</tr>
<tr>
<td>Field of view</td>
<td>whole Sun</td>
<td>whole Sun</td>
<td>2'40&quot; (6'/24&quot;)</td>
</tr>
<tr>
<td>Synthesis aperture</td>
<td>2'06&quot;</td>
<td>2'12&quot;</td>
<td>2'40&quot; (6'/24&quot;)</td>
</tr>
<tr>
<td>Time resolution</td>
<td>0.5 s</td>
<td>~10 s</td>
<td>1.5–9 s</td>
</tr>
<tr>
<td>Energy bands (keV)</td>
<td>4 channels (Ch. L: 15(19)–24</td>
<td>1 channel (Ch. M1: 24–35, 5(17)–40</td>
<td>6 channels (Ch. M2: 35–57, Ch. H: 57–100</td>
</tr>
<tr>
<td>Detector</td>
<td>NaI(Tl) scint. (25 mm □ × 64)</td>
<td>NaI(Tl) scint. (120 mm Ø × 2)</td>
<td>Gas prop. counter (7.5 mm Ø × 900)</td>
</tr>
<tr>
<td>Effective area</td>
<td>~70 cm²</td>
<td>~8 cm² × 2</td>
<td>0.07 cm² pixel⁻¹</td>
</tr>
</tbody>
</table>

Note: MC = modulation collimator; IC = imaging collimator; SC = subcollimator; 2D = two-dimensional; 1D = one-dimensional; (F) = fine field of view; (C) = coarse field of view.

decessors in Table I. As can be seen from the table, HXT has several advantages over its predecessors. These include:

− higher energy range to ~100 keV,
− higher sensitivity,
− improved angular and temporal resolutions,
− a wide field of view covering the whole Sun, and
− simultaneous observation with the Soft X-ray Telescope (SXT; Tsuneta et al., 1991) on board the same mission.

With these advanced characteristics, HXT will make the first imaging observations in the ≥ 30 keV hard X-ray range, collect many examples of hard X-ray flares, and help to answer the following specific questions about solar flares:

(1) Where are electrons accelerated in flaring magnetic flux loops: inside a highly-stressed single loop or at the interaction site of multiple loops?

(2) How does the acceleration process take place? Are electrons accelerated in a direction parallel to the magnetic lines of force or perpendicular? Or are electrons energized randomly? In what conditions does the process work?

(3) What causes the double-source structure of hard X-ray sources in impulsive (type B) flares? Do down-streaming electron beams exist and play an important role?

(4) Is there a different acceleration process operating in gradual hard (type C) flares from that of impulsive (type B) flares? What makes hard X-ray sources appear high in the corona?
(5) What determines the type of a flare? Is it a plasma parameter such as density or plasma $\beta$, or the magnetic field topology?

(6) Are electrons and ions accelerated simultaneously by a single process or separately? Are ions accelerated in a specific type of flare? If ions are accelerated in a different phase or step from electrons, what causes the second phase or step? (This topic will be pursued with simultaneous observations with the Gamma-Ray Spectrometer (GRS; Yoshimori et al., 1991) on board the same mission.)

(7) How are the energized electrons confined in a magnetic flux loop or an arcade of loops? Does reacceleration of electrons take place?

(8) As a whole, what role does the acceleration of particles play in a flare? Is it a minor episode in a complicated flare process, or is it the main cause of subsequent thermal responses of the flaring solar atmosphere?

3. Design and Image Synthesis Principles

The HXT instrument is the world’s first X-ray telescope that adopts the Fourier synthesis principle for taking images. This type of telescope was first discussed by Makishima et al. (1978) as multi-pitch modulation collimator (MPMC). Recently, in the course of design study for an advanced flare-oriented hard X-ray telescope, Prince et al. (1988) proposed a Fourier-transform telescope using position-sensitive detectors, each using one subcollimator and measuring one complex Fourier component.

The HXT is a Fourier-synthesis telescope with a novel design principle. Each subcollimator has a normal, non-position-sensitive detector and measures only one of a Fourier component pair. Here we use the term Fourier component for simplicity. Note that here and in the following the term does not have the usual sense – a coefficient in a series of trigonometric expansion of a function – but is generalized.

The design principle of HXT is based upon the fact that a single modulation collimator, with two identical grids having pitch (slit spacing) twice the slit width, gives a transmission function that is a repetitive triangular pattern. The function resembles the trigonometric (cosine or sine) function if we disregard the DC component involved. A brief explanation of the principle is given in Figure 2 and in what follows.

Let us represent the transmission function of one of a pair of subcollimators by

$$ F_c(k\rho); \quad \rho = X \cos \theta + Y \sin \theta, $$

where $k (= 1, 2, \ldots)$ denotes the wave number, $k\rho$ the modulation phase, $\theta$ the position angle of the grid pattern, and $X$ and $Y$ the spatial coordinates normalized to the fundamental ($k = 1$) period of repetition. In addition to this first subcollimator of the pair, there is a second whose position angle and pitch are the same as those of the first but whose relative slit positions are shifted by a quarter of the pitch. The transmission function of the second is then

$$ F_s(k\rho) = F_c(k\rho - \pi/2), $$

i.e., the pattern is the same as the first, but its phase is shifted by 90° from the first.
This relation is analogous to that between the cosine and sine functions. The subscript of $F$ (C or S) is added to express this relation. Using the pair of subcollimators, we obtain two photon count data:

$$b_c(k, \theta) = A \int B(X, Y) F_c(k \rho) \, dX \, dY,$$

$$b_s(k, \theta) = A \int B(X, Y) F_s(k \rho) \, dX \, dY,$$

which represent one generalized complex Fourier component. Here $B(X, Y)$ is the X-ray brightness distribution to be imaged and $A$ is an effective area of the subcollimator/detector system.
If the data actually represented a usual complex Fourier component, and also if measurements were made at a sufficient number of \((k, \theta)\)-points, \(B(X, Y)\) could be calculated from an inverse Fourier transform. In HXT as in other applications, however, the two conditions are not fully satisfied. In the case of super-synthesis radio telescopes, radio astronomers have developed an image synthesis procedure called CLEAN (Högbohm, 1974) for the reconstruction of an image from an incomplete set of measurements. Even the first condition is not a vital one; radio and X-ray astronomers have introduced the maximum entropy method (MEM) for reconstructing an image, where no specific requirement is made on the transmission patterns (e.g., Frieden, 1972; Gull and Daniell, 1978; Willingale, 1981). Thus the sophisticated problems such as the orthogonality and completeness of a system of functions in the mathematical sense are not required to be directly related to the HXT image synthesis problem of ours. Rather our problem is a more practical one.

The following describes our practical approach to image synthesis, using simulated sources and realistic HXT response properties. First we wrote computer programs to simulate the observations and to perform image syntheses. For the image synthesis step, using the analogy of HXT with radio telescopes of Fourier-synthesis type and also benefiting from our previous HINOTORI observations (Tsuneta, 1984; Kosugi and Tsuneta, 1983), we adopted two methods in parallel: one is MEM and the other modified CLEAN. The original CLEAN technique makes use of the Fourier transform to synthesize dirty maps and this transform cannot be applied to our case, so that this part was replaced by a newly-developed procedure.

Next we made numerous computer simulations for a wide variety of model brightness distributions and at different intensity levels. The purposes of the simulations are threefold:

1. to confirm that the design principle of HXT is correct and that the above-mentioned image synthesis methods work well;

2. to find the minimum number of subcollimators and also the optimum arrangement of them on the \((k, \theta)\)-plane; and

3. to know the effect of observation errors, namely the effective area error and the phase error, on the quality of synthesized images.

Before making the simulations, a few \textit{a priori} assumptions and restrictions were introduced in the HXT design study. An assumption was that the angular extent of the hard X-ray flare is less than \(\sim 2\) arc min; this determines the fundamental period of repetition or the ‘synthesis aperture’ (= 2’06”). The SMM and HINOTORI results suggest that this assumption is not unreasonable. We chose the highest wave number, \(k_{\text{max}}\), to be 8 (in units of the fundamental spatial frequency). This choice is a compromise with the difficulty of fabricating fine grids. Finally we used a symmetrical polar diagram \((k, \theta)\), not a rectangular grid for arranging the subcollimators on the \((u, v)\)-plane. This is because an arrangement of subcollimators at regular lattice points on the \((u, v)\)-plane produces on the image plane a repetitive pattern with the fundamental period (so-called grating response) resulting in ambiguity of the flare position.

From the simulations we confirmed the feasibility of partial \((u, v)\)-plane coverage, at
least as far as a sufficient number of, say, more than $\sim 50$, complex Fourier components are available. As the number of subcollimators is reduced, the quality of the synthesized images becomes gradually worse. At the same time, the synthesized images from a set of Fourier elements alone tend to deteriorate for relatively extended sources. We found that this tendency can be overcome by replacing the Fourier elements at low wave numbers by what we call 'fanbeam elements' (cf. Figure 3). On the other hand, replacement of Fourier elements at high wave numbers by fanbeam elements results in reduced angular resolution.

Considering all these results together with construction and maintenance problems, we have determined the number of subcollimators to be 64 and chosen as the optimum design the subcollimator arrangement on the $(k, \theta)$-plane as shown in Figure 3.

Fig. 3. (a) Arrangement of subcollimators in Fourier-transform space, the $(u, v)$-plane in which $u$ and $v$ represent the spatial wave numbers of the modulation pattern. Each dot denotes the position at which one pair of Fourier-element subcollimators provides angular information. The fanbeam elements provide information along the arrows near the origin of the $(u, v)$-plane. The wave number $k$ is given in units of the fundamental repetition period, i.e., 2.1 arc min. (b) The modulation patterns for a set of fanbeam elements. (c) Same as (b) for a Fourier-element pair.
Fig. 4. Examples of image-synthesis simulations by MEM for the actual HXT design. Restored maps (bottom) are compared with the corresponding original maps (top) for scattered compact sources (a), double sources (b), and diffuse sources (c). Contour levels are 10% steps (solid lines) and 5% (dashed lines) of the peak. Each box is $\sim 2 \times 2'$. The incident X-ray fluence is given at the top. The separations between the adjacent sources in (a) are 6", 8", 11", and 15". The phase error of 1.0" (r.m.s.) of the 64 transmission functions is incorporated in addition to the Poisson noise in (c).
Examples of synthesized images obtained from the simulations corresponding to the actual design of HXT are shown in Figure 4. The angular resolution experimentally determined from simulations is \( \sim 5 \) arc sec.

With regard to the observation errors, we obtained the following results:

1. The effective area and phase errors do not severely deteriorate the image quality if they are correctly evaluated, since they can be removed in the image synthesis procedure.

2. The synthesized images become quite unstable, when:
   - the effective areas of the 64 subcollimators are not evaluated with an accuracy of less than 5\% in the r.m.s. sense, or
   - the peak positions of the 64 transmission functions are not evaluated with an accuracy of less than 1 arc sec in the r.m.s. sense.

It is to be remarked that the effective area errors are not only related to the subcollimator optics but also to the detector/electronics system of HXT, since the photon count is very sensitive to the energy discrimination levels. Considering the steepness of the flare hard X-ray spectrum (power-law spectrum with the index around \( \gamma \approx 4 \)), the \( \sim 5\% \) accuracy in effective area corresponds to \( \sim 1\% \) accuracy requirement on the gain of the pulse-height analysis. The peak position error criterion may be slightly relaxed for subcollimators at low wave numbers.

4. The Instrument

From the viewpoint of structure, HXT is divided into three major sections, i.e., the collimator (HXT-C), the detector assembly (HXT-S), and the electronics unit (HXT-E). Functionally it is divided into the X-ray optics part, the X-ray detection/signal processing part, the aspect system (HXA) part, and the power/mode control part. The spacecraft data processor (DP) also plays a role in editing HXT data.

Thus in the following, first we will give an outline of HXT-C, HXT-S, and HXT-E in Sections 4.1 through 4.3, respectively, with concentrated attention to the X-ray detection/signal processing part. The HXA-related items will be described separately in Section 4.4 and the data handling in DP in Section 4.5. The power/mode control of HXT will be mentioned where it is necessary.

4.1. Collimator (HXT-C)

The roles of HXT-C are the X-ray optics, which provide the 64 independent transmission (modulation) patterns necessary for synthesizing images, and the HXA optics. The two sets of optics require high standards of structural stability to permit coalignment between the individual subcollimators and also between the X-ray and HXA optics systems; note that, if absolute alignment of the order of 1 arc sec is required, a relative shift of one grid with respect to the others smaller than \( \sim 10 \mu m \) should be held. Thus the whole system of HXT-C (except for some minor portions corresponding to two visible-light paths for HXA) is covered by a thermal shield to maintain as homogeneous and stable a temperature as possible. The HXT-C is thermally completely passive.
4.1.1. Metering Tube

The metering tube of HXT is a box 1400 mm long and sustains two grid assemblies each 402 mm × 362 mm wide and \( \sim 3 \) kg in weight at both ends by face plates. Because of weight and stiffness requirements, the tube is made of CFRP (carbon-fiber reinforced plastic; \( \rho \sim 1.7 \text{ g cm}^{-3} \)) with twelve carbon-fiber sheets stratified quasi-isotropically for minimizing the coefficient of thermal expansion \( (\alpha < 1 \times 10^{-6} \text{ deg}^{-1}) \) is achieved. The CFRP box is \( \sim 1.3 \) mm thick at the side plates and \( \sim 2.1 \) mm thick at the face plates, with three stiffeners encircling the side plates. The stiffeners are also used as attachment points to the spacecraft body (cf. Figure 1). The metering tube itself weighs \( \sim 8.0 \) kg.

Mechanically the tube is very resistive against deforming forces. Since any small lateral shift of the rear face plate with respect to the front one can be calibrated by HXA, the most damaging deformation mode for the X-ray optics is a twist between the front and rear plates. The tube stiffness against a twisting torque \( T \) is given by

\[
\theta \text{(arc min)} = 0.025T \text{(kg m)}.
\]

The metering tube is thus extremely stiff, stiffer than the spacecraft center panel to which HXT-C is attached; however, it is still possible that thermal expansion or mechanical deflection of the center panel would deform the metering tube at a certain level. Accordingly a special attachment has been devised to avoid such an effect.

4.1.2. Grid Assemblies

The two grid assemblies carry the tungsten grids for the 64 X-ray subcollimators. The aspect lenses with filters are at the center of the front grid assembly, and the fiducial marks at the corresponding position on the rear. The two grid assemblies are fastened by screws to the CFRP face plates.

Each grid assembly consists of a base plate, four fanbeam element units, and six Fourier element units (Figure 5(a)). The base plate is a single molybdenum plate 1.5 mm thick and holds both the X-ray elements and the aspect optics. The plate has 64 square holes (with rounded corners) for the X-ray optics. Each hole has a dimension of 37 mm (front) and 23 mm (rear). The size of the rear hole determines the aperture (effective area) of each subcollimator, and the front hole is larger than the rear one to give full aperture efficiency at any point on the Sun.

Each of the fanbeam element units is a 0.5-mm thick tungsten plate with four fanbeam grids of one position angle, and is set at a corner of the base plate. The grids are fabricated by the electric discharge method. On the other hand, the six Fourier element units, each with eight Fourier grids of one position angle, are the stack of ten tungsten foils, each 50 \( \mu \text{m} \) thick, with a molybdenum covering plate 0.5 mm thick. The grids are fabricated by the photo-etching processing. The grid parameters are summarized in Table II.

Figure 5(a) schematically shows the geometrical arrangement of the 64 subcollimators. This diagram shows the slit directions, wave numbers, and the locations of the cosine and sine pairs. The rules for the layout are:
Fig. 5a. Arrangement of the 64 subcollimators on the grid assemblies (top view). The slit directions of the individual grids are represented by the hatching. The cosine and sine Fourier element pairs are shown by solid and broken hatching lines, respectively, with the number of lines denoting the wave numbers.

Fig. 5b. Top view of the detector assembly (HXT-S). The numbered (in octal) squares represent the 64 scintillation counters, grouped in units of 8 modules as shown. At the left- and right-hand sides, the sketch shows the 8 high-voltage supplies, one for each detector unit. The inclined oblong boxes represent the one-dimensional CCD arrays of the HXT aspect system.
TABLE II
Grid main parameters

<table>
<thead>
<tr>
<th></th>
<th>Fanbeam elements</th>
<th>Fourier elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of elements</td>
<td>16</td>
<td>48</td>
</tr>
<tr>
<td>Mosaic structure</td>
<td>4 el. × 4</td>
<td>8 el. × 6</td>
</tr>
<tr>
<td>Position angles</td>
<td>0, 45, 90, 135 deg</td>
<td>0, 30, 60, 90, 120, 150 deg</td>
</tr>
<tr>
<td>Number of phases</td>
<td>4 (90° step)</td>
<td>2 (cosine and sine)</td>
</tr>
<tr>
<td>Wave numbers</td>
<td>$k = 1, 2$</td>
<td>$k = 3, 4, 5, 6, 7, 8$</td>
</tr>
<tr>
<td>Pitch (arc sec)</td>
<td>126</td>
<td>42.0, 31.5, 25.2, 21.0, 18.0, 15.8</td>
</tr>
<tr>
<td>Slit width (μm)</td>
<td>210</td>
<td>140, 105, 84, 70, 60, 60</td>
</tr>
<tr>
<td>Wire width (μm)</td>
<td>630</td>
<td>140, 105, 84, 70, 60, 45</td>
</tr>
<tr>
<td>Material</td>
<td>0.5 mm thick tungsten</td>
<td>0.05 mm thick tungsten foil × 10</td>
</tr>
<tr>
<td>Process method</td>
<td>electric discharge</td>
<td>photo etching</td>
</tr>
</tbody>
</table>

(i) The elements of the same position angle are put together in the same unit. This is to make it easy to synthesize one-dimensional images with less danger of phase errors between the same position-angle elements.

(ii) The cosine–sine pair are located adjacent to each other, because to keep the phase difference at exactly 90° is of vital importance.

(iii) Elements with higher wave numbers are concentrated toward the central portions of the assemblies, and the slit directions are selected to be as nearly tangential as possible. This is for reducing a bad effect in case the metering tube happens to twist.

In order to assemble the X-ray optics with very high accuracy, each component has an appropriate number of knockpin holes which ensure a positional accuracy of ~5 μm. Also the grid assemblies have six additional grid patterns (two at the center near the aspect optics and four on the fanbeam element units) together with through holes which transmit visible light. They are used for the purpose of coalignment between the front and rear assemblies.

4.2. DETECTOR ASSEMBLY (HXT-S)

As shown in Figure 5(b), the detector assembly is composed of 64 identical detector modules, eight high-voltage power supplies (each for eight detector modules), and two one-dimensional CCD arrays for the aspect optics.

4.2.1. Detector Modules

A detector module consists mainly of a NaI(Tl) scintillation crystal and a photomultiplier tube; each module has a high-voltage bleeder string and pre-amplifier in its housing (Figure 6). Eight detector modules are packed together to form a detector unit in a magnesium frame, and eight detector units are tied together to form the detector assembly. The detector part is thermally shielded from the high-voltage power supplies, the main heat sources. The high heat conductivity helps to keep the temperature inside the detector assembly homogeneous.

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The crystal has a slightly larger dimension (25 mm) than the grid aperture. It is 5 mm thick, which determines the X-ray detection efficiency at high energies. The crystal is surrounded by an aluminum case. The case, 0.8 mm (± 0.01 mm) thick at the front of the crystal, plays the role of an X-ray filter to avoid pulse pile-up due to the flare soft X-rays. In addition to the aluminum filter, X-rays pass through the two CFRP face plates each 2.1 mm thick. Figure 7 shows the spectral response of HXT. (Also is given in this figure the absorption efficiency or the stopping power of the 0.5-mm tungsten plate.)

The photomultiplier tube (HPK 2497 from the Hamamatsu Photonics Co.) is of an anti-vibration type, and is magnetically shielded by μ-metal to suppress gain variation.

The energy resolution (FWHM) of a typical module is given experimentally as

$$\Delta E/E \sim 1.3E^{-1/2} \quad (E \text{ in keV}),$$

a normal value for a NaI(Tl) crystal.

For calibrating the pulse-height gain, a calibration source is attached for each module at the center of the aluminum case front cover. The source is a radioisotope $^{241}$Am whose line emission at 59.5 keV is used as a reference point of the pulse-height gain. Since the source is physically small (4 mm$^2$; ~0.6% of the aperture) and gives only a few to several counts s$^{-1}$ per detector, it does not interfere with flare observations. (A special output mode of HXT data exists for calibration data, see Section 4.3.)

The time constant of the charge amplifier is ~10 μs so that each detector can measure incident photon counts up to a few times $10^4$ cts s$^{-1}$ without being strongly bothered by the pulse pile-up problem. This limit is large compared to the largest flare yield expected to be ~$10^4$ cts s$^{-1}$.

4.2.2. High-Voltage Power Supply Units

One DC-DC converter supplies high voltage to the eight modules in one detector unit. The output voltage of each converter can be chosen from eight levels by a command from the ground. The eight levels are initially set to be between ~800 V and ~1050 V.
Fig. 7. Spectral responses of HXT-S and HXT-C. The detection efficiency against X-ray photon energy of the NaI(Tl) scintillation crystal (5 mm thick) is shown by the thick line; the transmission efficiencies of the Al filter (0.8 mm thick) alone and plus the two CFRP face plates (each 2.1 mm thick) by dashed and thin lines, respectively; and the absorption efficiency or the stopping power of the tungsten grids (0.5 mm thick) by dotted line.

with a step of $\sim 35$ V. This enables us to adjust the pulse-height gain of the eight modules simultaneously by a step of $\sim 20\%$ (coarse gain adjustment).

The high-voltage output can be reduced to nearly zero without turning off the control circuit of the supply. This function is used when the spacecraft enters the radiation belt, where photomultiplier tubes could be damaged if high voltage continued to be supplied; leaving the control circuit on increases the stability of the output. This function is also used during satellite night when all the HXT analogue electronics part turns off to reduce the power consumption.

4.3. Hard X-ray Signal Processing in the Electronics Unit (HXT-E)

The block diagram of the X-ray signal processes is shown in Figure 8. Each of the analogue signals sent from the 64 modules is first gain-adjusted by an operational amplifier. Here the level of the gain is chosen by a command from 64 levels with a step
of $\sim 1\%$ (fine gain adjustment). Then, in the peak detection circuit, pulses contained in the signal are detected one by one and digitized by a 6-bit flash A/D converter (RCA CA3306D) whenever the pulse height exceeds the analogue discrimination level (selectable from two levels corresponding to $\sim 15$ and $\sim 19$ keV, both slightly lower than the corresponding digital discrimination levels; see below). The 6-bit value is nominally related to the incident photon energy as
\[
\text{energy (keV)} = (1.35 \times \text{value}) + 13.6.
\]

Up to this point the 64 modules are independent, each with its own circuit. Further signal processing depends on the operation mode of HXT, observation or calibration.

4.3.1. Observation Mode (Pulse Count Mode)

When observing the Sun, each digital data value is sent to an encoder for binning into one of the four counters as detailed in Table III with the nominal photon energy range. The digital value that corresponds to the lower limit of channel ‘L’ (digital discrimination level) is selectable between values of 1 or 4. Pulses with values lower than this number are not counted in any of the channels.

All photon count data from the 256 ($= 4 \times 64$) counters are sent to the spacecraft data processor every 0.5 s simultaneously. Each counter is 12 bits so that the maximum count is 4095. It can be used cyclically when the photon count exceeds this number, although such big flares rarely occur.
### TABLE III

Four PC channels in the observation mode

<table>
<thead>
<tr>
<th>Channel</th>
<th>Digital data value</th>
<th>Energy range (nominal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>1(4) – 7</td>
<td>15.0(19.0)–24.4 keV</td>
</tr>
<tr>
<td>M1</td>
<td>8–15</td>
<td>24.4–35.2</td>
</tr>
<tr>
<td>M2</td>
<td>16–31</td>
<td>35.2–56.8</td>
</tr>
<tr>
<td>H</td>
<td>32–63</td>
<td>56.8–100.0</td>
</tr>
</tbody>
</table>

#### 4.3.2. Calibration Mode (Pulse Height Mode)

This mode starts and ends when so commanded from the ground. In this mode each digital value is sent together with the detector module number to the counter memory, where the photon count is binned in 64 channels directly corresponding to the digital pulse heights. The memory consists of two buffers, each of which is 4096 ( = 64 x 64)-channel, 8-bit counters, for ensuring data accumulation during the data transfer. These pulse height data are sent to the data processor every 8 s.

Since this mode is used for calibrating the pulse-height gain of the individual modules, it is turned on when the background noise is expected to be the smallest during spacecraft night. In good conditions and with an integration time of \( \sim 1000 \) s, we can measure the peak position of the 59.5 keV emission line to an accuracy less than a few percent. Actually the gain calibration measurement will be repeated till a uniformity of the gain to \( \sim 1\% \) between the 64 modules is attained. Thanks to the stability of the modules and circuits we expect readjustment to be necessary less than once per month.

#### 4.4. Aspect System (HXA)

The scientific return of HXT strongly depends on whether the positions of hard X-ray sources can be determined with respect to the soft X-ray and visible-light features observed with the Soft X-ray Telescope and ground-based instruments. This is achieved by the aspect system (HXA) with approximately 1 or 2 arc sec accuracy. Although the spacecraft has an attitude control system equipped with aspect sensors (a Sun sensor and a star tracker) and an inertial reference unit which can provide the aspect of the spacecraft with less than 1 arc sec accuracy and a sufficient time resolution, none of them can be coaligned with the X-ray optics of HXT accurately enough for this purpose. The HXA optics, mounted at the center of the two grid assemblies, provide the precise information necessary.

The HXA optics consist of two identical systems. Each is composed of an achromatic, doublet imaging lens 10 mm in diameter with filters on the front grid assembly, a set of fiducial marks located on the rear grid assembly, and a one-dimensional CCD which is placed at the top of HXT-S and measures the white-light brightness distribution of the Sun. The lens center and fiducial marks determine the HXA optical axis, which is referred to as the X-ray ‘axis’ by metrology. The two CCD’s are set to the orthogonal directions to each other.
In HXT-E the CCD video signals are digitized and processed in two complementary ways in parallel. One is that the addresses of pixels whose video signals intersect the discrimination level (selectable from four levels) are sent to the data processor one every second. The other is the output of the complete brightness distributions at a slower rate of once every 64 s (high telemetry bit rate case).

4.5. ONBOARD DATA HANDLING IN THE DATA PROCESSOR (DP)

The spacecraft data processor (Ogawara et al., 1991) receives HXT data and edits them together with other scientific and auxiliary data into a telemetry format according to the observing mode (quiet, flare, night, and BCS-out mode) and the telemetry bit rate (32, 4, or 1 kbps). Here we briefly summarize HXT-related items.

4.5.1. Pre-storage of X-Ray Data for 4 s

The HXT data have no allocation of telemetry words in quiet mode except for channel ‘L’. This is not unreasonable because almost no hard X-rays are emitted from outside flaring regions. The problem is, however, that the flare flag can only be set after a flare commences, so that a few seconds elapse before the automatic mode change. In order to avoid loss of initial data of a flare, all the X-ray data from HXT are kept in a buffer for 4 s before sent to the subsequent processing, regardless of mode or the telemetry bit rate.

4.5.2. Time Resolution and Sampling

In flare mode the data processor transmits four-channel HXT data at 0.5 s resolution (high bit rate) or at 4 s resolution after integration (medium bit rate). In addition to this, the channel ‘L’ data are separately transmitted at 2 s (high bit rate) or 16 s (medium bit rate) resolution as a backup for all observing modes except during spacecraft night when the HXT analogue electronics turn off. Although this backup output is mainly for house-keeping purposes, it also provides scientific data for preflare or postflare hard X-ray images.

4.5.3. Data Compression

Each 12-bit pulse count data word is reduced (after any summing of individual 0.5 s data) to an 8-bit number according to the following function:

\[
    m = n \quad (n = 0-15), \\
    m = \text{int}(4 \times \sqrt{n}) \quad (n = 16-4080), \\
    m = 255 \quad (n = 4081-4095),
\]

where int(x) represents the truncated integer value of x. This mapping ensures that digital error due to the bit reduction is always smaller than the Poisson noise statistical error by a factor of two, i.e.,

\[
    \Delta n' = [(m + 1)^2 - m^2]/16 \sim m/8 \sim \sqrt{n}/2.
\]
Because of this, the $n'$ values estimated from 8-bit $m$'s have almost the same standard deviations as the original $n$ values.

5. Final Remarks

As is summarized in Table I, the design characteristics of HXT greatly improve on those of its two predecessors. Because it is a Fourier-synthesis telescope, it achieves both high sensitivity and wide field of view. The modulation of X-rays up to $\sim 100$ keV becomes possible owing to the precise fabrication of tungsten grids by the electric discharge and photo-etching methods. The HXT owes its improvement over the HINOTORI hard X-ray imager not only to the precision of its fine grids but also the increased length of the metering tube. Nevertheless, almost all these improvements are simply elements of the design and do not directly determine the practical performance of HXT as an imager. Since HXT is a telescope with 64 independent subcollimators, what determines the image quality of HXT is very complicated. The most important factors are:

- preciseness of the individual grids,
- coalignment between the 64 subcollimators within $\sim 1$ arc sec accuracy,
- evaluation of the individual patterns as functions of X-ray energy as accurately as possible, and
- calibration and adjustment of the individual pulse-height gain with accuracy of $\sim 1\%$.

None of these four have been achieved easily. In addition, for hard X-ray images to be successfully compared with images taken with other telescopes, coalignment between the X-ray and HXA optics within a few arc sec is highly desirable.

We have carefully examined the following points during assembling since all the components of HXT were completed in the summer of 1990:

1. The X-ray grids, examined with microscopes, are well fabricated; individual slits in a grid are cut with accuracy less than 10 $\mu$m in position and the average slit pitch differs from the design value by less than 1 $\mu$m.

2. We have examined the coalignment among the 64 subcollimators, using both optical and X-ray methods with the separation between the front and rear grid assemblies reduced, and obtained accurate enough phase-error data for the 64 subcollimators.

3. The X-ray modulation patterns for the individual subcollimators have been evaluated at photon energies below $\sim 40$ keV. (No X-ray beams are available at higher photon energies.)

4. We have checked that the pulse-height gain of the individual detector modules can be adjusted to an accuracy of $\sim 1\%$.

5. Regarding the coalignment between the X-ray and HXA optics, we have measured the misalignment due to the prism effect, etc., of the HXA optics with an accuracy of a few arc sec.

Calibration measurements will be continuously executed with higher accuracy until the launch.
Acknowledgements

We acknowledge Professors Minoru Oda, Yasuo Tanaka, and the late Prof. Katsuo Tanaka, without whose efforts the SOLAR-A project would not have existed. Dr Keizo Kai, Principal Investigator of HXT and one of the authors of this paper, passed away on 11 March, 1991, one day after this paper was submitted to Solar Physics. The rest of the authors wish to express their deep sorrow as well as their will to successfully accomplish this project. The HXT project is a joint effort between the Institute of Space and Astronautical Science, the National Astronomical Observatory, and the University of Tokyo (including both the Department of Physics and the Institute of Astronomy). This work is partially supported by the Scientific Research Fund of the Japanese Ministry of Education, Science and Culture under Grant Nos. 01540214 and 02452011.

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THE SOFT X-RAY TELESCOPE FOR THE SOLAR-A MISSION*

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Abstract. The Soft X-ray Telescope (SXT) of the SOLAR-A mission is designed to produce X-ray movies of flares with excellent angular and time resolution as well as full-disk X-ray images for general studies. A selection of thin metal filters provide a measure of temperature discrimination and aid in obtaining the wide dynamic range required for solar observing. The co-aligned SXT aspect telescope will yield optical images for aspect reference, white-light flare and sunspot studies, and, possibly, helioseismology. This paper describes the capabilities and characteristics of the SXT for scientific observing.

1. Introduction

The Soft X-ray Telescope (SXT) will provide, for the first time, the opportunity to image the Sun in X-rays over a long period of time with both high temporal and spatial resolution. It gives SOLAR-A an important capability for solar science beyond the study of flares, the primary objective of the mission. The SXT instrument was jointly developed by the Lockheed Palo Alto Research Laboratory and the National Astronomical Observatory of Japan. Collaborators include the University of Tokyo, Stanford University, the University of California at Berkeley, and the University of Hawaii.

The SXT instrument that makes the observations in support of our scientific objectives is a glancing incidence telescope of 1.54 m focal length which forms X-ray images in the 0.25 to 4.0 keV range on a 1024 × 1024 virtual phase charge coupled device (CCD) detector. A selection of thin metallic filters located near the focal plane provides the capability to separate different X-ray energies for plasma temperature diagnostics.

* After the launch the name of SOLAR-A has been changed to YOHKOH.
Knowledge of the location of X-ray images with respect to features observable in visible light is provided by a coaxially mounted visible-light telescope which forms its image on the CCD detector when the thin metallic filter is replaced by an appropriate glass filter.

The ability of the instrument to perform its observational tasks to the levels necessary to achieve our objectives is highly dependent on the optical performance of the X-ray mirror and the quality of the CCD detector. Other determining factors are the stability of the metering structure and the quality of the instrument calibration. Finally, versatility of instrument control and discriminating utilization of limited telemetry are key to the success of the experiment.

1.1. SCIENTIFIC OBJECTIVES

Soft X-ray images reveal the distribution of high-temperature coronal gas and, thus, the structure of the confining magnetic field and thus the topological context of solar activity. SOLAR-A will, for the first time, provide simultaneous soft and hard X-ray images with good angular and temporal resolution. The SXT X-ray images will be searched for the following kinds of information:

- The geometry of the X-ray emitting structures and the inferred coronal magnetic field topology;
- the temperature and density of X-ray emitting plasma;
- the spatial and temporal characteristics of flare energy deposition;
- the transport of energetic particles and conduction fronts;
- the presence of waves or other magnetic field disturbances associated with sprays, filament eruptions, and coronal transients; and
- the locations of energy release and particle acceleration.

The SXT will, by itself, contribute new insights into solar physics. Yet, many studies will benefit from study of correlated observations made with all the SOLAR-A instruments and simultaneous observations made with ground-based solar radio and optical telescopes. Concrete steps have been taken (e.g., Morrison et al., 1991) to facilitate joint analysis of different types of solar observations. The primary objective of the SOLAR-A mission is flare research. SXT will contribute to answering the questions of the following type:

- Are there observable pre-flare conditions which give rise to an energetic flare?
- Are there observable discriminators between flares with strong nonthermal effects, e.g., high-energy particle acceleration and mass ejection, and those that exhibit primarily thermal properties?
- Is flare energy released continuously or in discrete pulses (elementary flares)?
- What is the filling factor of coronal and flare loops?
- What is the characteristic time for the acceleration process?
- Are electrons and ions accelerated simultaneously by the same process? Are there multiple phases or steps in the acceleration process to cover the wide range of energy (non-relativistic to relativistic) and mass (electrons, protons, and heavier ions)?
- Are there observational clues to the location and dimensions of the acceleration
region? Might it be spatially coincident with the location of hard X-ray and gamma-ray emission?

- How is the energy, generated during a flare, redistributed during evolution through different flare phases?
- Is it possible to observe or infer how and where the energetic particles propagate from the acceleration region? Do they diffuse or propagate in well-collimated beams?
- What is the relationship between the energetic particles which escape from the Sun into the interplanetary space and those which remain at the Sun and produce hard X-ray, gamma-ray, radio, and other emissions?

In addition to the objectives for flare studies the SXT will provide a powerful instrument for non-flare coronal physics. Regular full-disk coronal images will be acquired for the purpose of study of the evolution of the magnetic morphology of the Sun's corona. We hope to elucidate better the appearance, migration, and reconnection of magnetic flux over time scales of a few minutes to a few years by following the creation, change and disappearance of coronal X-ray structures. Studies of the appearance and evolution of coronal magnetic holes will contribute to both solar and solar system physics. We are interested to observe systematically X-ray bright points and clarify their role in the appearance (or disappearance) of magnetic flux. Careful cinematographic studies of the X-ray corona, along with coordinated observations of the visible layers below, may provide new clues to the nature of coronal heating.

The SXT visible-light aspect telescope will provide, in addition to its primary use for precise X-ray/visible alignment information, cinematographic observations of white-light flares and sunspots. Furthermore, a possibility exists to use it for helioseismological studies. It is estimated that intensity oscillations as small as $\Delta f/f \approx 10^{-7}$ may be detected if the SXT data stream is dedicated to this experiment for several months (Sakurai, 1990).

1.2. SXT INSTRUMENT REQUIREMENTS

The SXT has been designed to provide the following capabilities:

- A dynamic range of $>10^7$ to cover the expected brightness range;
- time resolution of 2 s or better to cover the evolution of the impulsive phase;
- angular resolution of $\leq 3$ arc sec to locate flare footpoints and observe the filling of loop structures;
- a field-of-view large enough to image the whole solar disk;
- a spectral diagnostic capability sufficient to estimate plasma temperature;
- the capability to record images in visible light, co-aligned with the soft X-ray images, for study of relationships of X-ray and white-light flares and to enable precise registration with other solar data;
- ability to withstand a severe launch environment (20 g r.m.s. vibration levels);
- fundamental mechanical resonance frequency above 100 MHz; and
- the SXT must operate over a temperature range of 0 to $+25^\circ$C.
2. Optics

In concept, the SXT is a very simple instrument. It has a fixed focus and comprises a sensor, a shutter, dual filter wheels and two co-aligned imaging elements, a mirror for X-rays and a lens for visible light. The position of the filter wheels determine whether an X-ray or an optical picture is taken. There is a commandable door behind the lens, not shown in Figure 1 for clarity, used to exclude visible light from the telescope when desired.

The mechanical and optical design of the SXT required maintaining focus and alignment through a difficult launch and thermal environment with low mass, power,
and dollar budgets. The technical solution to these challenges has been described by Bruner et al. (1989). The description of SXT in this paper will be limited to that useful for understanding the scientific performance of the instrument. Although the calibration and characterization of SXT given here is preliminary, it is mature enough for confident use in predicting SXT performance and for first-order data interpretation.

2.1. Overall SXT Response

Characteristics of the SXT are presented in Table I. The composite spectral sensitivity of the basic telescope is illustrated in Figure 2(a). Figures 2(b–e) show how this sensitivity is modified by the X-ray analysis filters. These filters have been carefully designed to optimize the ability to determine solar plasma temperature (Section 2.5). The variation of the effective area of the SXT as a function of off-axis angle is illustrated in Figure 3.

The same CCD detector (Section 2.4) is used for X-ray and visible-light images. The metallic X-ray analysis filters or a commandable door block the visible light from the aspect telescope aperture so that it does not contaminate the X-ray images. The angular pixel size of the CCD (2.45") is approximately the same as the angular resolution of both the X-ray and aspect telescopes. The CCD subtends 42 × 42 min of arc and so furnishes full-disk and coronal coverage in a single image. SXT provides for commandable on-chip pixel summation in order to increase the field of view for the same time resolution. The angular resolution in each summation mode is 1 × 1 (2.45"), 2 × 2 (4.9"), and 4 × 4 (9.8"). The image data are normally compressed and decompressed from 12 to 8 for telemetry and back to 12 bits on the ground for analysis through the use of look-up tables based on a square-root algorithm (Section 3).

Both aspect and X-ray exposures are controlled by a rotating mechanical shutter driven by a constant velocity motor. The shutter blade has two sector openings, one of 3 deg and one of 60 deg. For the very shortest exposure (1 ms) the narrow sector is driven past the CCD without pause. Three such passes in quick succession provide a 3 ms exposure while driving the 60 deg sector past provides a nominal 20 ms exposure. For longer exposures the 60 deg sector is used and the shutter blade stops in the open position for a prescribed period of time. The exposure duration is measured on board by a hardware timer. The shutter is used in combination with a 8.05% transmission metal mesh in the filter wheel to obtain the effective exposures listed in Table II. Note that the exposure error and non-uniformity do not add algebraically. For example, total uncertainty for command 0 will be about 3.0%.

2.2. X-ray Telescope

Within the SXT, the X-rays are brought to a focus by a glancing incidence mirror of unique technology. This optic utilizes hyperboloids of revolution for both optical surfaces (Nariai, 1987, 1988) to achieve better wide-field angular resolution on a flat focal plane than would the familiar paraboloid-hyperboloid design. Wide-field performance is further enhanced by making the mirror unusually short (4.5 cm total) along the optical axis (Watanabe, 1987). Both optical surfaces of the mirror are formed in a single cylinder
of low-expansion Zerodur glass-ceramic which is bonded into a lightweight titanium stress-free mount. The reflecting surfaces are covered with an evaporated coating of 420 Å of gold on top of 80 Å of chromium. For wavelengths longer than 6 Å where scattering is moderate the agreement between predicted and calibrated mirror effective area agree to better than 90%. Further description of this optic and its calibration is published separately (Lemen et al., 1989, 1991).
Fig. 2. Effective area of the SXT: (a) no analysis filter, (b) 1265 Å Al filter, (c) composite filter comprising 2930 Å Al, 2070 Å Mg, 562 Å Mn, and 190 Å C, (d) 2.52 μm Mg, (e) 11.6 μm Al, and (f) 119 μm Be. (b)–(f) compare the no-filter case (light line) with the filtered case (heavy line). (a) is plotted on a logarithmic scale to better illustrate regions of small effective area, which may dominate SXT response when the solar spectrum is intense at those wavelengths.

Glancing incidence X-ray mirrors are often troubled by broad, intense, scattering haloes. This is especially troublesome for solar flare observing where scene contrast over small angular scales is extreme and, at the same time, scientifically important. This small angle scattering is dominated by surface roughness and mid-frequency errors of figure. For SXT, a surface roughness of 3.8 Å r.m.s. and mid-frequency error of 51 Å r.m.s. was achieved. The point spread profile of the telescope, acquired with a flight-type CCD, is illustrated in Figure 4.

The angular resolving power of an under-sampled X-ray telescope like SXT is not
Fig. 3. Variation of effective area of SXT with off-axis angle determined by ray tracing (without X-ray scattering) for three different wavelengths. Calibration data at 8.34 Å are shown with a straight line fit to the calibration results inside of 23 arc min.

easy to characterize in simple terms. The X-ray point spread function (PSF) of the instrument is defined as the empirical expression that describes the intensity distribution over the image of a point source at infinity. The PSF is a function of wavelength and off-axis angle. One figure of merit useful for X-ray mirrors is the diameter, $D_{50}$, of the circle that encloses 50% of the imaged energy. For SXT, calibration data yields the following expression for this parameter (on-axis) over the 4–45 Å interval:

$$D_{50} = 7.0 - 2.4 \log_{10} \lambda \text{ arc sec},$$  \hspace{1cm} (1)

where $\lambda$ is the wavelength in Å.

A second common means of characterizing the PSF is the full width at one-half maximum (FWHM) of the best fitting 2-dimensional Gaussian (Figure 5). Quantitatively, this is a poor choice for comparing telescopes because the intrinsic PSF has a very sharp central spike (Lemen et al., 1989). For such a PSF the FWHM is sensor-dependent because the definition of maximum reflects pixel size down to very small pixels (or film grain). Also, the wings of the profile are distinctly non-Gaussian. A modified Moffat PSF (Bendinelli, 1991) has been found to fairly accurately characterize the PSF of the SXT. The form of this expression is

$$N = \frac{C}{\left[1 + \left(\frac{r}{a}\right)^2\right]^b},$$  \hspace{1cm} (2)
TABLE II

SXT effective exposures

<table>
<thead>
<tr>
<th>Command</th>
<th>Effective exposure</th>
<th>Error (%)</th>
<th>Non-uniformity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.077 ms&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.4</td>
<td>2.6</td>
</tr>
<tr>
<td>1</td>
<td>0.23 ms&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.4</td>
<td>2.6</td>
</tr>
<tr>
<td>2</td>
<td>0.96 ms</td>
<td>1.4</td>
<td>2.6</td>
</tr>
<tr>
<td>3</td>
<td>1.38 ms&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.4</td>
<td>2.3</td>
</tr>
<tr>
<td>4</td>
<td>2.88 ms</td>
<td>1.4</td>
<td>2.6</td>
</tr>
<tr>
<td>5</td>
<td>3.08 ms&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.3</td>
<td>≤0.1</td>
</tr>
<tr>
<td>6</td>
<td>4.69 ms&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.8</td>
<td>≤0.1</td>
</tr>
<tr>
<td>7</td>
<td>6.30 ms&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.6</td>
<td>≤0.1</td>
</tr>
<tr>
<td>8</td>
<td>9.50 ms&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>9</td>
<td>17.2 ms</td>
<td>1.4</td>
<td>2.3</td>
</tr>
<tr>
<td>10</td>
<td>28.8 ms</td>
<td>3.2</td>
<td>1.0</td>
</tr>
<tr>
<td>11</td>
<td>38.2 ms</td>
<td>1.3</td>
<td>≤0.1</td>
</tr>
<tr>
<td>12</td>
<td>58.3 ms</td>
<td>0.8</td>
<td>≤0.1</td>
</tr>
<tr>
<td>13</td>
<td>78.3 ms</td>
<td>0.6</td>
<td>≤0.1</td>
</tr>
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<td>14</td>
<td>118 ms</td>
<td>0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>15</td>
<td>168 ms</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>16</td>
<td>238 ms</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>17</td>
<td>338 ms</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>18</td>
<td>468 ms</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>19</td>
<td>668 ms</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>20</td>
<td>948 ms</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>21</td>
<td>1.34 s</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>22</td>
<td>1.89 s</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>23</td>
<td>2.67 s</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>24</td>
<td>3.78 s</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>25</td>
<td>5.34 s</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>26</td>
<td>7.55 s</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>27</td>
<td>10.7 s</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>28</td>
<td>15.1 s</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>29</td>
<td>21.4 s</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>30</td>
<td>30.2 s</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>31</td>
<td>42.7 s</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>32</td>
<td>60.4 s</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>33</td>
<td>85.4 s</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>34</td>
<td>121 s</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>35</td>
<td>171 s</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
<tr>
<td>36</td>
<td>242 s</td>
<td>≤0.4</td>
<td>≤0.1</td>
</tr>
</tbody>
</table>

<sup>a</sup> The 8.05% transmission mask is applied.

where \( N \) is the signal in a pixel in digital data numbers (DN), \( C, a, \) and \( b \) are parameters of the fit, and \( r \) is the radial coordinate of the function, expressed in pixels.

The SXT is equipped with two entrance filters in series for the purpose of excluding visible and UV light from the telescope. The filters comprise Lexan as the support material, Al for thermal control and to exclude visible light, and Ti to exclude the intense solar He 304 Å emission. The dual filter design was chosen to minimize the possibility of stray light entering the instrument through a pinhole in the metal films.
Fig. 4. Measured point spread profile of SXT at 8.34 Å (Al K line) for 1" source at 310 m. Equivalent curve for Skylab SO-54 telescope (Vaiana et al., 1977) is shown as a dashed line for comparison. Great improvement in decreased scattering wings for SXT is evident.

Fig. 5. Approximate FWHM of the SXT image of a point source versus distance from optical axis. The vertical scale is seconds of arc with an estimated uncertainty of about 10%. The inset shows the surface plot of the image at the point indicated by the arrow. A typical 1σ error bar is shown. A parabola has been fitted through the points. The CCD has been deliberately placed 0.1 mm ahead of the position of best on-axis focus in order to achieve a more uniform resolution across the solar disk.
The 5 X-ray analysis filters of the SXT, located in the rear filter wheel, are designed to provide attenuation, increasing the dynamic range of the instrument, and a measure of flare temperature information (Section 2.5). Four of the filters are supported on stainless steel mesh. Figure 2 illustrates the response of the SXT through the various filters. The 8.05\% transmission stainless steel mesh located in the front filter wheel can be used in tandem with any of the positions of the rear wheel to extend the dynamic range of the instrument. Analysis of calibration images has not revealed any measurable effect on images taken with this attenuating mesh.

2.3. Aspect Telescope

The SXT aspect sensor is a high-quality, albeit small, optical telescope in its own right. It serves several purposes:

1. Sunspot and limb images for determining SXT pointing to an accuracy of 1 sec of arc or better and to aid image registration with ground-based data.
2. To record magnetic plage, sunspot and pore motions and development in and around active regions.
3. To observe white-light flares.
4. For helioseismology.
5. To provide flat field illumination for CCD gain calibration.
6. To provide a source of blue light for photon flood of the CCD for the purpose of annealing soft X-ray degradation of the sensor.

The objective lens assembly forms an image of the same scale as the X-ray image that is co-aligned to approximately one pixel. The actual co-alignment will be verified in orbit by overlay of the white-light limb with the X-ray absorption limb using full-disk images. The assembly allows just enough light into the SXT to acquire properly exposed aspect pictures in about 0.1 s.

The entrance filter consists of a white-light attenuator and a bandpass filter. The white-light attenuator is composed of a synthetic fused silica substrate with a 500 Å aluminum attenuating layer, under a dielectric coating for durability, on the rear surface. The bandpass filter is deposited on a 6 mm thick substrate of Hoya CM-500 blue glass. The transmission of the white-light attenuator and the bandpass filter in tandem is illustrated in Figure 6. The combined out of band rejection of the white-light attenuator and bandpass filter is of order $10^{-8}$.

The image of the aspect telescope is formed by a doublet lens, which is achromatic across the entrance filter's passband. The lens has a 50 mm clear aperture and a focal length of 1538 mm, forming a beam which is approximately $f/31$. The doublet has a depth of focus of approximately ±0.5 mm, with an Airy disk diameter of about 50 microns. Lenses have been selected to give the best match to the measured effective focal length of the SXT X-ray mirror. Optical materials for the objective lens assembly have been selected, by specification or test, for their radiation resistance. All appropriate surfaces have been anti-reflection coated.

The SXT filter wheel carries two optical band pass filters. Magnetic plage in and around active regions will be readily visible in the 30 Å filter centered on the CN band
at 4308 Å. In order to acquire a continuum image with a filter that is less subject to drift over the life of the mission we have also included a 140 Å filter centered at about 4580 Å. These filters are equipped with neutral density attenuators on the rear side to balance the exposure times and to attenuate ghosts from back reflections off of the CCD to less than 1%. The bandpasses of these two filters are illustrated in Figure 7.

2.4. CCD IMAGE SENSOR

The CCD camera for the SXT utilizes a 1024 × 1024 virtual phase CCD (VPCCD) with 18.3 μm pixels, manufactured specifically for SXT by Texas Instruments at their Miho, Japan, facility. The principal of operation of the VPCCD has been described by Hynecek (1979) and Janesick, Hynecek, and Blouke (1981). Virtual phase technology is a good choice for SXT because the thin oxide layer covering the virtual well provides excellent soft X-ray response without the difficulties of thinned, back illuminated, operation.

The SXT camera is operated in a charge-collection, rather than a photon counting, mode. Solar features are typically bright enough to produce near full well images with exposures of less than 1 s. Because of the high signal levels, SXT requirements on read
noise and dark current are not stringent. Dark-current control and gain stability are obtained by cooling the CCD to $-18 \, ^\circ\text{C}$ with a closed-loop 3-stage thermoelectric cooler. CCD read noise is about 85 electrons pixel$^{-1}$ r.m.s. Average dark current at $-18 \, ^\circ\text{C}$ is about 9 electrons pixel$^{-1}$ s$^{-1}$ (0.4 picoamp cm$^{-2}$). Charge transfer efficiency of the SXT flight sensor measured 0.999989 for signals $> 10^4$ electrons. The forward filter wheel includes an opal glass diffuser to provide flat field illumination of the CCD for the purpose of gain calibration through use of the photon transfer curve technique (Janesick, Klaasen, and Elliott, 1987). Figure 8 shows the pixel structure and the measured quantum efficiency of the SXT flight device. The quantum efficiency of the CCD for blue light from the aspect sensor is roughly 30%.

The full well capacity of the CCD is about 250 000 electrons. At the conversion constant of 3.65 eV electron$^{-1}$ for Si this results in a full well capacity of about $10^3 \times 1$ keV (12.4 Å) photons. Extensive use of $2 \times 2$ and $4 \times 4$ on-chip summing is anticipated so the camera gain has been set low (100 electrons per digital number (DN)) to preclude excessive saturation of the 12 bit analog to digital convertor. For full-resolution observations (no on-chip summation) the CCD will saturate before the 12-bit ADC attains full scale in order to assure that maximum CCD signal capacity is available. For summed exposures the ADC will saturate first. Managing to achieve correct exposures, especially on flares, will be challenging. This task will normally be assigned to the on-board automatic exposure control described below. The CCD
camera can also be operated in a pseudo-frame transfer mode in the event of problems with the mechanical shutter.

The SXT CCD is subject to degradation from cosmic rays, energetic protons trapped in the Earth’s radiation belts and from the solar X-rays themselves. These problems have been treated in detail for SXT by Acton et al. (1991). Because the sensor is operated cooled and exposures are normally a fraction of a second, the increased dark current and dark spikes (pixels with greatly enhanced dark current) produced by energetic particles do not appear to pose a significant threat to SXT science over the 3–5 year mission lifetime. However, ionization produced in the thin oxide layer of the CCD by the solar X-rays produces increased dark current and, eventually, loss of charge transfer efficiency with resulting smearing of the solar images. It has been discovered that illumination of the CCD with blue light from the aspect telescope apparently creates free electrons at the Si–SiO₂ interface, neutralizing the charge and annealing the damage. The SXT filter wheel has been equipped with a slightly negative quartz lens for the purpose of flooding the entire CCD with 3300–4700 Å light. The duration of this photon flood can be set by command. Present plans call for doing such a flood for approximately the first 4 min of each daylight pass, while the spacecraft’s attitude is stabilizing.
2.5. SXT RESPONSE TO THE SUN

The SXT is capable of imaging solar plasma over the temperature range of \(<1\) to \(>50\) MK for a wide range of intensities. The sensitivity of the SXT for detecting solar features of different temperatures is illustrated in Figure 9. These curves are produced by convolving the instrument response functions of Figure 2 with the theoretical X-ray emission line spectra of Mewe, Gronenschild, and van den Oord (1985) and the continuum expression of Mewe, Lemen, and van den Oord (1986). Note that these curves assume an emission measure of \(10^{-44}\) \(\text{cm}^{-3}\). In thinking of SXT sensitivity it is important to keep in mind that, even for a point source, only about half of the CCD signal will appear in the brightest pixel.

Because the solar soft X-ray spectrum is predominantly a line spectrum, the well-defined absorption edges (Figure 2) of the SXT analysis filters emphasize detection of certain spectral lines or groups of lines. This provides rudimentary spectral, and hence temperature, discrimination. Figure 10 presents the ratio of signals versus \(\log_{10} T\) for selected pairs of analysis filters. The two thickest filters will, in general, not work for non-flare temperatures because of inadequate sensitivity. Similarly, the open telescope (no analysis filter) and thinnest filters may saturate in flares, even for the shortest exposures. For isothermal sources the uncertainty in plasma temperature determined by this technique is of about 0.1 in \(\log_{10} T\).

In principle, the response curves of Figure 9 can be treated in the same way as the emissivity curves for an atomic emission line for differential emission measure (DEM)
Fig. 10. Ratios of the SXT response functions of Figure 9. In 2 cases, 5e/d and f/2e, observing time with e, the 11.6 μm Al filter, must be increased by factors of 5 and 2, respectively, with respect to the other filter to achieve the given ratio.

analysis of a multi-thermal plasma. In practice, the problem is more ill-conditioned (Craig and Brown, 1986) than the atomic line case. Figure 11 illustrates the results of a simulation of such an analysis. Here, SXT signals were predicted for the given DEM and put through a version of the Sylwester analysis program (Fludra and Sylwester, 1986) to generate a DEM (Strong et al., 1991). This work indicates that the DEM reliably reflects the presence of high-temperature plasma and the total emission measure is well determined. However, detailed structure or peaks in the DEM distribution are not reproduced and the low-temperature end is poorly determined in the presence of Poisson counting statistics.

Photon statistics will contribute the dominant error in SXT photometry. A CCD signal of 100 electrons produced an increment of one digital number (DN) from the ADC. At 3.65 eV electron$^{-1}$, this corresponds to detecting a single photon of wavelength 34 Å. The 1σ readout and detector noise on a typical image will be roughly 1 DN. The true photon statistics in a thin-filter image will be additionally uncertain because of the factor of 10 range in photon energies to which the SXT is sensitive. Thicker filters restrict the spectral acceptance band of the instrument so that the statistical error can be more accurately estimated.

Table III demonstrates the predicted signal from a single SXT pixel through each of the SXT analysis filters for a variety of solar features (Strong and Lemen, 1987) and exposures appropriate for their observation. The angular extent of typical features is taken into account. McTiernan (1991) has examined the response of the SXT to two non-thermal (power-law spectrum) events which were partially occulted by the Sun from
Fig. 11. Results of a simulated derivation of a differential emission measure distribution (DEM) using SXT images through all 6 analysis filters (Strong et al., 1991). The histogram is the input distribution. The solid curve is the best-fit model derived from the input data. The dashed curves represent additional random solutions reflecting Poisson counting statistics.

the ISEE-3/ICE spacecraft (Kane et al., 1979). He estimated that the flare of 16 February, 1984, which was visible beyond 160 000 km above the surface of the Sun and exhibited a photon power-law spectral index of about 4.6, would have generated a signal of 500–1500 DN pixel $^{-1}$ s $^{-1}$ in the SXT with no filter. Such sources in the high corona above the limb should be observable by SXT. The spectral index of the emission can be found using thick/thin filter ratios. For this flare the uncertainty in the spectral index using a ratio of the thick beryllium filter to the thin aluminum filter would be approximately 0.6, although the SXT alone could not distinguish between power law and thermal spectra.

3. SXT Image Data

The acquisition of solar images by the SXT is controlled by electronics and software operating within the SOLAR-A Data Processor (DP). This function is slaved in frequency to the SOLAR-A telemetry rate. Images will normally be taken under either high (32 kbps) or medium (4 kbps) rate. Low rate (1 kbps) is used only for night mode. In the discussion to follow, examples of image frequency will always assume high-rate telemetry unless otherwise noted. For medium rate operation, picture frequency decreases by a factor of eight.

The CCD camera employs a 12-bit ADC but data are transferred to the DP as 8-bit numbers. For purposes of gain calibration and helioseismology it is important to maintain the full 12-bit accuracy. This is accomplished by transferring either the high-
<table>
<thead>
<tr>
<th>Feature</th>
<th>Temp. (MK)</th>
<th>Em. meas. (cm(^{-3}))</th>
<th>Exposure (s)</th>
<th>Open</th>
<th>Al 1265</th>
<th>Al/Mg/Mn Signal (DN) in one pixel</th>
<th>Mg 2.5</th>
<th>Al 11.6</th>
<th>Be 119</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coronal hole</td>
<td>1.3</td>
<td>2E + 42</td>
<td>60.4</td>
<td>18</td>
<td>10</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X-ray bright point</td>
<td>1.8</td>
<td>7E + 43</td>
<td>0.948</td>
<td>34</td>
<td>23</td>
<td>11</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Large-scale loops</td>
<td>2.1</td>
<td>6E + 42</td>
<td>5.34</td>
<td>30</td>
<td>22</td>
<td>11</td>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Active region</td>
<td>2.5</td>
<td>3E + 45</td>
<td>0.468</td>
<td>sat.</td>
<td>2034</td>
<td>1064</td>
<td>878</td>
<td>37</td>
<td>2</td>
</tr>
<tr>
<td>Long duration event (LDE)</td>
<td>7.5</td>
<td>1E + 48</td>
<td>0.00096</td>
<td>sat.</td>
<td>sat.</td>
<td>1958</td>
<td>1515</td>
<td>201</td>
<td>74</td>
</tr>
<tr>
<td>Impulsive C flare</td>
<td>12</td>
<td>5E + 48</td>
<td>0.00023</td>
<td>sat.</td>
<td>sat.</td>
<td>2047</td>
<td>1449</td>
<td>286</td>
<td>180</td>
</tr>
<tr>
<td>M flare</td>
<td>17</td>
<td>2E + 48</td>
<td>0.00023</td>
<td>1191</td>
<td>938</td>
<td>690</td>
<td>464</td>
<td>101</td>
<td>92</td>
</tr>
<tr>
<td>X flare</td>
<td>20</td>
<td>1E + 49</td>
<td>0.000077</td>
<td>1886</td>
<td>1501</td>
<td>1101</td>
<td>723</td>
<td>162</td>
<td>163</td>
</tr>
<tr>
<td>Post-flare loop</td>
<td>7</td>
<td>3E + 46</td>
<td>0.0172</td>
<td>2084</td>
<td>1671</td>
<td>1070</td>
<td>856</td>
<td>104</td>
<td>344</td>
</tr>
</tbody>
</table>
order or low-order 8 bits, selectable by command. Normally, the ADC numbers are
compressed to 8 bits according to the following algorithm. Taking, \(N\), \(X\), and \(M\) to be
the original, compressed and decompressed digital numbers, respectively,
- for \(N \leq 64\):

\[
X(N) = N, \quad M = X = N
\]  

(3)

- for \(N > 64\):

\[
X(N) = \text{round} \left( 59.249 + \sqrt{3510.39 - 9.50(431.14 - N)} \right), \\
M = \text{round} \left( 0.10526 X^2 - 12.473 X + 431.14 \right), \quad (X < 255),
\]  

(4)

\[
M = 4085, \quad (X = 255),
\]

where \(N\) is the CCD camera output (Digital Number or DN), \(X\) is the 8-bit compressed
number, \(M\) is the 12-bit decompressed value.

Ignoring read noise, dark current, and spurious charge, which are on the order of
1 DN, the data number is given by

\[
N = \frac{nh\nu}{3.65c} + 11.5,
\]  

(5)

where \(n\) = number of photons detected, \(h\nu\) = mean photon energy in eV, \(c\) = CCD
camera gain constant of 100 electrons DN\(^{-1}\); 11.5 is a digital offset in the CCD camera.

This yields the relation

\[
n = \frac{(N - 11.5)\lambda}{34},
\]  

(6)

and correspondingly

\[
m = \frac{(M - 11.5)\lambda}{34},
\]  

(7)

where \(\lambda\) is the photon wavelength in Å.

Finally, the compression error may be expressed in terms of photon statistics as

\[
\varepsilon = \sqrt{\frac{\lambda}{34}} \frac{N - M}{\sqrt{N - 11.5}}.
\]  

(8)

3.1. Image Formats

Images from the CCD camera of the SXT are transferred to image buffers in the
SOLAR-A Data Processor (DP) for processing and read out to telemetry. There are
three types of pictures, Full Frame Images (FFI), Partial Frame Images (PFI) and patrol
images. In the following discussion a 'line of CCD data' will include 1024 × 1, 1024 × 2,
or 1024 × 4 actual CCD pixels and be 1024, 512, or 256 output pixels long depending
on whether $1 \times 1$, $2 \times 2$, or $4 \times 4$ on-chip summation is used. The FFI comprise 512, 256, 128, or 64 lines of CCD data so that at highest resolution (i.e., no on-chip pixel summation) they are, at most, only one half of a CCD picture. For on-chip summation modes, however, full CCD pictures can be taken. For PFI 64 lines of CCD data are always transferred to the buffer but, normally, only a subset of these data are sent to telemetry. In our terminology a PFI is a $64 \times 64$ sub-image that will include $64 \times 64$, $128 \times 128$, or $256 \times 256$ actual CCD pixels, depending upon the use of on-chip summation. For both FFI and PFI the band of CCD lines transferred to the DP is referred to as a Region of Interest (ROI). Patrol images are always 128 lines of CCD data acquired with $4 \times 4$ pixel summation (one-half of a CCD picture). Patrol images are used in the DP for Automatic Observing Region Selection (ARS). The patrol images are not normally sent to telemetry.

For FFI the entire content of the image buffer is always sent to telemetry, i.e., is read out to the 10 Mbyte Bubble Data Recorder or transmitted directly to ground in real time. From the contents of the PFI buffer up to 16 adjacent (in the E–W direction) $64 \times 64$ pixel PFI are extracted from the 64 line image strips and sent to telemetry. Finally contiguous assemblies of PFI of any rectangular shape from a single PFI on up are called Observing Regions (OR). Four different shapes of observing regions are illustrated in Figure 12.

The arrangement and size of an X-ray or optical solar image on the CCD of the SXT

![Diagram](image_url)

Fig. 12. Arrangement of a solar image on the CCD. Ecliptic north is up and the solar west limb is to the left. Locations of 43 large flares observed by SMM in 1980 are indicated by black squares. The ‘full frame’ image comprises the largest number of pixels that can be sent to telemetry as an individual image. More typically, a partial frame image comprising $64 \times 64$ pixels, extracted from a designated region of interest, is sent to telemetry. In order to increase the size of an observing region the partial frame images may be grouped as illustrated by (a), (b), and (c). Observing regions of type (a) can be imaged with a single exposure whereas (c) requires 2 exposures and (b) requires 3 individual exposures. These examples are the size obtained when on-chip pixel summation is not used, i.e., at best angular resolution.
is shown in Figure 12. The vertical or column direction of the CCD is oriented towards ecliptic north. The solar image is deliberately de-centered upwards on the sensor to provide an unilluminated area at the bottom of the CCD. This area may serve as a frame transfer register to permit shutterless operation of the instrument in the event of trouble with the rotating mechanical shutter. In the frame transfer mode the portion of the picture to be saved would be rapidly shifted down into the frame transfer and then read into the image buffer at the normal rate of 131072 pixels s\(^{-1}\).

Considerable flexibility has been introduced into schemes of SXT image acquisition in order to make optimum use of the telemetry capacity of SOLAR-A. First, on-chip 2 \(\times\) 2 and 4 \(\times\) 4 pixel summation can be used to trade resolution for data rate. Second, the full frame images of 64, 128, 256, or 512 lines can be taken anywhere on the CCD to observe solar active longitudes of interest. Third, the region of interest of the partial frame images can be taken anywhere on the CCD and the 64 \(\times\) 64 PFIs may be grouped together into larger Observing Regions (OR) as illustrated by examples (a), (b), and (c) of Figure 12. Observing regions of type (a) which are only extended E–W are acquired in a single exposure. Each block in the N–S direction, such as in examples (b) and (c), require a separate exposure. Although ORs with multiple-PFI extent N–S are assembled on the ground, they are treated as a single entity in planning and commanding. The angular extent of an FFI and a single PFI for the 3 summation modes are given in Table V.

3.2. EXPERIMENT CONTROL

SXT operation is under the control of software running in the SOLAR-A data processor (DP) computer and the SXT microprocessor. It is the function of the DP to command the SXT and to receive, format, and transfer all data to telemetry. It is the function of the SXT microprocessor to control the SXT mechanisms and CCD camera as directed by the DP. Command and status information is exchanged between the two computers via a block of memory in the SXT microprocessor which serves as a 'mailbox'.

The DP has the capability to examine SXT image data to select regions of interest and to adjust the length of the SXT exposure. It also monitors data from the hard X-ray, soft X-ray, or Bragg crystal spectrometers and may issue a flare flag to initiate SOLAR-A flare mode.

3.2.1. Sequence Tables

At the most fundamental level, the following parameters must be specified for each SXT exposure:

- Location and size of portion of CCD image to be sent to telemetry;
- on-chip CCD pixel summation of 1 \(\times\) 1, 2 \(\times\) 2, or 4 \(\times\) 4;
- exposure duration;
- filter(s) to be used.

In addition, there are secondary instrument functions which may need to be altered and parameters that must be set (in all about 20 items).

The setup of the SXT for each observation is accomplished from tables of parameters.
stored in the DP called sequence tables. Each table provides all of the information necessary to define an SXT observing sequence, which can be quite complex. These tables, in turn, address other tables of fixed or adjustable control parameters. A sequence table is organized as a set of nested 'do-loops' in which a sequence of commands is executed repetitively until the prescribed number of cycles has been completed, at which time the program continues on to the next task.

This structure is illustrated in Table IV along with an example of an observing sequence for study of the evolution of a medium-sized active region. The sequence starts off with a single $10 \times 10$ arc min, 5 arc sec resolution, image centered on the observing region. This serves to place subsequent smaller images in a broader solar context. The large image is followed by a sequence of $5 \times 5$ arc min images at full resolution through each SXT filter. In this example there is no looping within the sequence. The sequence takes about 1.5 min per execution and is arranged to provide thin-filter images and optical images at uniform cadence at twice that rate. This enhances our ability to observe small white-light flares and low-level activity.

The image intervals, $dt$, include set-up and data transfer time as well as exposure time. Except for the thick beryllium filter the intervals are dominated by the time to transfer data to telemetry. The interval $dt$ can either be held fixed, with the automatic exposure control permitted to operate only within this constraint, or allowed to increase in response to the automatic exposure software in the DP. Note that while this simple example concentrates on a single target, every numbered image in the sequence is independent and could image any one of the locations stored in the nine observing-region registers. Thus, it is feasible to continuously monitor the activity at several locations on the Sun in quiet mode.

There are 8 sequence tables stored in non-volatile memory in the DP, 4 each for partial frame (PFI) and full frame (FFI) images. At any given time 6 tables are designated for use under the 4 SOLAR-A science modes, QT/HIGH, QT/MED, FL/HIGH, and FL/MED. Sequence tables optimized for quiet-Sun or flare observations are sometimes quite different. Furthermore, the design of the cadence (number of loops) depends on the telemetry bit rate so the sequence table may be different between FL/HIGH mode (impulsive phase) and FL/MED mode (gradual phase) following the FL/HIGH mode. An 'entry table' is used to point to the desired sequence table for specific DP modes as shown in the following example:

<table>
<thead>
<tr>
<th>Data mode</th>
<th>TLM rate</th>
<th>Seq. table</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUIET (QT)</td>
<td>HIGH</td>
<td>FFI No. 1</td>
</tr>
<tr>
<td>QUIET (QT)</td>
<td>HIGH</td>
<td>PFI No. 1</td>
</tr>
<tr>
<td>QUIET (QT)</td>
<td>MED</td>
<td>FFI No. 2</td>
</tr>
<tr>
<td>QUIET (QT)</td>
<td>MED</td>
<td>PFI No. 2</td>
</tr>
<tr>
<td>FLARE (FL)</td>
<td>HIGH</td>
<td>PFI No. 3</td>
</tr>
<tr>
<td>FLARE (FL)</td>
<td>MED</td>
<td>PFI No. 4</td>
</tr>
</tbody>
</table>
For PFI observations in this example, No. 1 sequence table is used in the QT/HIGH mode. This will be automatically switched to sequence table No. 3 when FL/HIGH mode starts. (In this case, the sequence table No. 1 is optimized for QT/HIGH mode, and No. 3 for FL/HIGH mode.) If the bit rate is changed to MED in the gradual phase of the FL mode, the sequence table is switched to No. 4. The entry table numbers may be modified by real time or stored commands to achieve observing objectives. For instance, if we specify the sequence table No. 1 in the FL/HIGH column, then the same experiment sequence will continue regardless of the DP mode change to FL mode.

3.2.2. Automatic Observing Region Selection

The Automatic OR Selection (ARS) function utilizes patrol images taken for this purpose at regular intervals set by time commands or in response to a flare flag. There are two different ARS algorithms available when in the Quiet (QT) Mode and one algorithm while in the Flare (FL) Mode. Search mode ARS is used to search the whole solar image for the four brightest sources in both QT and FL modes. Tracking mode ARS is used to track a feature as the region moves due to solar rotation, spacecraft pointing drift, or as the location of brightest emission evolves in QT mode. The QT ARS and FL ARS have separate parameters available to set up the exposure characteristics. The FL ARS has available its own automatic exposure control to help deal with the inordinate variation in X-ray brightness of flares. The accuracy of ARS source location is normally one patrol image pixel or 10 arc sec.

A patrol image is 42 × 21 arc min in size with a 10 arc sec (4 × 4 pixel) resolution. The area of the Sun covered in the search is therefore equivalent to the area labelled ‘Full Frame Image’ in Figure 12. As can be seen by comparison to the SMM flare locations plotted there, this adequately encompasses the active latitudes of the Sun.

The patrol image has highest priority and will interrupt acquisition of FFI or PFIs. The taking of patrol images is set in absolute time with an interval of 16 s to over an hour. Thus, by setting the time interval very long it is possible to prevent the taking of patrol images from interrupting, say, a movie sequence. QT and FL patrol images have independent cadences. It is possible to inhibit both patrol images and the ARS function.

There are nine observing region (OR) target registers in the DP to specify the locations of SXT observing regions. Five of these are filled by the ARS function and four by ground command. If ARS is inhibited, all nine registers may be loaded by ground command. Each register contains the location of the OR on the CCD and the number and shape of the mosaic of PFIs comprising an observing region.

The ninth OR register is redundantly filled with the location of the brightest feature by QT mode ARS to serve as the starting point for a flare search in response to a flare flag. The CCD exposure in process is aborted, a patrol image is taken and the FL ARS is activated at the time of the flare flag. The object is to center the flare observing region on the brightest feature as early as possible. If the flare is in the same observing region as was stored in the ninth OR register, flare observations will commence within 4 s. For an arbitrary flare location the repositioning of the OR may require up to 6 s. The OR revised flare location is finally stored in the flare OR register.
3.2.3. Automatic Observing Region Tracking

While ARS will be useful to track bright X-ray structures on the Sun, sometimes it is necessary to keep the OR centered on a location, e.g., a coronal hole or emerging active region, that is not the brightest X-ray feature in the neighborhood. The Automatic OR Tracking (ART) software provides this function by tracking the movements of observing regions due to spacecraft attitude drift. Instead of changing the pointing of the telescope, the same function is served by choosing a different part of the CCD image. ART software uses the fine Sun sensor data of the SOLAR-A attitude control system for this purpose. At high data rate the correction is applied every 32 s. ART only works on the ground-commanded OR locations, not those selected by ARS – unless the contents of those registers are manually transferred to the four non-ARS registers.

3.2.4. Automatic Exposure Control

Because of the tremendous range in the X-ray brightness (e.g., Table III) of solar phenomena and the rapid change in X-ray intensity during flares it has been necessary to incorporate an Automatic Exposure Control (AEC) function in the SXT software. Every numbered image in a sequence table (Section 3.2.1) has its own AEC. This is implemented as follows. As a given image is read out from its image buffer to telemetry the number of pixels with intensity above an upper and the number below a lower threshold are counted and recorded. If the number of overbright pixels exceeds the table value (typically 10 pixels) the exposure is decreased or, if that is not possible, a thicker filter is selected. If the over-exposure test is passed, then the number of underbright pixels is compared to the table value (typically 100). If under-exposure is indicated, i.e., there are more pixels below the lower threshold than allowed, the exposure is increased or a thinner filter is selected for the next execution of that sequence table entry.

The AEC software runs in the DP which is a very busy real-time computer. However, the AEC algorithm is very fast so it takes only 6 s to update the exposure from the time the exposure was made. Since the AEC is a feed-back system with time delay, to assure stability of the AEC loop it is necessary that there be enough intervening images in the
sequence table to allow exposure adjustment before the same sequence table entry is again commanded. If necessary, say for a high cadence movie in which only a single kind of picture was desired, this can be accomplished by simply duplicating the desired parameters in at most 3 sequence table positions and setting the rest of the table positions to ‘No operation’.

The AEC only works on partial frame images (PFI) or observing regions comprised of PFIs. The actual implementation of the AEC is more complicated than this simple description implies. The logic tree for achieving proper exposure under the formidable range of observing conditions experienced by the SXT is quite complex.

3.3. Image Cadence

The time resolution of the SXT depends in a complex way upon many different factors, some determined by the experiment itself and some dictated by things such as the time since a downlink contact and the occurrence of flares. SOLAR-A science operation utilizes two SXT control and telemetry modes. In the quiet (QT) mode 62.5% of available telemetry is devoted to SXT images because the Hard X-ray Telescope does not produce science data (cf. Ogawara et al., 1991). In flare (FL) mode, SXT uses 50% of the telemetry. In QT mode interleaved full frame and partial frame images of up to eight different observing regions may be acquired. In FL mode FFI are not taken. In either mode images are acquired at a cadence determined by the rate of transfer of the data to telemetry. SXT housekeeping and status data are telemetered regularly in addition to the image data. These status data contain image header information such as filter combination and exposure time which are telemetered in synchronism with the image data.

In normal QT mode both FFI and PFI are acquired, with periodic interruption by patrol images. The priority order for image acquisition is (1) patrol, (2) FFI, and (3) PFI. This normally results in gaps in PFI cadence as schematically illustrated in Figure 13. Note that a patrol image is automatically taken at the time of switch to FL mode. If there is a high scientific priority for obtaining PFI movies with no gaps, the control structure of SXT makes this possible at the sacrifice of FFI and the taking of patrol images. It is also possible to structure the SXT sequence control tables to continue the QT PFI cadence on into the FL mode in order to provide unchanged monitoring of a specific region.

A switch from QT to FL mode can occur because of a flare flag or by command. The transition from FL to QT mode normally occurs because energetic flare emission has dropped below preset thresholds and preset time intervals have expired. See Ogaware et al. (1991) for a description of use of the flare flag and the SOLAR-A bubble data recorder to store and sometimes overwrite less important data in response to flares.

3.3.1. Quiet Mode

In quiet (QT) mode SXT always acquires both full frame (FFI) and partial frame (PFI) images. The cadence of exposures is strictly determined by telemetry transfer time unless the exposure and set-up time exceed this, in which case a dummy image is transmitted.
There are two telemetry modes. In the PFI dominant mode, PFI data are transferred with telemetry rate 4 times faster than that of FFI, while in the FFI dominant mode, vice versa. This effect is evident in the times tabulated in Table V. The observing sequence example given in Table IV corresponds to the case of PFI dominant mode and telemetry rate high.

Separate image registers or buffers are used within the DP to receive pictures from the CCD camera and pass the desired portions on to telemetry. Although FFI and PFI may use either buffer A or B, it is not possible to combine the telemetry allocated to A and B to achieve yet higher time resolution, nor is it possible to devote both buffers simultaneously to only FFI or PFI.

For the fastest PFI cadence of 2 s image$^{-1}$ the maximum allowable exposure duration is approximately 0.5 s in order to provide time to read out the CCD image and position the filter wheels. Table V provides a summary of information on SXT pixel size, image size, time resolution and maximum exposure times for basic full frame and partial frame images. Note that the very long maximum exposure times given for full frame images, while formally correct, are not generally desirable because of image smearing from pointing drift and waste of telemetry, i.e., no PFI can be taken during the long FFI exposure. Only very faint features such as the interior of coronal holes will require exposures greater than 10 or 20 s.

3.3.2. Flare (FL) Mode

In flare (FL) mode SOLAR-A assigns 12.5% of telemetry (which in QT mode is available to SXT) to the Hard X-ray Telescope and commands high telemetry rate for a predefined time interval. As illustrated in Figure 13, the taking of FFI is stopped, although the current contents of the FFI image buffer will eventually be transferred to telemetry and are not lost. In FL mode the interval between SXT images will be determined by the number of PFI in the observing region. For a single PFI the image cadence is 2 s at high telemetry rate and 16 s at medium rate.
### TABLE IV
**SXT sequence table structure**

<table>
<thead>
<tr>
<th>Basic sequence table</th>
<th>PFI sequence table (example)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LOOP 1 ((n = \infty))</strong></td>
<td></td>
</tr>
<tr>
<td>Image 1-1</td>
<td>Image 1-1</td>
</tr>
<tr>
<td><strong>LOOP 2 ((n = n2))</strong></td>
<td>Image 1-1</td>
</tr>
<tr>
<td>Image 2-1</td>
<td>4308 Å</td>
</tr>
<tr>
<td>Image 2-2</td>
<td>4600 Å</td>
</tr>
<tr>
<td><strong>LOOP 3 ((n = n3))</strong></td>
<td>Image 3-1</td>
</tr>
<tr>
<td>Image 3-1</td>
<td>Al/Mg/Mn</td>
</tr>
<tr>
<td>Image 3-2</td>
<td>Mg 2.52 μm</td>
</tr>
<tr>
<td>Image 3-3</td>
<td>Al 11.6 μm</td>
</tr>
<tr>
<td>Image 3-4</td>
<td>Al 1265 Å</td>
</tr>
<tr>
<td><strong>LOOP 4 ((n = n4))</strong></td>
<td>Image 4-1</td>
</tr>
<tr>
<td>Image 4-1</td>
<td>4308 Å</td>
</tr>
<tr>
<td>Image 4-2</td>
<td>4600 Å</td>
</tr>
<tr>
<td><strong>LOOP 5 ((n = n5))</strong></td>
<td>Image 5-1</td>
</tr>
<tr>
<td>Image 5-1</td>
<td>Be 119 μm</td>
</tr>
<tr>
<td>Image 5-2</td>
<td>Open</td>
</tr>
<tr>
<td>Image 5-3</td>
<td>NOP</td>
</tr>
<tr>
<td>Image 5-4</td>
<td>NOP</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Filter</th>
<th>Pixel sum</th>
<th>Obs. region</th>
<th>(\Delta t) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al 1265 Å</td>
<td>2 x 2</td>
<td>2 x 2</td>
<td>8</td>
</tr>
<tr>
<td>4308 Å</td>
<td>1 x 1</td>
<td>2 x 2</td>
<td>8</td>
</tr>
<tr>
<td>4600 Å</td>
<td>1 x 1</td>
<td>2 x 2</td>
<td>8</td>
</tr>
<tr>
<td>Al/Mg/Mn</td>
<td>1 x 1</td>
<td>2 x 2</td>
<td>8</td>
</tr>
<tr>
<td>Mg 2.52 μm</td>
<td>1 x 1</td>
<td>2 x 2</td>
<td>8</td>
</tr>
<tr>
<td>Al 11.6 μm</td>
<td>1 x 1</td>
<td>2 x 2</td>
<td>8</td>
</tr>
<tr>
<td>Al 1265 Å</td>
<td>1 x 1</td>
<td>2 x 2</td>
<td>8</td>
</tr>
<tr>
<td>4308 Å</td>
<td>1 x 1</td>
<td>2 x 2</td>
<td>8</td>
</tr>
<tr>
<td>4600 Å</td>
<td>1 x 1</td>
<td>2 x 2</td>
<td>8</td>
</tr>
<tr>
<td>Be 119 μm</td>
<td>1 x 1</td>
<td>2 x 2</td>
<td>16</td>
</tr>
<tr>
<td>Open</td>
<td>1 x 1</td>
<td>2 x 2</td>
<td>8</td>
</tr>
<tr>
<td>NOP</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>NOP</td>
<td></td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

**Total sequence time = 96 s**

**NOP** = no operation = skip.
<table>
<thead>
<tr>
<th>Telemetry</th>
<th>On-CCD sum</th>
<th>Pixel (arc sec)</th>
<th>Partial frame image</th>
<th>Full frame image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate</td>
<td>Mode</td>
<td></td>
<td>Image size (arc min)</td>
<td>Time resol. (s)</td>
</tr>
<tr>
<td>High</td>
<td>PFI dom.</td>
<td>1 × 1</td>
<td>2.45</td>
<td>2.6 × 2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 × 2</td>
<td>4.91</td>
<td>5.2 × 5.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 × 4</td>
<td>9.81</td>
<td>10.5 × 10.5</td>
</tr>
<tr>
<td>High</td>
<td>FFI dom.</td>
<td>1 × 1</td>
<td>2.45</td>
<td>2.6 × 2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 × 2</td>
<td>4.91</td>
<td>5.2 × 5.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 × 4</td>
<td>9.81</td>
<td>10.5 × 10.5</td>
</tr>
<tr>
<td>Med</td>
<td>PFI dom.</td>
<td>1 × 1</td>
<td>2.45</td>
<td>2.6 × 2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 × 2</td>
<td>4.91</td>
<td>5.2 × 5.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 × 4</td>
<td>9.81</td>
<td>10.5 × 10.5</td>
</tr>
<tr>
<td>Med</td>
<td>FFI dom.</td>
<td>1 × 1</td>
<td>2.45</td>
<td>2.6 × 2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 × 2</td>
<td>4.91</td>
<td>5.2 × 5.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 × 4</td>
<td>9.81</td>
<td>10.5 × 10.5</td>
</tr>
</tbody>
</table>

3.3.3. SXT High Time-Resolution Mode

It is possible that high-resolution pictures could reveal quite fast flare phenomena in soft X-rays. To permit investigation of this possibility a special high time-resolution mode has been implemented within the SXT. In this case a PFI is divided horizontally (E–W) into 2 or 4 sub-images, one of which is acquired at twice or four times the normal rate. Each sub-image is a separate exposure timed, and with its region of interest (ROI) selected, by logic in the SOLAR-A microprocessor. As these 16 or 32 line ROIs are transferred to the DP they are combined into what the DP thinks is a normal 64-line
PFI. The disassembly of the images into a high time resolution (0.5 or 1 s) movie of 16 × 64 or 32 × 64 pixel images is done on the ground.

In order to maintain the fast cadence of this the high time-resolution mode certain restrictions apply. Exposures must be short and filter alternation is not possible from one frame to the next. Only a single observing region can be used but the usual on-chip pixel summation is permitted. Automatic exposure control is allowed under the same considerations as for a normal PFI.

4. Conclusion

The opportunity to take scientific instruments beyond the atmosphere of the Earth has enabled scientists to gain new knowledge on a grand and beautiful scale. The X-ray telescopes of the Skylab missions in the decade of the 1970s provided humankind’s first extended look at phenomenon in the hot, dynamic outer atmosphere of a star. With the SOLAR-A soft X-ray telescope, thanks to improved technology, we have the opportunity to advance beyond Skylab with a simpler, smaller and less costly instrument. As we have described in the previous sections, the SXT provides innovative features catering to a wide range of observing targets. Thanks to phenomenal advances in data processing technology the SXT images should be much more easily and quickly accessible to the human mind than the earlier observations. For the best use of such elaborations, we hope that the SXT as well as the SOLAR-A mission survives for longer than is nominally expected, since it may be possible to study the solar-cycle dependency of various coronal parameters with a degree of reliability not previously attained. For flare studies the combination of SXT and the other SOLAR-A instruments provide a scientific capability much greater than the sum of the parts. We consider ourselves very fortunate to be able to contribute to these investigations and are eager to begin the mission.

Acknowledgements

We are grateful to our Japanese and American colleagues whose initiative and enthusiasm are responsible for the opportunity to have the SXT collaboration for the SOLAR-A mission. We especially recognize the leadership of Dr H. Hudson and the late Prof. K. Tanaka. We owe special thanks to our many scientific and engineering colleagues who have contributed to the design, fabrication, and testing of SXT. Among them K. Narita and T. Watanabe for X-ray optics; T. Cruz and W. Rosenberg for aspect optics; K. Appert and D. Kyrie for electronics; D. Akin for shutter design; D. Murray, B. Costanzo, T. Hasui, and A. Hagiwara for thermal design; J. Vieira and K. Gowen for mechanical design; R. Stern for the CCD; C. Feinstein, W. Brooker, and L. Shing for test and calibration; I. Kondo for control system architecture; T. Kato and A. Yamaguchi for supporting SXT testing at ISAS; D. T. Roethig for computer and e-mail support; B. Rix, M. Finch, F. Friedlaender, D. Kauffman, and W. Jaynes for contract and program management; R. Fielder, S. Taylor, and T. Iwata for secretarial support, and N. Nitta for quick-look software.
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The SXT program in the U.S. has been wisely and collegially managed and administered by C. Pellerin and J. Lintott of NASA headquarters and R. Ise and H. Hill of NASA Marshall Space Flight Center. The SXT CCD camera was provided by the Jet Propulsion Laboratory and we owe special thanks to L. Hovland, T. Bursch, J. Janesick, J. Daniels, M. Schwockert, T. Radey, E. Villegas, A. Collins, and R. White. It is only thanks to the expertise and cooperation of J. Hynecek and I. Fujii of Texas instruments that SXT has an excellent CCD. We have enjoyed outstanding teamwork and technical performance from our SXT subcontractors:

- **Carbon fiber metering tube**: Fiber Technology Corp. (B. Lundy).
- **Filter wheel and shutter motor**: Shaefver Magnetic
- **X-ray filters**: Luxel Corp. (G. Steele, F. Powell).
- **Optical filters**: Andover Corp., Perkin-Elmer.

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Lecture Notes in Physics, No. 367, p. 253.
Res. (to be published).
THE WIDE BAND SPECTROMETER ON THE SOLAR-A*

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Abstract. The SOLAR-A spacecraft has spectroscopic capabilities in a wide energy band from soft X-rays to gamma-rays. The Wide Band Spectrometer (WBS), consisting of three kinds of spectrometers, soft X-ray spectrometer (SXS), hard X-ray spectrometer (HXS) and gamma-ray spectrometer (GRS), is installed on SOLAR-A to investigate plasma heating, high-energy particle acceleration, and interaction processes. SXS has two proportional counters and each counter provides 128-channel pulse height data in the 2–30 keV range every 2 s and 2-channel pulse count data every 0.25 s. HXS has a NaI scintillation detector and provides 32-channel pulse height data in the 20–400 keV range every 1 s and 2-channel pulse count data every 0.125 s. GRS has two identical BGO scintillation detectors and each detector provides 128-channel pulse height data in the 0.2–10 MeV range every 4 s and 4-channel pulse count data (0.2–0.7, 0.7–4, 4–7, and 7–10 MeV) every 0.25–0.5 s. In addition, each of the BGO scintillation detectors provides 16-channel pulse height data in the 8–100 MeV range every 4 s and 2-channel pulse count data (8–30 and 30–100 MeV) every 0.5 s. The SXS observations enable one to study the thermal evolution of flare plasma by obtaining time series of electron temperatures and emission measures of hot plasma; the HXS observations enable one to study the electron acceleration and heating mechanisms by obtaining time series of the electron spectrum; and the GRS observations enable one to study the high-energy electron and ion acceleration and interaction processes by obtaining time series of electron and ion spectra.

1. Scientific Objectives

The SMM and HINOTORI satellites observed a large number of flares in the 21st solar maximum in the early 1980s. New findings of magnetic energy release processes, plasma heating, and particle acceleration were reported. The detailed scientific results were presented in the following special issues: Solar Phys. 86 (1983), No. 1, Solar Phys. 111 (1987), No. 1, Solar Phys. 113 (1987), Nos 1 and 2, Solar Phys. 118 (1988), Nos 1 and 2, Space Sci. Rev. 51 (1989), No. 1, and Astrophys. J. Suppl. 73 (1990). Some of the primary questions concerning these fundamentals of flare phenomena, however, still

* After the launch the name of SOLAR-A has been changed to YOHKOH.
remain unsolved. Attempts have been made to show how future observations with increased sensitivity and improved spatial and spectral resolutions will answer these questions. Explosive phenomena such as the solar flare are a common characteristic of cosmic plasma at many sites throughout the universe, and a detailed understanding of these high-energy processes is one of the major goals of astrophysics.

Spectroscopic observations in a wide energy band of soft X-rays to gamma-rays provide important clues to the plasma heating and particle acceleration processes. The soft X-ray spectrum consists of components of continuum and various lines. The emission in energies above 5 keV is mostly continuum which results from hot thermal plasma, with the exception of the strong line emission at 6.7 keV which results from excited iron ions. The electron temperature and emission measure of hot plasma can be derived from the soft X-ray continuum spectrum (e.g., Watanabe et al., 1983). Further, the thermal energy content is calculated from these two parameters. The thermal evolution of the flare plasma can be studied with these temporally resolved quantities. The soft X-ray spectral observation diagnoses the hot flare plasma and provides complementary data for other experiments on board SOLAR-A: the soft X-ray telescope (SXT) and the Bragg crystal spectrometer (BCS).

The hard X-ray observation provides the most direct information for understanding the energy release processes and the electron acceleration mechanisms. The hard X-ray intensity variations correlate with electron acceleration. The onset of the hard X-ray emission gives the most important signal for the earliest time of the magnetic energy release. The electron acceleration and plasma heating mechanisms can be deduced from the temporal and spectral analyses of the hard X-ray emission (e.g., Dennis, 1988). The conditions at the energy release site, the magnetic field configuration, and the parameters of the flare plasma before, during, and after the flare are determined from coincident observations of images in both hard and soft X-rays and at other wavelengths.

The gamma-ray observations provide irreplaceable information for study of the highest-energy flare phenomena (Chupp, 1984, 1987; Yoshimori, 1989). The radiation in the gamma-ray range is emitted by several processes including high-energy electron bremsstrahlung, nuclear de-excitation, positron annihilation, neutron capture, and neutral pion decay. The electron bremsstrahlung produces a continuum spectrum extending to the maximum energy of the accelerated electrons. Thus the electron acceleration to the highest energies can be studied from the temporal and spectral analyses of the gamma-ray emission. The other gamma-ray emissions result from energetic ion interactions with the solar ambient medium. The detection of these gamma-ray emissions gives evidence of nuclear reactions at the flare site. The nuclear de-excitation produces a prompt line emission in the MeV energies. The nuclear de-excitation lines are mostly produced by ions accelerated to 10–30 MeV nucl$^{-1}$. The positrons are mostly emitted by beta-decay nuclei produced by 10–100 MeV nucl$^{-1}$ ion interactions. The neutron capture on protons emits a delayed line at 2.22 MeV. The neutrons contributing to the 2.22 MeV line emission are produced by ions with energies $<100$ MeV nucl$^{-1}$. The pion decay gamma-ray spectrum with a broad peak at 70 MeV is different from the high-energy electron bremsstrahlung spectrum. Since the pions are produced by protons
accelerated to energies $> 1$ GeV, the pion decay gamma-ray emission provides evidence of very high-energy proton acceleration. High-energy neutron observation also provides similar evidence. The high-energy electron and ion acceleration processes are investigated from the temporal and spectral analyses of the gamma-ray emission over wide energy ranges. Sufficiently detailed information cannot be determined from the gamma-ray observations alone and coincident observations of solar energetic particles (SEP) in interplanetary space and high-energy neutron measurements at ground-based stations are required to complement the data.

The Wide Band Spectrometer (WBS), which consists of three kinds of spectrometers covering the energy range from soft X-rays to gamma-rays, is installed on the SOLAR-A to observe the detailed spectrum and temporal evolution of this wide-band photon emission. It will help to better understand the important processes of plasma heating and particle acceleration in solar flares.

2. Instrument Description

The WBS consists of the following subinstruments: (1) soft X-ray spectrometer (SXS), (2) hard X-ray spectrometer (HXS), (3) gamma-ray spectrometer (GRS), and (4) radiation belt monitor (RBM). SXS, HXS, and GRS are solar instruments pointed at the Sun. RBM has the capability of detecting the radiation belt passage and is pointed perpendicular to the solar direction. Descriptions of the WBS instrument can be found elsewhere (Yoshimori, 1988; Yoshimori et al., 1988; Kondo et al., 1990).

2.1. Soft X-ray spectrometer (SXS)

SXS consists of a gas proportional counter filled with Xe and CO$_2$ (1.16 atm) and covers the energy range of 2 to 30 keV. The gas proportional counter has three anode wires: two of them are connected together to form SXS-1 output and the third anode wire forms SXS-2 output. The cross-sectional view of the SXS detector is shown in Figure 1. The three anode wires are biased with one high-voltage power supply unit. SXS has a field of view of 10 deg $\times$ 10 deg (20 times the diameter of the Sun), reducing the background by an aluminum slit collimator. The SXS counters have beryllium windows of 150 $\mu$m thickness. The SXS-1 counter has an area of 11.88 cm$^2$ with the additional 150 $\mu$m thick aluminum filter and 0.0707 cm$^2$ without filters, while the SXS-2 counter has aluminum filters of 50 $\mu$m thickness (0.0353 cm$^2$) and 300 $\mu$m thickness (6.12 cm$^2$). The effective areas of SXS-1 and SXS-2 counters are calculated as a function of energy and shown in Figure 2. The SXS-1 counter has a large effective area suitable for detection of a small flare, whereas the SXS-2 counter has a small effective area suitable for detection of large flares. Thus the SXS, with the two different gas proportional counters, has the capability of detecting flares of various sizes.

The SXS spectral response to a 5.9 keV Mn K$\alpha$ line from the $^{55}$Fe radioactive source is shown in Figure 3. The energy resolution (FWHM) at 5.9 keV is about 20% and is shown as a function of energy in Figure 4. The in-flight energy calibration is achieved by detection of the 5.9 keV Mn K$\alpha$ line of the attached $^{55}$Fe calibration source.
Soft X-Ray Spectrometer

Fig. 1. Cross-sectional view of SXS gas proportional counter. (a) Top view and (b) side view. The SXS gas proportional counter has three anode wires: two of them are connected together to form SXS-1 output and the third wire forms SXS-2 output.

The SXS electronic block diagram is shown in Figure 5. The SXS primary output data from both SXS-1 and SXS-2 counters are 128-channel pulse height data in the 2–30 keV range every 2 s (SXS-PH1 for SXS-1 and SXS-PH2 for SXS-2) and 2-channel pulse count data every 0.25 s (SXS-PC11 and 12 for SXS-1 and SXS-PC21 and 22 for SXS-2). The energy ranges of the pulse count data are changeable by command. One of the 4 pulse count data is also used to monitor the occurrence of solar flares.

2.2. Hard X-ray Spectrometer (HXS)

The HXS consists of a NaI scintillator, which is 7.6 cm in diameter and 2.5 cm in thickness, optically coupled to a 7.6 cm diameter photomultiplier tube. The cross-sectional view of the HXS is shown in Figure 6. The HXS covers the energy range of
20–600 keV. The NaI scintillator is covered with two stainless steel absorbers (13.8 cm$^2 \times 0.08$ mm thick + 31.8 cm$^2 \times 1$ mm thick) to suppress low-energy X-ray events. The effective area of HXS is shown as a function of energy in Figure 7. The HXS spectral response to 30, 81, and 356 keV lines from $^{133}$Ba electron capture is shown in
Fig. 3. SXS spectral response to 5.9 keV Mn Kα line from $^{55}$Fe radioactive source.

Fig. 4. Energy resolution (FWHM) of the SXS counter as function of energy.

Figure 8. The energy resolution (FWHM) at 60 keV is 15% and is shown as a function of energy in Figure 9. The incident hard X-ray spectrum is obtained by deconvoluting the observed 32-channel energy-loss spectrum (Forrest, 1990). An HXS response matrix obtained from the Monte Carlo simulation is used for the spectral deconvolution. As an example, the incident hard X-ray spectrum of $E^{-3}$ below 100 keV and $E^{-5}$ above
Fig. 5. SXS electronic block diagram. Three anode wires are biased by one high-voltage power supply unit (HV). Each of the SXS-1 and SXS-2 outputs is fed to a similar electronic circuit. Each of the SXS counter outputs passes through a preamplifier and shaping amplifier, and is fed to a main amplifier. After amplification, the output is sent to an 8-bit ADC to produce 128-channel pulse height data (SXS-PH). The amplified output is also sent to a discriminator with 4 levels (LD, MD1, MD2, and UD) to produce 2-channel pulse height count data (SXS-PC11 and 12 for SXS-1 and SXS-PC21 and 22 for SXS-2). In addition, ADC triggering count (SXS-ADCT), and pulse count above upper discriminator level (SXS-UD) are monitored as housekeeping data. HV level, main amplifier gain, and MD1 and MD2 discrimination levels are changeable by block command (BC).

100 keV and the convoluted energy-loss spectrum are shown in Figure 10. The in-flight energy calibration is achieved by detection of a 60 keV line from $^{237}$Np nuclear de-excitation ($^{237}$Np is an $^{241}$Am $\alpha$-decay product). In this HXS calibration, the 60 keV line event in coincidence with an $\alpha$-particle (5.48 MeV) event detected with two silicon detectors is recorded. The in-flight energy calibration method is schematically shown in Figure 11. The HXS in-flight energy calibration spectrum measured with the coincidence method is shown in Figure 12. The details of the in-flight energy calibration system was described earlier (Yoshimori and Okudaira, 1988).

The HXS electronic block diagram is shown in Figure 13. The HXS primary output is 32-channel quadratic-spaced pulse height data in the 20–400 keV range every 1 s (HXS-PH), and 2-channel pulse count data (HXS-PC1 (20–50 keV) and HXS-PC2 (50–600 keV)) every 0.125 s. HXS-PC1 is also used to monitor the occurrence of solar flares.

2.3. Gamma-ray Spectrometer (GRS)

The GRS consists of two identical BGO scintillators. Each scintillator is 7.6 cm in diameter and 5.1 cm in thickness and is optically coupled to a 7.6 cm diameter photo-
Hard X-Ray Spectrometer

Fig. 6. Cross-sectional view of HXS NaI detector. A NaI(Tl) scintillator of 7.6 cm diameter and 2.5 cm thickness is optically coupled with a photomultiplier tube (PMT) biased by a high-voltage power supply unit (HV). CAL is an in-flight energy calibration device.

multiplier tube. The cross-sectional view of GRS is shown in Figure 14. Since the BGO (Bi₄Ge₃O₁₂) scintillator has high density and high effective atomic number, these properties contribute toward improving the detection sensitivity to gamma-rays. Each BGO scintillator is covered with a 0.5 mm thick lead absorber to suppress low-energy gamma-ray events. The GRS spectral responses to 3.08 and 4.07 MeV lines from ⁴⁹Ca nuclear de-excitation (⁴⁹Ca nuclear excitation state is produced by thermal neutron-capture reaction of ⁴⁸Ca nuclei) and 12.79 and 17.23 MeV lines from ⁷Be nuclear de-excitation (⁷Be nuclear excited state is produced by nuclear reaction of p(⁷Li, ⁷Be)n)
are shown in Figures 15(a) and 15(b). The energy resolution (FWHM) of GRS is shown as a function of energy in Figure 16. The BGO energy resolution is about twice that of the NaI scintillator due to the low scintillation efficiency of the BGO scintillator. The energy dependence of the effective area of GRS is calculated as a function of gamma-ray energy by the Monte-Carlo simulation. The result is shown in Figure 17. The incident gamma-ray spectrum is obtained by deconvoluting the observed 128-channel energy-loss spectrum. The GRS response matrix obtained from the Monte Carlo simulation is used for the spectral deconvolution. As an example, the incident gamma-ray spectrum of $E^{-3}$ continuum + lines and the convoluted energy-loss spectrum are shown in Figure 18.

The GRS electronic block diagram is shown in Figure 19. Each of two identical GRS detectors (GRS-1 and GRS-2) is connected to a similar electronic circuit. Since GRS covers the wide energy range of 0.2–100 MeV, the 0.2–10 MeV output pulse (GRS-L) and 8–100 MeV output pulse (GRS-H) are produced from the anode and the 6th dynode of the photomultiplier tube, respectively. The primary output data of GRS-L are 128-channel quadratic-spaced pulse height data every 4 s (GRS-PHL1 and
Fig. 8. HXS spectral response to 30, 81, and 356 keV lines from $^{133}\text{Ba}$ electron capture.

Fig. 9. Energy resolution (FWHM) of HXS as a function of energy.
GRS-PHL2) and 4-channel pulse count data (GRS-PC11 and 21 for 0.2–0.7 MeV, GRS-PC12 and 22 for 0.7–4 MeV, GRS-PC13 and 23 for 4–7 MeV and GRS-PC14 and 24 for 7–10 MeV). The time resolution is 0.25 s for GRS-PC11, 12, 21, and 22, and 0.5 s for GRS-PC13, 14, 24, and 25. The primary output data of GRS-H are 16-channel

Fig. 10. Hard X-ray incident spectrum ($E^{-3}$ below 100 keV and $E^{-5}$ above 100 keV) and convoluted energy-loss spectrum.

Fig. 11. HXS in-flight energy calibration method is schematically shown. 60 keV nuclear de-excitation line and 5.48 MeV α-ray are simultaneously emitted from $^{241}\text{Am}$ radioactive source. 60 keV line detected with HXS NaI(Tl) scintillator in coincidence with 5.48 MeV α-ray detected with two silicon solid state detectors (Si SSD) is recorded as calibration data.
Fig. 12. HXS in-flight energy calibration spectrum of 60 keV line from $^{237}$Np nuclear de-excitation.

Fig. 13. HXS electronic block diagram. NaI(T1) scintillation detector output passes through a pre-amplifier and shaping amplifier, and is fed to a main amplifier. After amplification, the output is sent to an 8-bit ADC to produce 32-channel pulse height data (HXS-PH). The amplified output is also sent to a discriminator with 3 levels (LD, MD, and UD) to produce 2-channel pulse count data (HXS-PC1 and HXS-PC2). Silicon solid state detector (SSD) output passes through a preamplifier and shaping amplifier, and is fed to a discriminator. A coincidence event between NaI(T1) and SSD detectors provides an in-flight energy calibration event. In addition, ADC triggering count (HXS-ADCT), pulse count above upper discrimination level (HXS-UD), and SSD pulse count (HXS-SSD) are monitored as house-keeping data. HV level, main amplifier gain, SSD discrimination level, and NaI(T1) discrimination level are changeable by block command (BC).
pulse height data every 4 s (GRS-PHH1 and GRS-PHH2) and 2-channel pulse count data every 0.5 s (GRS-PC15 and 25 for 8–30 MeV and GRS-PC16 and 26 for 30–100 MeV). The in-flight energy calibration in GRS-L is achieved by the detection of 1.17 and 1.33 MeV lines from $^{60}$Co nuclear de-excitation in coincidence with a $\beta$-ray (maximum energy 310 keV) detected with two Si detectors. The GRS in-flight energy calibration spectrum measured with the coincidence method is shown in Figure 20.

GRS also has detection sensitivity to solar neutrons. As an example, the GRS response to 45 MeV neutrons produced by $p$(Li, Be)$n$ reaction is shown in Figure 21. Although the GRS has sensitivity to neutrons, it is difficult to determine the incident neutron energy from the GRS pulse height spectrum.

2.4. Radiation belt monitor (RBM)

The RBM consists of two different detectors, NaI scintillation detector (5.1 cm in diameter and 1 cm in thickness) and Si detector (4 mm in diameter and 100 $\mu$m in thickness). These two detectors are pointed in the direction perpendicular to the Sun and are insensitive to solar flare X-rays and gamma-rays. The NaI detector produces

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Fig. 15. (a) GRS spectral response to 3.08 and 4.07 MeV lines from $^{40}$Ca nuclear de-excitation. (b) GRS spectral response to 12.79 and 17.23 MeV lines from $^7$Be nuclear de-excitation.
Fig. 16. Energy resolution (FWHM) of GRS as a function of energy.

Fig. 17. Calculated effective area of GRS as a function of energy.
32-channel quadratic-spaced pulse height data in the 5–300 keV range every 1 s and 2-channel pulse count data (5–60, 60–300 keV) every 0.25 s. The Si detector produces single channel pulse count data in energies above 20 keV every 0.25 s. When the pulse count of the NaI or the Si detector exceeds a certain threshold value, the alarm for the South Atlantic Anomaly (SAA) passage is sounded. The radiation belt alarm is used to avoid recording a false flare event.

2.5. Gamma-ray burst detection capability

The HXS and RMB NaI detectors are capable of monitoring non-solar X-ray and gamma-ray burst phenomena during solar quiet time and night time. When the HXS

---

Fig. 18. Gamma-ray incident spectrum \( E^{-3} \) + lines and convoluted energy-loss spectrum.

Fig. 19. GRS electronic block diagram. GRS consists of two identical BGO (Bi\(_4\)Ge\(_3\)O\(_{12}\)) scintillation detectors (GRS-1 and GRS-2). Each detector is connected to a similar electronic circuit and produces two outputs. One is an anode output pulse (0.2–10 MeV) and the other is a 6th dynode output pulse (8–100 MeV). The anode pulse passes through a preamplifier and shaping amplifier, and is fed to a main amplifier. After amplification, the output pulse is sent to an 8-bit ADC to produce 128-channel pulse height data (GRS-PHL). The amplified pulse is also sent to a discriminator with 5 levels to produce 4-channel pulse count data (GRS-PC11, 12, 13, and 14 for GRS-1 and GRS-PC21, 22, 23, and 24 for GRS-2). The dynode pulse is similarly processed to produce 16-channel pulse height data (GRS-PH) and 2-channel pulse count data (GRS-PC25 and 26 for GRS-2). Two silicon solid state detectors (SSD) output is fed to a preamplifier and shaping amplifier, and then sent to a discriminator. A coincidence event between the BGO and SSD detectors provides an in-flight energy calibration event. In addition, ADC triggering event (GRS-ADCLT and GRS-ADCHT), pulse count above upper discrimination level (GRS-UD), and SSD pulse count (GRS-CAL) are monitored as housekeeping data. HV level, main amplifier gain, and SSD discrimination level are changeable by block command (BC).
Fig. 20. GRS in-flight energy calibration spectrum of 1.17 and 1.33 MeV lines from $^{60}$Co nuclear de-excitation.

Fig. 21. GRS response to 45 MeV neutrons.
pulse count in the 50–600 keV range or the RBM pulse count in the 60–300 keV range exceeds a certain threshold value, both 32-channel pulse height data every 1 s and pulse count data every 0.25 s are recorded for 256 s.

**Table 1**

Principal WBS output data. SXS consists of two different gas proportional counters (SXS-1 and SXS-2) and each counter provides 128-channel pulse height (PH) data every 2 s, and 2-channel pulse count (PC) data every 0.25 s. HXS consists of a NaI scintillation detector and provides 32-channel PH data every 1 s, and 2-channel PC data every 0.125 s. GRS consists of two identical BGO scintillation detectors (GRS-1 and GRS-2) and each detector provides 128-channel (0.2–10 MeV) and 16-channel (8–100 MeV) PH data every 4 s, and 6-channel PC data every 0.25 or 0.5 s.

<table>
<thead>
<tr>
<th>Spectrometer</th>
<th>Output</th>
<th>PH-data (time resolution)</th>
<th>PC-data (time resolution)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SXS</td>
<td>SXS-1</td>
<td>128-ch (2–30 keV) (2 s)</td>
<td>2-ch (0.25 s)</td>
</tr>
<tr>
<td></td>
<td>SXS-2</td>
<td>128-ch (2–30 keV) (2 s)</td>
<td>2-ch (0.25 s)</td>
</tr>
<tr>
<td>HXS</td>
<td>HXS</td>
<td>32-ch (20–600 keV) (1 s)</td>
<td>2-ch (0.125 s)</td>
</tr>
<tr>
<td>GRS</td>
<td>GRS-1</td>
<td>128-ch (0.2–10 MeV) (4 s)</td>
<td>4-ch (0.25 s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16-ch (8–100 MeV) (4 s)</td>
<td>2-ch (0.5 s)</td>
</tr>
<tr>
<td></td>
<td>GRS-2</td>
<td>128-ch (0.2–10 MeV) (4 s)</td>
<td>4-ch (0.25 s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16-ch (8–100 MeV) (4 s)</td>
<td>2-ch (0.5 s)</td>
</tr>
</tbody>
</table>

The principal WBS data are given in Table I. In addition to the principal data, housekeeping data are also recorded. These data include command status, instrument status, sixteen digital housekeeping data (the counts above upper energy discrimination level, ADC triggering counts, and inflight energy calibration event counts) and nine analog housekeeping data (high voltage and temperature).

### 3. Expected Scientific Return

WBS is expected to produce the following results. From the SXS observation the time development of electron temperatures and emission measures of a heated plasma can be studied and the cutoff energy of the nonthermal electron spectrum will be determined. The SXS observations can contribute to solving some fundamental problems of plasma heating during solar flares. From the HXS and GRS observations the electron and ion acceleration processes can be characterized in greater detail and the physical conditions which dominate the time scale and the efficiency of the particle acceleration mechanisms can be better determined. The WBS observations will provide an essential key to our understanding of high-energy processes such as plasma heating, particle acceleration, and interaction processes during solar flares.

Furthermore, collaborations with the other instruments of SOLAR-A (soft X-ray telescope, hard X-ray telescope, and Bragg crystal spectrometer), gamma-ray instruments on GRO and GRANAT, Max '91 HIREGS (high-resolution gamma-ray spectrometer) and HEIDI (high-energy imaging device), radio imagers at microwave and
millimeter wavelengths, solar energetic particle (SEP) instruments on GEOTAIL and WIND, and ground-based solar neutron monitors will provide very fruitful and exciting results which may help us to solve a lot of questions related to the high-energy solar flare phenomena.

**Acknowledgement**

The authors wish to thank Toshiba Corporation for the detailed design, fabrication and testing of the electronics and for the integration of the WBS system.

**Note Added in Proof**

The HXS in-flight energy calibration method described here is not adopted. The HXS in-flight energy calibration is achieved by detection of 60 keV line of the attached Am-241 calibration source.

**References**


THE BRAGG CRYSTAL SPECTROMETER FOR SOLAR-A*

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\textbf{Abstract.} The Bragg Crystal Spectrometer (BCS) is one of the instruments which makes up the scientific payload of the SOLAR-A mission. The spectrometer employs four bent germanium crystals, views the whole Sun and observes the resonance line complexes of H-like Fexxvi and He-like Fexxv, CaXIX, and Sxv in four narrow wavelength ranges with a resolving power ($\lambda/\Delta\lambda$) of between 3000 and 6000. The spectrometer has approaching ten times better sensitivity than that of previous instruments thus permitting a time resolution of better than 1 s to be achieved. The principal aim is the measurement of the properties of the 10 to 50 million K plasma created in solar flares with special emphasis on the heating and dynamics of the plasma during the impulsive phase. This paper summarizes the scientific objectives of the BCS and describes the design, characteristics, and performance of the spectrometers.

1. Introduction

The solar flare problem represents one of the most difficult challenges posed in astrophysics. In the past 15 years it has become clear that progress can best be made with the aid of observations throughout the widest electromagnetic spectrum. The Bragg Crystal Spectrometer (BCS) will be used at X-ray wavelengths to study plasma heating and dynamics particularly during the impulsive phase of solar flares. The emission lines selected for observation allow the measurement of plasma velocity, temperature, and emission measure. Study of these flare plasmas will be undertaken jointly by all the SOLAR-A instruments. The measurement of element abundances and abundance variations will be an important aim of BCS observations in particular.

High spectral and temporal resolution coupled with high sensitivity are necessary features of an instrument designed to achieve the above objectives. The BCS will have almost ten times greater sensitivity than was available from the instruments flown on SMM (Acton \textit{et al.}, 1980), P78–1 (Doschek, 1983) and HINOTORI (Kondo, 1983) during the last solar maximum. It will employ fixed bent crystals with one-dimensional

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* After the launch the name of SOLAR-A has been changed to YOHKOH.

** Tragically Professor K. Tanaka died on January 2, 1990.
position-sensitive proportional counters to register the spectra. The spectral resolution will be comparable to that of the similar instrument on SMM but the enhanced sensitivity will permit a time resolution of better than 1 s. A flexible on-board data processing system, including a large queue memory, will allow a wide range of operating modes to be implemented during the mission.

In the rest of the paper the scientific aims of the BCS are summarized, the design of the spectrometers is described with particular reference to the Bragg crystal performance, the X-ray detectors and the on-board processor. A brief account will be given of the instrument calibration. We must emphasize that the instrument performance parameters presented are preliminary in nature and require verification following in-orbit operation. They should not be used for data analysis. A users manual is being prepared and will be updated after the launch of SOLAR-A.

2. Scientific Objectives

Following the impulsive release of energy in a solar flare, a large quantity (emission measure $\approx 10^{48} - 10^{50} \text{ cm}^{-3}$) of high temperature ($T \approx 10 - 50 \times 10^6 \text{ K}$) plasma is created. The manner of the plasma creation and the dynamics and other properties of the high-temperature gas all provide essential clues to understanding the flare mechanism. In the above temperature range the high-ionization stages (e.g., H-like and He-like) of abundant elements are formed and the plasma properties may be studied by observing the X-ray emission spectra of these ions. The sensitivity and wavelength resolution of the spectrometers permit line intensities and profiles to be measured with sufficient time resolution to obtain detailed observations throughout the impulsive phase of flares. The data will be used in the following investigations:

Plasma dynamics. Observations with high-resolution X-ray spectrometers during the past decade have demonstrated that the emission lines are significantly broadened during the flare impulsive phase. The ‘turbulent’ width, substantially greater than the Doppler width implied by simultaneous electron temperature measurement, indicates mass motion velocities approaching 200 km s$^{-1}$ (Doschek et al., 1980; Antonucci et al., 1982). There may also be a correlation of non-thermal line width with associated hard X-ray flux. In addition the broadening may be non-random on short time scales (Doyle and Bentley, 1987; Fludra et al., 1989). A blue-shifted component is often observed for disc flares (Doschek et al., 1980; Feldman et al., 1980; Antonucci et al., 1982) indicating upward moving plasma with velocity of 300 km s$^{-1}$ or greater. This plasma has been attributed to ‘chromospheric evaporation’ – the ablation of plasma heated by energy transported form the flare site (Antonucci et al., 1982; Antonucci, Gabriel, and Dennis, 1984) but the details of this process and of the energy transport mechanism, remain controversial. Use of the enhanced sensitivity and time resolution of the SOLAR-A BCS will lead to major advances in this important area of flare physics.

Plasma heating and diagnostics. There is significant evidence from previous observations that heating and turbulence occur even before the impulsive phase of the flare. The increased sensitivity of the BCS will permit early measurement of temperature with
much increased statistical precision. It will also be possible to search for anomalous line ratios which will indicate transient ionization effects thus allowing the estimation of electron densities in the range below $10^{11} \text{ cm}^{-3}$. Greater sensitivity will permit improved estimation of plasma parameters such as temperature and emission measure. Comparison of these measurements with Soft X-ray Telescope (SXT) images which are expected to have better than 3 arc sec spatial resolution will allow the direct estimation of electron density and the determination of differential emission measure over a wide temperature range.

**Superhot component.** Observations of the H-like iron (Fe xxvi) emission line spectrum will be particularly important for the study of the plasma at temperatures of around $50 \times 10^6 \text{ K}$ that is detected in some flares (Lin et al., 1981; Tanaka et al., 1982). Temperatures will be obtained from the intensity ratio of the Fe xxv dielectronic lines to those of the Fe xxvi Lx lines. In addition it will be possible for the first time to obtain statistically significant profiles for the Lx lines and so investigate the dynamics of this important component. Data from HINOTORI (Tanaka, 1987) provided a tentative indication of variability in the Fe xxvi line profiles. The enhanced spectral resolution of the BCS will permit detailed observations of line profile variations with time.

**Flare decay phase.** Although the main release of energy in the flare occurs during the impulsive phase, there is evidence for continued energy injection during the decay phases of some flares. The BCS will permit a detailed study of this process. For large limb flares, it may be possible to observe the increase in height of the emitting plasma since spatial displacement translates into spectral displacement in the BCS. Such plasma, contained in large post-flare loops, was observed with the SMM BCS to have a temperature of $\approx 5-6 \times 10^6 \text{ K}$ many hours after the flare had occurred (Švestka et al., 1982). Combined observations by the SXT and the BCS will allow a substantial advance in this area. Finally the measurement of line to continuum ratios during flare decay will allow flare-to-flare abundance variations to be studied for a range of elements (Sylwester, Lemen, and Mewe, 1984; Sylwester, 1987).

### 3. Design of the SOLAR-A Bragg Crystal Spectrometer System

The crystal spectrometers constructed for flight on SOLAR-A are similar to those successfully launched on the Solar Maximum Mission (Rapley et al., 1977; Acton et al., 1980). In the case of SOLAR-A however the presence of high-quality imaging X-ray telescopes, the smaller mass and volume available, and the results obtained by the SMM have led to a somewhat different approach to the instrument design.

Conventional Bragg spectrometers scan in wavelength by rotating a flat crystal so that a range of angular positions ($\theta$) converts a range of wavelengths ($\lambda$) according to Bragg’s law $n\lambda = 2d \sin \theta$. For SOLAR-A each spectrometer crystal is curved with a fixed radius so that a parallel beam of solar X-rays is incident at a range of Bragg angles $\theta_1$ to $\theta_2$. Diffracted radiation, at corresponding wavelengths $\lambda_1$ to $\lambda_2$, is registered in a one-dimensional position-sensitive proportional counter (see Figure 1). Given the existence of the imaging X-ray telescopes, the small probability of simultaneous flare
occurrence in different active regions and the relatively small mass and volume available for the BCS, a multi-grid collimator was not employed on SOLAR-A and so the BCS views the entire solar disc. This, coupled with increased crystal area, allows a factor approaching ten increase in sensitivity relative to the SMM instrument. The sensitivity of a bent crystal spectrometer can be obtained from the relation given by Rapley et al. (1977) as

$$S = \frac{[T_w T_f F_b \eta_d A_p R_c]}{\Delta \theta},$$

where $S$ is the sensitivity in cm$^2$, $T_w$ and $T_f$ are the transmissions of the detector window and the thermal filter, $F_b$ is the fractional detector area lost due to the window support bars, $\eta_d$ is the X-ray absorption efficiency of the detector gas, $A_p$ is the projected area of the crystal in cm$^2$, $R_c$ and $\Delta \theta$ are the integrated reflectivity of the crystal and the range of incident Bragg angles, both in radians.

From (1) $S$ is inversely proportional to $\Delta \theta$ and therefore to the wavelength range $\lambda_2 - \lambda_1$ covered by each crystal. In order to maximize $S$ it is therefore necessary to select the minimum wavelength range that is consistent with achieving the scientific aims. However, since Bragg angle range translates to wavelength range, the minimum spectral coverage must be increased to allow for uncertainties in spacecraft pointing, for spectrometer alignment errors, and for the range of flare locations on the surface of the Sun. With the crystal dispersion direction aligned approximately perpendicular to the solar equator, the allowance of an additional $\pm 12$ arc min in Bragg angle permits the chosen spectral ranges to be registered for all possible spacecraft pointing directions which lie inside a circle of $5$ arc min angular radius about Sun centre and for most flares which occur mainly in a latitude range of $\pm 7$ arc min about the equator.

The BCS employs four bent crystals to cover selected wavelength ranges of diagnostic importance. These ranges are shown in Figure 2 superimposed on spectra of Fe xxvi taken from HINOTORI data (Tanaka, 1987), Fe xxv and Ca xix taken from SMM BCS data (Culhane et al., 1981) and S xv taken from SMM Flat Crystal Spec-
Fig. 2. Bragg crystal spectra of solar flares. (a) Fe XXVI obtained with HINOTORI, (b) Fe XXV and (c) Ca XIX obtained with the SMM bent crystal spectrometer, and (d) S XV obtained with the SMM flat crystal spectrometer. The solid lines indicate the spectral coverage for the four SOLAR-A spectrometers. See text for references.

The Bragg crystal spectrometer (FCS) data (Acton et al., 1981). The Fe XXVI range will permit velocity and temperature measurements for the superhot component. Coverage of the Ca XIX range has been essentially restricted to the resonance transition to allow velocity measurements at maximum resolution and sensitivity. However, there is some temperature information available from the intensity of the $n = 3$ satellite lines that fall close to the long wavelength side of the resonance line. The more complete coverage of the Fe XXV and S XV ranges will permit both velocity and temperature measurements.

The four crystals are mounted in two structures as shown in Figure 3. X-rays from the Sun (Z-direction) enter the open apertures of the spectrometers through a pair of thin aluminized Kapton thermal filters (not shown in the figure) which are mounted over openings in the front panel of the spacecraft. The incoming radiation strikes the crystals which are curved and fixed in place before launch so as to cover the selected wavelength ranges. The radiation is then diffracted into detectors located inside each structure. The
only moving parts are two stepper motors which can rotate to admit 5.89 keV Mn–K X-rays from Fe\textsuperscript{55} radioactive sources to the detectors to enable their gas gain and energy resolution to be measured in flight.

Within the spectrometers an optical technique is used to set each crystal at the appropriate Bragg angle with a precision of better than $\pm 15$ arc sec with respect to the plane defined by the feet of the spectrometers. Each spectrometer has three feet with precisely located and sized screw holes to enable accurate mounting on the spacecraft centre panel. Precision shoulder screws attach the feet to the centre panel. An optically located drill template is used to position the mating holes in the centre panel in the correct relationship to the $Z$-axis of the spacecraft. The openings in the centre panel mounting holes are accurately reamed to accept the barrels of the shoulder screws. Clearances of 25 $\mu$m are maintained so that the shoulder screws serve both as attach-
ments and as locating pins. The alignment procedure ensures that the optical axis of the BCS is co-aligned with the Z-axis of the spacecraft. As the centre panel is specified to be flat to within $\pm 3.4$ arc min, provision is made for shimming the spectrometer during mounting on the spacecraft to optimize the Bragg angle ranges.

The two spectrometer units, labelled BCS-A and BCS-B, each contain two germanium crystals which have been paired so as to have approximately the same Bragg angles. The spectrometer structures are built with reference surfaces having the average of the two Bragg angles machined into the crystal support structure. Each crystal mount has three mounting pads that can be ground to ensure that the crystal offers the required range of Bragg angles to incoming solar radiation. The crystal mounts are made from titanium whose thermal expansion coefficient is well matched to that of germanium. The front surfaces of the mounts are ground to a concave cylindrical shape of the required radius. The 0.6 mm thick crystals are bent to the correct curvature and then attached to the mount with epoxy.

The crystal parameters and the wavelength ranges covered are listed in Table I. The crystals are somewhat larger than those flown on earlier missions. While Ge (220) crystals were used in both the P78–1 and SMM spectrometers, the Ge (111) crystal has not been flown previously. Before mounting in the spectrometer each crystal was characterized by measurements of its curvature and integrated reflectivity using X-rays.

The BCS instrument response is summarized in Table II. The wavelength resolution is set by the geometry of the spectrometers, the crystal rocking curves and the X-ray position resolution of the detectors. Each detector has a single position encoding arrangement – a modified wedge and strip pattern. X-rays from pairs of crystals are registered in each detector and are identified by signals from separate anode wires. The operation and performance of the detectors is dealt with in the next section.

Spectra are accumulated in the on-board digital processing system for a fixed time interval after which the total count in each spectral bin is compressed to an 8-bit number. At the flare-mode telemetry rate of 2 kbits s$^{-1}$ for the BCS, four complete spectra can be transmitted every 4 s. However, the digital system incorporates a large queue memory which can be filled with spectra at a faster rate for later transmission. For example, the spectrometer can store a series of four spectra with 1 s time resolution for up to 7 min thus acquiring a total of 420 sets each of four spectra. This mode of operation can be initiated by an on-board flare occurrence flag thus enabling spectra to be acquired at higher time resolution during the impulsive phase. The digital data system will be described more fully in Section 5.

4. Detectors and Analogue Electronics

An exploded view of the one-dimensional position-sensitive proportional counter is given in Figure 4. The detector is filled with a mixture of Ar and Xe both at 47.5% with CO$_2$ (5%) as a quench gas to an overall pressure of 1.2 atm. The body is in two stainless steel halves. A beryllium foil window of 125 $\mu$m thickness is brazed to the upper section while the anodes, cathodes, and readout pattern are installed in the lower section. The
<table>
<thead>
<tr>
<th>Channel No.</th>
<th>Ion</th>
<th>Resonance line $\lambda$ ($\AA$) (Bragg angle)</th>
<th>$2d$ ($\AA$)</th>
<th>Crystal (rocking curve)</th>
<th>Crystal bend radius (m)</th>
<th>Wavelength range ($\AA$) ($\Delta \theta$, mrad)</th>
<th>Crystal size (cm)</th>
<th>$R_c$ (μrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BCS-A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Fe xxvi</td>
<td>1.7780 (26.39°)</td>
<td>4.000</td>
<td>Ge 220</td>
<td>13.64</td>
<td>1.7636–1.8044 (11.40)</td>
<td>3.98 × 18.1</td>
<td>67</td>
</tr>
<tr>
<td>2</td>
<td>Fe xxv</td>
<td>1.8509 (27.56°)</td>
<td>4.000</td>
<td>Ge 220</td>
<td>10.20</td>
<td>1.8298–1.8942 (18.19)</td>
<td>3.98 × 18.1</td>
<td>68</td>
</tr>
<tr>
<td>BCS-B</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Ca xix</td>
<td>3.1769 (52.58°)</td>
<td>4.000</td>
<td>G2 220</td>
<td>9.60</td>
<td>3.1631–3.1912 (11.57)</td>
<td>3.98 × 11.4</td>
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</tr>
<tr>
<td>4</td>
<td>S xv</td>
<td>5.0385 (50.46°)</td>
<td>6.532</td>
<td>Ge 111</td>
<td>4.56</td>
<td>5.0160–5.1143 (23.83)</td>
<td>3.98 × 11.4</td>
<td>121</td>
</tr>
<tr>
<td>Channel No.</td>
<td>Ion</td>
<td>Wavelength range (Å)</td>
<td>Wavelength resolution (mÅ)</td>
<td>( \lambda/\Delta\lambda ) (Å)</td>
<td>Thermal Doppler width FWHM (mÅ)</td>
<td>( T_{\text{ion}} ) (10⁶ K)</td>
<td>Sensitivity S (cm²)</td>
<td>SOLAR-A/SMM</td>
</tr>
<tr>
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<tr>
<td><strong>BCS-A</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Fe XXVI</td>
<td>1.7636–1.8044</td>
<td>0.38</td>
<td>4700</td>
<td>1.20</td>
<td>50</td>
<td>0.15</td>
<td>9</td>
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<tr>
<td>2</td>
<td>Fe XXV</td>
<td>1.8298–1.8942</td>
<td>0.53</td>
<td>3500</td>
<td>0.90</td>
<td>25</td>
<td>0.10</td>
<td>9</td>
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<tr>
<td><strong>BCS-B</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Ca XIX</td>
<td>3.1631–3.1912</td>
<td>0.53</td>
<td>6000</td>
<td>1.60</td>
<td>20</td>
<td>0.20</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>S XV</td>
<td>5.0160–5.1143</td>
<td>1.86</td>
<td>2700</td>
<td>2.50</td>
<td>15</td>
<td>0.04</td>
<td>63</td>
</tr>
</tbody>
</table>

*a* SMM bent crystal spectrometer.

*b* SMM flat crystal spectrometer scanning the S XV resonance line at 10 arc sec.
two sections are then sealed together by electron beam welding. The detector has two pairs of 15 μm dia. anode wires separated by a cathode screen of 9 grounded 25 μm dia. wires. Each pair of anodes is connected to a separate pre-amplifier. Thus X-rays from each of the two crystals can be registered separately. Anodes are maintained at a potential of ~1.5 kV by a high voltage unit (HVU). In order to monitor the gain and energy resolution of each detector, a 32-channel diagnostic pulse-height analyzer (PHA) is available (Figure 5) whose input can be switched to any one of the four detector channels. Used in conjunction with the on-board Fe^{55} calibration sources, the PHA allows detector performance to be checked during spacecraft night.

The double-wedge readout pattern is shown schematically in Figure 5. It is manufactured photolithographically on a gold-coated fused silica plate. The substrate material is chosen for low dielectric constant so as to minimize the capacitance between the two sets of gold wedge electrodes. This ensures low noise in the wedge 1 (W1) and wedge 2 (W2) pre-amplifiers. Following the absorption of an X-ray photon, a charge avalanche occurs on one of the anode wires and the induced charge distribution on the two interlocking wedge electrodes provides the event position determination. If $Q_{W1}$ and $Q_{W2}$ are the induced charges on each electrode then the one-dimensional position...
coordinate for the X-ray event is given by

$$x = \frac{Q_{W1}}{(Q_{W1} + Q_{W2})}.$$  

(2)

The induced charge pulses $Q_{W1}$ and $Q_{W2}$ are digitized in two ADC's (Figure 5) and the value of $x$ is determined by means of a look-up table (Figure 6). Events are ascribed to the appropriate crystal depending from which anode preamplifier (A1 or A2) the pulse originated. Since hard solar X-rays can cause the germanium crystals to emit 9.9 keV fluorescence radiation, single-channel pulse analyzers are employed to define windows which can accept photons from the crystals ($E_{\text{max}} = 6.9$ keV for Fe xxvi) while rejecting the germanium fluorescence photons. A position resolution of 350 μm FWHM together with a photon energy resolution of 17% has been achieved with the SOLAR-A detectors. The former ensures good spectral resolution, while in the Fe xxvi and Fe xxv channels the uniformity of gas gain over the detector window to better than 5% allows a reduction of a factor 500 or more in the rate of processed fluorescence photons for the loss of less than 2% of the diffracted X-rays.
5. The On-Board Processor and Data Handling

The need to acquire spectral data with good time resolution and to make optimum use of a relatively small telemetry allocation has led to the use of a sophisticated on-board data acquisition and control system which is illustrated schematically in Figure 6. Following each detected X-ray event, a pair of outputs, $Q_{W1}$ and $Q_{W2}$ of either 8 or 9 bits, is presented to the position encoder which is implemented as a look-up table. Using the 8-bit wavelength bin address produced by the position encoder (x in Equation (2)) together with information as to the channel of origin, an event is integrated in the accumulator. This consists of two buffers each of $(4 \times 256)$ 16-bit deep wavelength bins. This double buffer system allows data acquisition in one buffer while the other is being read out. The accumulators are sized to accommodate up to 256 bins in each channel although only 128 bins will normally be used for the Ca XIX and SXV channels. In order to optimize the number of wavelength bins used, before the event is deposited in the accumulator it is re-grouped into a ‘smaller’ number of bins through the use of a data grouper which is also implemented by a look-up table. Several possible grouping plans are always selectable. After the data has been accumulated for an integration period controlled by the accumulator timer, the accumulator buffers are swapped and the data is transferred from the accumulator to a hardware data compressor which is again implemented by a look-up table. Here the accumulated value of each 16-bit wavelength bin is reduced to an eight bit value before being stored in the data queue memory by the microprocessor.

Event data is output through the BCS-PH or main digital data interface to the spacecraft data processor in 256 byte blocks. The rate at which data is transferred by the interface is purely a function of the overall telemetry rate. The 384 kbyte data queue
memory allows the BCS to produce bursts of spectral data for storage at rates that are in excess of the 2 kbits s\(^{-1}\) accepted by the spacecraft telemetry system in flare mode. The amount of spectral data produced is a function of the selected data grouping plan and the accumulator integration time. The microprocessor can change the values of these parameters as a flare develops to allow a trade-off between temporal and spectral resolutions through the flare. The criteria for switching between accumulation modes and the definition of the modes themselves are contained in lists that can be loaded into the microprocessor. Since the use of the queue memory makes the PH data asynchronous to the rest of telemetry, each accumulator block in the queue is headed by a block which contains the start time and other important information.

Even rate counters (Figure 5) driven from different parts of the event control circuitry are available in the housekeeping data stream. The counters report ‘total’, ‘in-window’, and ‘encoded’ photons for each channel and can be used to apply deadtime corrections when the countrates are high. They are also used by the microprocessor to watch for flares and to monitor the background rate. The diagnostic PHA data used to analyze the detector performance and a field containing information generated by the microprocessor are also contained within the housekeeping data stream.

BCS electronic subsystems such as high voltage units (HVU) and single-channel analyzers (SCA) are controlled through the microprocessor data bus. Parameters may be loaded through this bus, either directly from the command interface or from the microprocessor. The value of these parameters and other information on the status of relays and switched circuitry, together with the last two received command bytes, is given in the status data stream. Structure temperatures and HV monitors are measured through the analogue data interface. In the event of a hardware problem with the microprocessor, a backup path has been provided by which spectral data flows directly from the data compressor to the BCS-PH interface. In this mode, since the data queue is not available, the number of wavelength bins produced per second must be matched to the telemetry rate by selecting an appropriate combination of the data grouping plan and accumulator integration time.

6. Instrument Calibration

Although elements of the spectrometers were calibrated and tested individually, each spectrometer was also tested end-to-end when finally assembled for flight. These tests were designed to provide a wavelength calibration and an intensity calibration at one wavelength for each of the four BCS channels.

The apparatus is shown schematically in Figure 7. The X-ray source was used to illuminate a monolithic channel-cut crystal (Quartz 1011, 2d = 6.952 Å) which was placed about 0.8 m from the source. The channel-cut crystal was used as a two-crystal monochromator with the crystals in the (1, −1) setting. Four narrow slits, two between the X-ray source and the channel cut crystal and two between the channel-cut crystal and the test chamber served to limit the beam divergence and to select the output wavelength range of the monochromator. For source radiation incident on the crystal
Fig. 7. The end-to-end X-ray calibration system.

Fig. 8. Results of the end-to-end X-ray calibration of the BCS. Spectra of (a) Co Kα in the FeXXVI channel (Ch. 1), (b) Ho Lα in the FeXXV channel (Ch. 2), (c) Ca Kα in the CaXIX channel (Ch. 3), and (d) Mo Lα in the SXXV channel (Ch. 4).
at the correct Bragg angle for a particular Kα line, the output had the line wavelength as seen by the BCS with a profile characterized by the source linewidth, the double crystal rocking curve of the monolithic crystal and the geometry of the slits. When measured using BCS-A by rotating the instrument, the line profile had a full-width-at-half-maximum (FWHM) of around 70 arc sec for the Fe xxvi channel. The channel-cut crystal was mounted in a holder whose position was adjusted to allow changes of Bragg angle for different source wavelengths. Spectrometer units were placed about 2 m from the double crystal. The precision ground feet of each spectrometer were fixed to a vertical surface which could be moved horizontally. With the BCS aligned correctly to an X-ray beam of appropriate and known wavelength, spectral calibrations were obtained with a precision ranging from 5 mÅ for the S xv channel to better than 1 mÅ for the Fe xxvi channel. The intensity calibrations were also established with a precision of ±15% using a proportional counter of known quantum efficiency and geometry to interrupt the beam incident on the BCS.

For the calibration of BCS-A, lines of Co Kα1 at 6.930 keV (1.786 Å) and Ho Lα1 at 6.720 keV (1.842 Å) were used for the Fe xxvi and Fe xxv channels, respectively. In the case of BCS-B it was necessary to rotate the spectrometer slightly in the plane of dispersion so that lines of Ca Kα1 at 3.691 keV (3.354 Å) and Mo Lα1 at 2.293 keV (5.399 Å) could be used for the Ca xix and S xv channels. The response of all four spectrometer channels to the calibration lines is indicated in Figure 8.

Acknowledgements

We gratefully acknowledge the role of the Japanese Institute for Space and Astronautical Science (ISAS) who are responsible for the SOLAR-A mission and who made it possible for the BCS team to participate in this unique study of the solar flare phenomenon. We have had through all phases of the programme the help of many colleagues at the Mullard Space Science Laboratory, the National Astronomical Observatory of Japan, the US Naval Research Laboratory (NRL), the Rutherford Appleton Laboratory, the US National Institute for Standards and Technology and of course ISAS. To all of them we give our sincere thanks. The UK groups acknowledge the support of the Science and Engineering Research Council and the British National Space Centre. The Japanese activities were made possible by the support of the grant-in-aid for International Scientific Research Program No. 63044163 and No. 01044044 of the Japanese Ministry of Education, Science and Culture. Work in the U.S.A. was supported by the US Naval Research Laboratory.

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SOLAR-A REFORMATTED DATA FILES AND OBSERVING LOG*

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Abstract. All of the SOLAR-A telemetry data will be reformatted before distribution to the analysis computers and the various users. This paper gives an overview of the files which will be created and the format and organization which the files will use. The organization has been chosen to be efficient in space, to ease access to the data, and to allow for the data to be transportable to different machines. An observing log file will be created automatically using the reformatted data files as the input. It will be possible to perform searches with the observing log to list cases where instruments are in certain modes and/or seeing certain signal levels.

1. Introduction

It is universally recognized that solar research, and especially flare studies, profit greatly from coordinated analysis of different types of observational data. Yet, in the past, little preplanning of data formatting and archiving has been done to facilitate joint analysis. Each experimenter tended to act independently, solving their own analysis and archiving problems in their own way. Data have been formatted and stored in a plethora of formats and media. Those data in digital form, and thus presumably universally available, reside in incompatible machines addressable only with specialized, esoteric software. Often the comparison of results has been seriously impeded. Joint analyses, other than the most qualitative comparisons, have been accomplished with great difficulty and in a sadly limited number of cases.

The SOLAR-A investigators have determined to do better. It has been decided to produce a common reformatted data base for all of the SOLAR-A experiments for

* After the launch the name of SOLAR-A has been changed to YOHKOH.
distribution to all of the investigators. This will be produced with a synoptic file structure to ease access for scientific analysis and in a form as transportable as possible between computers with different operating systems. In the end, this work may be as important to the scientific productivity of the mission as the capabilities of the SOLAR-A instruments.

2. SOLAR-A Data Flow

The SOLAR-A data will be received by the Kagoshima Space Center (KSC) station in Japan, and by several NASA Deep Space Network (DSN) stations around the world (Canberra, Goldstone, and Madrid). The spacecraft uses a bubble data recorder (BDR) to store the data when a real-time station downlink is not available. The 10 Mbyte capacity of the BDR can store 40 min of high rate (32 kbps) data. There will be 5 downlinks to KSC every day plus four to ten downlinks to the DSN stations. The KSC data is available in real time; the DSN data could take up to two or three days before being available. All of the SOLAR-A raw telemetry data will be time-ordered and stored on-line in the large SIRIUS data base at the Institute of Space and Astronautical Sciences (ISAS). The maximum data telemetered down is 4.7 Gigabyte per month. The SOLAR-A reformatter will work from this data base.

The SOLAR-A reformatter will run on a Unix workstation at ISAS. The reformatter will be written in Interactive Data Language™ (IDL) Version 2.0 which is available from Research Systems, Inc. We intend to create data files that are portable and which can be read on any machine. The information necessary to tell the user how to read the file are present in the beginning of each data file. That information along with a copy of the SOLAR-A File Control Document should allow any user to access the data. The reformatter will create seven files as follows:

- **BCS**  Bragg Crystal Spectrometer;
- **HXT**  Hard X-ray Telescope;
- **SXT–PFI**  Soft X-ray Telescope/Partial Frame Images;
- **SXT–FFI**  Soft X-ray Telescope/Full Frame Images;
- **WBS**  Wide-Band Spectrometer;
- **ATT**  Spacecraft Attitude Data;
- **CBA**  Spacecraft Common Basic Part.

The first five files contain the data from the scientific instruments. A complete copy of the raw spacecraft attitude data will be available in the ATT file. This will be the first file created and the reformatter will use this file to generate processed pointing information which will be included with each scientific data set entry. The CBA section contains a complete duplicate copy of the spacecraft common 'Basic Part' data. This is for possible unanticipated use in the future as we intend that all necessary information in this section of telemetry has been included in the respective scientific data files. The reformatted data files will initially be distributed on 8 mm tapes, about 1 such tape per week. We hope eventually to archive the data on CD-ROM.
3. Organization and Format of Reformatted Data Files

The data files are a simple stream of bytes, organized to allow direct access into the data file. The data is padded where necessary in order to package the data such that Vax VMSTM can use fixed records (probably 16 bytes long). Unix allows the user to directly access any byte and does not use record structures. This organization should allow us to maintain full compatibility between a large variety of machines.

The data files make full use of the structure data types which are available in FORTRAN (Vax and SunSTM FORTRAN extensions) and IDL. Each structure has a version number associated with it so structures can be changed and expanded without requiring difficult changes to the access software. Full flexibility to expand structures and add structures allows the user to maintain a full history of what processing has been done to the data. In addition to the raw reformatted data files, all processed data files will follow the same organization in order to allow existing software routines to display, analyze and process those new files.

The organization of the files is illustrated in Table I. Its sections will now be discussed in turn.

File pointer and information section. The first section in the file contains information needed to read the file. It contains pointers to the start of all of the major sections (file header, quasi-static index, data, optional data, and road map). It also contains information on what machine convention was used for integer and real variables, the file organization used, and the VMS record length. There are also two fields which hold sample integer and real values to confirm that any routine used for conversion between machine representations is working correctly.

File header section. The file header section contains information on what data is present in the file. Information about the range of dates and times covered, the program that created the file, the time and date that the data file was created, the total number of data sets, the machine that created the file, the spacecraft and instrument, the number of quasi-static index entries, and other similar information is contained in this section.

Quasi-static index section. The quasi-static index section is used to provide calibration and scientific data conversion information. The data present in this section seldom changes and does not need to be duplicated in each data index section. Information such as detector gain, coefficients for converting temperature and voltage, instrument pointing offsets, information on versions used for certain algorithms, etc., are included here.

Index and data section. The data are broken up into data sets, and each data set has an index section and a data section. The data are broken up by modes for SXT and BCS (WBS and HXT provide a continuous stream of data and do not have modes).

<table>
<thead>
<tr>
<th>BCS</th>
<th>One data set per spectra.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HXT</td>
<td>One data set per telemetry major frame.</td>
</tr>
<tr>
<td>SXT</td>
<td>One data set per image exposure.</td>
</tr>
<tr>
<td>WBS</td>
<td>One data set per 2 telemetry major frames.</td>
</tr>
</tbody>
</table>
The data index section will contain the information necessary to analyze the data. Information on the data word type (byte, integer, real), the amount and quality of the data, the data compression, the instrument mode, the status of instrument peripheral hardware (filters, door positions, etc.), temperatures, spacecraft pointing, and spacecraft mode, rate, and flare status.

The data index section can be expanded with a variety of structures to reflect data processing performed on the data saved in the file. A full history of the data processing...
can be maintained in this manner. The data described in the data index section immediately follows the data index section.

Optional data section. Some instruments require an additional data section to provide a complete copy of the telemetry data. The BCS spectral data comes down asynchronously, but there is other synchronous information available. For simplicity, a complete copy of the synchronous BCS data is available in the optional data section. For HXT, there are two one-dimensional arrays used to find the limb of the Sun. This data comes down at a different telemetry cadence and will be placed in the optional data section. SXT and WBS do not use the optional data section.

Road map section. The final section contains a short summary of each of the data sets available in the file and a pointer to the beginning of each data set. The section gives information on the instrument mode and a brief summary of the data (e.g., average or total counts). This section is almost an exact duplicate of the observing log entry, which is described in Section 4.

4. Log Files

A program will use the reformatted data files from the scientific instruments and create an observing log. This log will be produced automatically with little or no human interaction. Other log files will also be created using the reformatted data and the observing log as input. Some of these logs will require user interaction.

The observing log will provide a full summary of the modes and data available for each of the SOLAR-A instruments. There will be one entry for each SXT image, a BCS entry for each spectra (but not more often than every 4 s), and an entry every 2 major frames (every 4 s during high telemetry rate) summarizing the WBS and HXT count rates and modes. Information on the spacecraft orbital solutions, the reformatted data file IDs, and conversion coefficients are also provided in this log. A single file will contain the log for one month which should be about 30 Mbyte.

A user will be able to search the observing log and obtain a list of all cases where a given set of conditions are satisfied. For example, one could search for occasions when a certain mode occurs or when the signal was above a certain threshold. The user could cross reference to other instruments to select only cases where several instruments were in a given mode seeing a particular count level. It is possible that a similar log will eventually be generated with information on what ground-based instruments were in operation and the data available from that instrument. It will also be possible to create light curves from the instrument count rates with a time resolution of about 4 s.

An event log will be created listing the times when the instrument or spacecraft modes change. The event log will be generated from the observing log, but will be much smaller since it only logs changes in modes and will not contain information about the data count levels. Because of the small size, this log could easily contain several years of information and would remain readily transportable to machines with limited disk space.

A flare and active region log is contemplated. This log will require a user to identify which regions should be included. The log will probably contain information on which
instruments saw that region at what times, and the mode that the instrument was in. Ground-based observations could also be incorporated into this log.

Acknowledgements

We thank I. Kondo for help in defining the SOLAR-A data base. The work at Lockheed was supported under contract NAS8–37334.
TEMPERATURE-SENSITIVE LINE RATIOS OF THE LITHIUM-LIKE ION O VI

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Abstract. The intensity ratios of emission lines from the lithium-like ion O VI are calculated as a function of electron temperature using recent computations of collision strengths by Zhang, Sampson, and Fontes (1990). The line ratios are strongly dependent on temperature and are appropriate as a diagnostic of hot thin plasmas such as in the solar transition region and corona.

1. Introduction

The level spacings of lithium-like ions are sufficient to allow the intensity ratio of emission lines to be strongly dependent on electron temperature (Heroux, 1964; Heroux and Cohen, 1971). This property is used to measure the temperature of hot plasmas such as in the solar chromosphere and corona. The oxygen ion O VI has maximum abundance at temperatures around $T = 3 \times 10^5$ K (Arnaud and Rothenflug, 1985) so it is appropriate as a diagnostic of the solar transition region and corona where the electron density is low and the spectral lines are optically thin. The O VI emission lines at $\lambda = 150$ Å, 173 Å, and 1032 Å are within the wavelength range of the instruments CDS and SUMER to be flown aboard the SOHO satellite (Patchett et al., 1989; Wilhelm et al., 1989). Therefore the O VI line ratios have been selected for temperature diagnostic studies. In the past years the oscillator strengths and collisional excitation rates by electron impact for the O VI ion have been calculated with reliable accuracy (Clark et al., 1982; Cochrane and McWhirter, 1983; Zhang, Sampson, and Fontes, 1990). Thus it is worth evaluating the intensity ratios of the above lines. The determination of electron temperature in plasmas by means of line ratios of lithium-like ions was discussed by Gabriel and Jordan (1972). Previous calculations of the line ratios were performed by Heroux and Cohen (1971), however just for the ratios of the multiplets.

2. Calculation of the Line Ratios

The ions of the lithium isoelectronic sequence are quite simple in that they have no metastable levels. For the allowed transitions the radiative decay rates are very large, and virtually the total population of the ion resides in the ground level, $2s^2S_{1/2}$. Thus the upper states are excited by electron collisions from the ground level and decay by radiative transitions. Transitions amongst the fine structure levels induced by electron impact begin to play a role only at electron densities $N_e > 10^{15}$ cm$^{-3}$ and can, therefore,
be completely neglected in connection with solar plasmas. Therefore, the ratios of the spectral line intensities will be independent of the electron and ion densities.

Consider the line originating from the transition $j \rightarrow i$. The upper level $j$ can be populated by direct collisional excitation from the ground state $0$ or by radiative transitions from levels $k > j$. Then the rate of photon emission ($\text{cm}^{-3} \text{s}^{-1}$) is given by

$$I_\lambda = N_{\text{ion}} N_e \left\{ C_{ij} \sum_{r < j} \frac{A_{ji}}{A_{jr}} + \sum_{k > j} C_{ok} \frac{A_{kj}}{A_{kr}} \right\},$$

where $N_{\text{ion}}$ is the number density of the emitting ion, $C_{ij}$ is the coefficient for collisional excitation from the ground state, and $A_{ji}$ are the radiative transition probabilities.

Clark et al. (1982) have computed collision strengths for the excitation of the levels with principal quantum numbers $n = 2$ and $n = 3$ of Li-like ions by means of the distorted-wave method. They fitted their results to an analytical formula which could readily be integrated over a Maxwellian velocity distribution yielding the excitation rate coefficients. Cochrane and McWhirter (1983) applied the Gaunt factor formalism to specify the collisional excitation rate coefficients $C_{ij}$ for lithium-like ions.

The most recent and sophisticated computations of collision strengths and electric dipole oscillator strengths of Li-like ions were performed by Zhang, Sampson, and Fontes (1990) with the aid of the relativistic distorted-wave method. The collision strengths $\Omega(E')$ were given for 6 values of the final electron energy, $E'$, which cover the range of energies needed for determining the collision rates.

By means of a least-squares method I have fitted the collision strengths of Zhang, Sampson, and Fontes (1990) to the analytic expression for spin-allowed transitions (Clark et al., 1982):

$$\Omega = c_0 + \frac{c_1}{x} + \frac{c_2}{x^2} + c_3 \ln x,$$

where

$$x = \frac{E}{E_{ij}} = 1 + \frac{E'}{E_{ij}}$$

is the initial electron energy in units of the threshold energy $E_{ij}$. The fit coefficients $c_i$ are presented in Table I. Equation (2) can be integrated over a Maxwellian energy distribution resulting in the excitation rate coefficient

$$C_{ij} = \frac{8.010 \times 10^{-8}}{g_i \sqrt{kT}} \int_{E_{ij} / kT}^{\infty} e^{-E/kT} \Omega(E) \frac{E}{kT} \text{d}(E/kT) \text{ cm}^3 \text{s}^{-1} =$$

$$= \frac{8.010 \times 10^{-8}}{g_i \sqrt{kT}} \{(c_0 + c_2 y) e^{-y} + (c_3 + c_1 y - c_2 y^2) E_1(y)\} \text{ cm}^3 \text{s}^{-1},$$

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TABLE I

Fit coefficients of the collision strength $\Omega(E)$

<table>
<thead>
<tr>
<th>Transition</th>
<th>$E_j$ (eV)</th>
<th>$c_0$</th>
<th>$c_1$</th>
<th>$c_2$</th>
<th>$c_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2s,^2S_{1/2} - 2p,^2P_{1/2}$</td>
<td>11.949</td>
<td>0.7274</td>
<td>1.6738</td>
<td>-0.6447</td>
<td>0.7480</td>
</tr>
<tr>
<td>$2s,^2S_{1/2} - 2p,^2P_{3/2}$</td>
<td>12.015</td>
<td>1.448</td>
<td>3.401</td>
<td>-1.370</td>
<td>1.500</td>
</tr>
<tr>
<td>$2s,^2S_{1/2} - 3s,^2S_{1/2}$</td>
<td>79.355</td>
<td>0.1655</td>
<td>0.0601</td>
<td>-0.0399</td>
<td>0.0298</td>
</tr>
<tr>
<td>$2s,^2S_{1/2} - 3p,^2P_{1/2}$</td>
<td>82.588</td>
<td>-1.685(-2)$^a$</td>
<td>0.963(-2)</td>
<td>3.33(-2)</td>
<td>8.06(-2)</td>
</tr>
<tr>
<td>$2s,^2S_{1/2} - 3p,^2P_{3/2}$</td>
<td>82.607</td>
<td>-3.25(-2)</td>
<td>1.47(-2)</td>
<td>6.99(-2)</td>
<td>0.1603</td>
</tr>
<tr>
<td>$2s,^2S_{1/2} - 3d,^2D_{3/2}$</td>
<td>83.643</td>
<td>8.66(-2)</td>
<td>3.32(-2)</td>
<td>1.86(-4)</td>
<td>6.56(-2)</td>
</tr>
<tr>
<td>$2s,^2S_{1/2} - 3d,^2D_{5/2}$</td>
<td>83.649</td>
<td>0.1302</td>
<td>5.02(-2)</td>
<td>-3.2(-4)</td>
<td>9.84(-2)</td>
</tr>
<tr>
<td>$2s,^2S_{1/2} - 4s,^2S_{1/2}$</td>
<td>105.721</td>
<td>1.73(-2)</td>
<td>4.00(-2)</td>
<td>-2.00(-2)</td>
<td>1.29(-2)</td>
</tr>
<tr>
<td>$2s,^2S_{1/2} - 4p,^2P_{1/2}$</td>
<td>107.040</td>
<td>-2.17(-3)</td>
<td>7.7(-4)</td>
<td>9.43(-3)</td>
<td>2.015(-2)</td>
</tr>
<tr>
<td>$2s,^2S_{1/2} - 4p,^2P_{3/2}$</td>
<td>107.048</td>
<td>-4.42(-3)</td>
<td>1.46(-3)</td>
<td>1.894(-2)</td>
<td>4.021(-2)</td>
</tr>
<tr>
<td>$2s,^2S_{1/2} - 4d,^2D_{3/2}$</td>
<td>107.479</td>
<td>1.823(-2)</td>
<td>3.85(-3)</td>
<td>4.88(-3)</td>
<td>1.091(-2)</td>
</tr>
<tr>
<td>$2s,^2S_{1/2} - 4d,^2D_{5/2}$</td>
<td>107.482</td>
<td>2.752(-2)</td>
<td>6.01(-3)</td>
<td>7.00(-3)</td>
<td>1.636(-2)</td>
</tr>
<tr>
<td>$2s,^2S_{1/2} - 4f,^2F_{5/2}$</td>
<td>107.504</td>
<td>6.93(-3)</td>
<td>-1.88(-3)</td>
<td>5.19(-3)</td>
<td>1.95(-3)</td>
</tr>
<tr>
<td>$2s,^2S_{1/2} - 4f,^2F_{7/2}$</td>
<td>107.505</td>
<td>1.529(-2)</td>
<td>-2.88(-3)</td>
<td>1.147(-2)</td>
<td>4.94(-3)</td>
</tr>
</tbody>
</table>

$^a$ - 1.685(-2) represents $-1.685 \times 10^{-2}$.

where $g_i = 2$ is the statistical weight of the ground level, $kT$ is the electron temperature in units of eV, $y = E_j/kT$, and

$$E_1(y) = \int_{1}^{\infty} \frac{e^{-yt}}{t} \, dt$$

is the exponential integral.

For the transition $2s\,^2S_{1/2} - 2p\,^2P_{3/2}$ giving the main contribution to the intensity of the line at the wavelength $\lambda = 1032$ Å, there is excellent agreement between the results of Equation (4) and of Clark et al. (1982), the difference being less than 0.65% in the temperature range $T = 5 \times 10^4$ K to $T = 4 \times 10^6$ K. The rate coefficient for the transition $2s\,^2S_{1/2} - 3d\,^2D$, responsible for the bulk of the emission at $\lambda = 173$ Å, is lower by 5% to 10% compared to Clark et al. and by 4% to 6% compared to Cochrane and McWhirter (1983). For the transition $2s\,^2S_{1/2} - 3p\,^2P$ the coefficients $C_{ij}$ compare favourably to the results of Clark et al. – the present values are lower by 1% to 6% – whereas there is a large discrepancy between 17% and 60% with the coefficients of Cochrane and McWhirter. Finally, the coefficients for the transition $2s\,^2S_{1/2} - 3s\,^2S_{1/2}$ contributing to the line strength at $\lambda = 1032$ Å, are close to the results of Cochrane and McWhirter (difference 1% to 3%), while the values of Clark et al. are higher by 4% to 12%. Since the computations of Clark et al. (1982) and Cochrane and McWhirter (1983) are restricted to the excitation of levels with principal quantum numbers $n = 2$ and $n = 3$, there is no possibility of comparing the present results for $n = 4$. However,
the contribution of the cascading transitions from higher levels to the strengths of the lines considered is very low (see the fitting coefficients for $C_{ij}$ in Table I), so that the accuracy of the corresponding rate coefficients is not essential for the line ratios to be calculated. For instance, it follows from the line intensities that the cascading transitions $3d^2D - 2p^2P$ and $3s^2S_{1/2} - 2p^2P$ contribute only about 1% to the population of the 2p level in O vi (Heroux, Cohen, and Malinovsky, 1972).

Taking into account the collisional excitation of O vi levels up to the principal quantum number $n = 4$, the intensities of the three lines originating from the transitions $2p^2P_{3/2} - 2s^2S_{1/2} (\lambda = 1031.924 \text{ Å})$, $3d^2D - 2p^2P (\lambda \approx 173.0 \text{ Å})$ and $3p^2P - 2s^2S_{1/2} (\lambda \approx 150.1 \text{ Å})$ are given by

$$I_1 \equiv I(1032 \text{ Å}) \approx N_e N_{\text{ion}} \left\{ C(2p^2P_{3/2}) + \frac{2}{3} C(3s^2S_{1/2}) + C(3d^2D_{5/2}) + ight.$$ \begin{align*} &+ \frac{1}{6} C(3d^2D_{3/2}) + 0.39 C(4s^2S_{1/2}) + 0.77 C(4d^2D_{5/2}) + \\ &+ 0.35 C(4d^2D_{3/2}) \right\}, \tag{5} \end{align*}

$$I_2 \equiv I(173 \text{ Å}) \approx N_e N_{\text{ion}} \left\{ C(3d^2D) + 0.036 C(4p^2P + C(4f^2F)) \right\}, \tag{6}$$

$$I_3 \equiv I(150 \text{ Å}) \approx N_e N_{\text{ion}} \left\{ C(3p^2P) + 0.41 C(4s^2S_{1/2}) + 0.23 C(4d^2D) \right\}. \tag{7}$$

where $C(X)$ denotes the rate coefficient for collisional excitation of level $X$ from the ground state. The factors of the $C_{ij}$ were derived from the oscillator strengths of Zhang, Sampson, and Fontes (1990).

3. Results

Figures 1 and 2 show the intensity ratios $R_1 = I_1/I_2$ and $R_2 = I_1/I_3$ for temperatures between $T = 3 \times 10^5$ K and $T = 2 \times 10^6$ K. Both ratios are strongly dependent on the temperature, in particular around the temperature of maximum abundance of O vi, $T_{\text{max}} \approx 3 \times 10^5$ K. They are well suited for measuring the electron temperature in laboratory plasmas with uniform electron density if $N_e$ is sufficiently low. In the solar atmosphere the density and temperature gradients introduce difficulties which complicate the interpretation of the observed line ratios (Gabriel and Jordan, 1972). Since the radiation originates from volumes with varying temperature and density, the rate of photon emission (1) has to be replaced by the integral over the line of sight, $h$,

$$I_x = \int N_{\text{ion}} N_e \left\{ C_{0j} \frac{A_{ji}}{\sum_{r < j} A_{jr}} + \sum_{k > j} \frac{C_{0k} A_{kj}}{\sum_{r < k} A_{kr}} \right\} \theta(h) dh =$$ \begin{align*} &\int \frac{N(H)}{N_e} \frac{N(O)}{N(H)} \frac{N_{\text{ion}}}{N(O)} \left\{ C_{0j} \frac{A_{ji}}{\sum_{r < j} A_{jr}} + \sum_{k > j} \frac{C_{0k} A_{kj}}{\sum_{r < k} A_{kr}} \right\} \Phi(T) dT, \tag{8} \end{align*}

where $N(H)$ and $N(O)$ are the number densities of hydrogen and oxygen, respectively, and $\Phi(T)$ denotes the differential emission measure defined by $N_e^2 \theta dh = \Phi(T) dT$. 

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Fig. 1. Theoretical O\textsc{vi} emission line ratio $R_1 = I(1032 \, \text{Å})/I(173 \, \text{Å})$ as a function of temperature.

Fig. 2. Theoretical O\textsc{vi} emission line ratio $R_2 = I(1032 \, \text{Å})/I(150 \, \text{Å})$ as a function of temperature.
Assuming that the element abundance of oxygen relative to hydrogen is constant throughout the emitting volume, Equation (8) can be written as

$$I_\lambda = \frac{N(O)}{N(H)} \int G(T) \Phi(T) \, dT,$$

where the atomic physics function

$$G(T) = \frac{N(H)}{N_e} \frac{N_{\text{ion}}}{N(O)} \left\{ C_{ij} \sum_{r < j} A_{ji} + \sum_{k > j} C_{k} \sum_{r < k} A_{kj} \right\}$$

has a fairly sharp peak at the temperature $T_m$. Therefore the integral over $T$ in Equation (9) is restricted to an $h$ interval corresponding to the region where $T$ is near $T_m$. Due to the large differences between the excitation energies $E_{ij}$ of the levels with $n = 2$ and $n = 3$, $T_m$ is lower for the 1032 Å line than for the two $\Delta n = 1$ transitions. Because the differential emission measure $\Phi(T)$ of the solar atmosphere increases with $T$ above $T \approx 2 \times 10^5$ K (Lang, Mason, and McWhirter, 1990), the higher $T$ plasma dominates the emission of the lines at 150 Å and 173 Å compared with the line at 1032 Å. Therefore, the uncritical application of the results presented in Figures 1 and 2 will yield too high temperatures as discussed by Gabriel and Jordan (1972). In addition one should bear in mind that the 1032 Å line can become optically thick if observations are made near the solar limb (Burton et al., 1971). Then the present results do not apply since collisional transitions between the $n = 3$ levels have to be taken into account.

In the ultraviolet spectrum of the Sun the prominent line at 1032 Å yields high count rates (Heroux, Cohen, and Malinovsky, 1972; Malinovsky and Heroux, 1973) so that its strength can be determined accurately. The lines at $\lambda = 150$ Å and $\lambda = 173$ Å comprise the multiplets (2 and 3 components, respectively). Therefore, their intensity is sufficiently high to be measured to within about 20% (Heroux, Cohen, and Malinovsky, 1972; Malinovsky and Heroux, 1973). Taking into account the effects caused by the density and temperature gradients, the determination of $T$ by means of the OVI line ratios results in an upper limit of the average temperature in the regions along the line of sight where the OVI ion is abundant.

References


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RAY-TYPE SPECTRA OF PLASMA TURBULENCE IN CORONAL MAGNETIC LOOPS

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SibIZMIR, U.S.S.R.

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Abstract. The problem of stationary spectra of Langmuir, l, and electromagnetic, t, waves excited in a magnetic trap (loop) by a group of suprathermal electrons, whose velocity distribution includes a 'loss cone', is considered. Within the framework of weak turbulence theory, accurate spectra of l- and t-waves are found. These spectra have the form of thin rays in wavevector space. Forms of plasma emission radio lines of a homogeneous source near the plasma frequency and its second harmonic are determined.

1. Introduction

Sporadic radio emission of the Sun is often associated with a plasma mechanism for electromagnetic wave generation (Ginzburg and Zheleznyakov, 1958). This mechanism is invoked to explain, in particular, the origin of type IV radio bursts (Stepanov, 1973; Kuijpers, 1974) as well as intense bursts in the microwave range (Zaitsev and Stepanov, 1983). As flare-accelerated electrons get into a magnetic loop – a radio emission source – a typical (of mirror traps) distribution of energetic particles with a 'loss cone' in velocity space is established in the loop. Langmuir oscillations, l, which are excited with the development of a loss-cone instability, are transformed into electromagnetic waves, t, during an induced scattering-off background-plasma ions (l-t-scattering) as well as during coalescence \( l + l' \rightarrow t(2\omega_p) \), leading to an emission on the double plasma frequency.

Despite the fact that the above scheme of plasma radio emission of coronal loops was suggested rather long ago, a complete solution of the problem has not yet been obtained. Theoretical investigations of nonlinear stabilization mechanisms for the loss-cone instability and for conversion of potential oscillations of electromagnetic waves, as presented in a number of studies (see, for example, Stepanov, 1975, 1980, 1985; Melrose, 1975) have largely a phenomenological character. In the references just cited, the spectra of Langmuir and electromagnetic waves are considered isotropic and are characterized by the only integral quantity, i.e., the wave energy density. With such an approach, it is impossible to associate finer characteristics of electromagnetic emission – its angular distribution and spectral intensity – with parameters of background plasma and of suprathermal particles. Such a relationship can be established by a consistent solution of a system of kinetic equations for Langmuir and electromagnetic waves. It is known (Breizman, Zakharov, and Mushur, 1973; Breizman and Ryutov, 1974) that stationary solutions of these equations can be singular ones: the wave distribution turns out to be different from zero on some surfaces (lines) in wavevector space. These surfaces (lines) have been called the rays. In a paper by Breizman (1975), stationary
spectra of \( l \)- and \( t \)-waves were found under the assumption that oppositely directed beams of relativistic electrons are the instability source. An interesting feature of the solution is the fact that stabilization of an instability can be ensured by electromagnetic waves rather than Langmuir waves.

In the present paper, for a given unstable (with a 'loss cone') distribution of suprathermal electrons in a magnetic trap, accurate spectra of Langmuir and electromagnetic waves will be determined and the emission intensity in the vicinity of the fundamental and the second harmonics of the plasma frequency will be calculated. We shall confine our attention to considering a homogeneous plasma with a sufficiently weak magnetic field, taking into account, however, the finite dimensions of the emitting region. The solutions obtained are essentially anisotropic ones and differ qualitatively from those reported earlier. Note that differential transfer of plasmons into the long-wavelength region does not lead to formation of a Langmuir condensate because of a strong re-absorption of waves by high-energy particles. This circumstance permits the problem to be solved, without leaving the scope of weak-turbulence theory.

The structure of this article is as follows. In Section 2 we shall obtain the solution of the kinetic equation for waves under conditions when the \( lt \)-scattering is suppressed, and shall determine the emission intensity on the double plasma frequency. The intensity of electromagnetic emission produced due to the \( lt \)-scattering off background plasmons will be determined in Section 3. The concluding Section is devoted to a discussion of the results obtained and of applicability conditions of the model presented.

2. Ray-Type Spectra; Emission at the Second Harmonic

Let us consider a trap with magnetic mirrors, whose transverse size is \( R \) and length, \( L \gg R \). The trap is filled with a homogeneous Maxwellian plasma with density, \( n \), and temperature, \( T \). After energetic collisionless electrons get into the trap, part of them are confined by magnetic mirrors and the other part escaped freely through the ends. As a result, in the trap there forms a distribution of suprathermal particles with a deficit in longitudinal velocities with respect to the magnetic field. By assuming the mirror ratio of the trap \( \sigma \) to be not very large, \( \sigma \approx 2 \), we specify the steady-state distribution function of hot electrons in the form

\[
f(v_\parallel; v_\perp) = A v_\perp^2 \exp \left[ - \frac{v_\parallel^2 + v_\perp^2}{2v_h^2} \right]
\]  

(1)

with \( \int \int f(v_\parallel; v_\perp) \, dv = 1; v_\parallel \) and \( v_\perp \) denote, respectively, the longitudinal and transverse components of velocity \( v \) with respect to the loop's magnetic field. Bearing in mind the parameters of coronal loops it will be assumed that the density of hot electrons \( n' \ll n \) and their typical energy \( E = mV_h^2 \) is large compared with the plasma temperature. The anisotropic distribution of suprathermal particles (1) is unstable to excitation of plasma oscillations, whose growth rate \( \gamma(k) \) in a weak magnetic field \( \omega_B \ll \omega_p \) (a more accurate
condition is given in Section 4) has the form

\[
\gamma(k, x) = \frac{\omega_p}{4} \sqrt{\frac{\pi}{n}} \left( \frac{\omega_p}{kV_h} \right)^5 \left[ \frac{k^2 V_h^2}{\omega_p^2} - 1 - x^2 \left( 3 \frac{k^2 V_h^2}{\omega_p^2} - 1 \right) \right] \times 
\exp \left( - \frac{\omega_p^2}{2k^2 V_h^2} \right).
\]  

Here \( k \) is the wave number, \( x \) is a cosine of the angle between the wave vector and the magnetic field of the loop, and \( \omega_B \) and \( \omega_p \) are the electron cyclotron and Langmuir frequencies, respectively. As is evident from the expression (2), this growth rate reaches a maximum on the \( x = 0 \) line. In the region \( (kV_h/\omega_p) < 1, \gamma < 0 \) for any \( x \), i.e., waves are absorbed by high-energy electrons. The behaviour of the normalized growth rate

\[
\gamma(\kappa; x) = 22.88 \frac{n}{n'} \frac{n}{\omega_p} \gamma(k; x)
\]

as a function of dimensionless wave number \( \kappa = (kV_h/\omega_p)^2 \) on the \( x = 0 \) line is shown in Figure 1; a hatched region in Figure 2 corresponds to \( \gamma > 0 \).

![Fig. 1. The normalized growth rate as a function of dimensionless wavenumber on the line \( x = 0 \).](image)

The increase in energy of excited oscillations can be limited by an escape of waves from the generation region and due to saturation of the instability. The transfer of waves from the instability region under conditions of coronal loops is ineffective due to the low group velocity of plasmons, and the damping rate of the waves due to electron-ion
collisions is small compared with the growth rate. It will be assumed that saturation of the instability occurs due to nonlinear effects and in Section 4 we shall give the applicability conditions for such an approach*. The main nonlinear processes stabilizing the instability are the transfer of Langmuir waves through the spectrum into the region of small wave numbers, where \( \gamma(k; \chi) < 0 \), and their transformation into electromagnetic waves during induced scattering off background plasma ions (\( ll \)- and \( lt \)-scattering, respectively). The system of kinetic equations governing the dynamics of spectra of Langmuir and electromagnetic waves \( N'_k \) and \( N_{\lambda k} \), with the \( ll \)- and \( lt \)-scattering taken into account, has the form:

\[
\frac{\partial N'_k}{\partial t} = N'_k \left\{ 2\gamma(k) - v + \int A_{kk'}N'_k \, dk' + \sum_\lambda \int B^2_{kk'}N_{\lambda k} \, dk' \right\},
\]

\[
\frac{\partial N_{\lambda k}}{\partial t} = N_{\lambda k} \left\{ \int B^2_{kk'}N'_k \, dk' - \nu \right\}.
\]

The nuclei of the integrands \( A_{kk'} \) and \( B^2_{kk'} \) specify the probabilities of \( ll \)- and \( lt \)-scattering processes, the quantity \( \nu \) characterizes the wave damping due to Coulomb collisions, and the index \( \lambda = 1, 2 \) defines the polarization of electromagnetic waves**. The energy

* The problem of quasi-linear relaxation of energetic electrons confined in an open magnetic trap was solved in a paper by Breizman (1986), and the stationary regime of loss-cone instability in the presence of suprathermal particle sources was considered by Ledenev (1984).

** As a consequence of axial symmetry of the problem, for describing electromagnetic waves it is sufficient to have two scalar functions \( N_{\lambda k} \) instead of the tensor that defines the four Stokes parameters (Breizman, 1975).
densities of Langmuir and electromagnetic waves $W'$ and $W''$ are related to the respective spectral functions $N'_k$ and $N''_k$:

$$W' = \int \omega'(k) N'_k \frac{dk}{(2\pi)^3}, \quad \omega'(k) = \omega_p (1 + \frac{3}{2}k^2 r_D^2),$$

$$W'' = \sum_\lambda \int \omega'(k) N''_{\lambda k} \frac{dk}{(2\pi)^3}, \quad \omega'(k) = \omega_p \sqrt{1 + \frac{k^2 c^2}{\omega_p^2}}. \quad (6)$$

The dispersion correction for Langmuir waves is much less than unity, $r_D = v_T e / \omega_p$ is the Debye radius and $v_T e$ is the thermal velocity of background electrons. Assuming the excited spectrum to be sufficiently wide and bearing in mind that, with a not too low plasma temperature, $T > 0.1 (m/M) E$, a change of the wave number in each scattering event is small compared with the wave number itself, we shall use in Equations (3) and (4) a differential approximation ($m$ and $M$ being the electron and ion masses, respectively). As a consequence of the problem with respect to the replacement $x \rightarrow -x$, one can restrict attention to considering the region $0 \leq x \leq 1$ and, upon integration over the azimuthal angle, to represent the system of Equations (3) and (4) as (Brezin, 1975)

$$\frac{\partial N'_k}{\partial \tau} (\kappa; x) = N'_k(\kappa; x) \left\{ 2\Gamma(\kappa; x) - \eta + \right.$$  

$$+ 2\kappa^{1/2} \frac{\partial}{\partial \kappa} \kappa^{1/2} \int_0^1 N'_k(\kappa; x') T(x; x') \, dx' +$$

$$+ 2\kappa \frac{\partial}{\partial \kappa} \sum_\lambda \int_0^1 N''_{\lambda k}(\kappa; x') T_{\lambda}(x; x') \, dx' \right\}, \quad (7)$$

$$\frac{\partial N''_{\lambda k}}{\partial \tau} (\kappa; x) = N''_{\lambda k}(\kappa; x) \left\{ \frac{\partial}{\partial \kappa} \kappa \int_0^1 N'_k(\kappa; x') T_{\lambda}(x'; x) \, dx' - \eta \right\}. \quad (8)$$

In Equations (7) and (8), we have introduced the following dimensionless quantities:

$$\kappa = \frac{k^2 V_h^2}{\omega_p^2}, \quad \tau = \frac{3}{2} \frac{\omega_p}{T} \frac{T}{\tau}, \quad \eta = \frac{2}{3} \frac{E}{E} \frac{v}{\omega_p},$$

$$\Gamma(\kappa; x) = \frac{2}{3} \frac{E}{E} \frac{1}{\omega_p} \gamma(\kappa; x) = \Gamma_0 \gamma(\kappa; x),$$

$$\Gamma_0 = \frac{1}{3a} \sqrt{\pi \frac{E}{8} \frac{n'}{T} \frac{n}{n}}, \quad a = 7, 17, \ldots,$$

$$\gamma(\kappa; x) = \frac{a}{\kappa^{5/2}} \left[ \kappa - 1 - x^2 (3\kappa - 1) \right] \exp \left( -\frac{1}{2\kappa} \right).$$
The constant $a$ is chosen such that at the point of maximum $\kappa_{\text{max}} = 1 + \sqrt{\frac{2}{3}}$ the growth rate $\gamma(\kappa_{\text{max}}; 0) = 1$. The dimensionless spectral functions $N^l(\kappa; x)$ and $N_\lambda(\kappa; x)$ are defined as

$$N^l(\kappa; x) \, d\kappa \, dx = \frac{1}{27\pi} \left( \frac{E}{T} \right)^2 \frac{m \, \omega_p}{M \, nT} \, N^l_k k^2 \, dk \, dx,$$

$$N_\lambda(\kappa; x) \, d\kappa \, dx = \frac{1}{27\pi} \left( \frac{E}{T} \right)^2 \frac{m \, \omega_p}{M \, nT} \, N_\lambda k^2 \, dk \, dx.$$ 

The even (with respect to variables $x$ and $x'$) parts of the integral nuclei $A_{kk'}^\lambda$ and $B_{kk'}^\lambda$ involved in Equations (7) and (8) have the form:

$$T^l(x; x') = 1 - x^2 - x'^2 + 3x^2 x'^2,$$

$$T_1(x; x') = x^2 + \frac{1}{2} x'^2 - \frac{3}{2} x^2 x'^2,$$

$$T_2(x; x') = \frac{1}{2} (1 - x^2).$$

Stationary solutions of the system of Equations (7) and (8) are determined from the relationships

$$N^l(\kappa; x) \tilde{T}^l(\kappa; x) = 0 ,$$

$$N_\lambda(\kappa; x) \tilde{T}_\lambda(\kappa; x) = 0 , \quad \lambda = 1, 2 ,$$

supplemented with the stability conditions

$$\tilde{T}^l(\kappa; x) \leq 0 , \quad \tilde{T}_\lambda(\kappa; x) \leq 0 .$$

Here $\tilde{T}^l$ and $\tilde{T}_\lambda$ denote the expressions put in braces in Equations (7) and (8). The properties of the integral nuclei $T_1$ and $T_2$ make it possible, without loss of generality, to put $N_2 = 0$ and to solve only the first two equations of the system (9) (Breizman, 1975). Thus, nontrivial stationary solutions for the spectral functions $N^l(\kappa; x)$ and $N_1(\kappa; x)$ are determined from the following equations:

$$2\Gamma(\kappa; x) - \eta + 2\kappa^{1/2} \frac{\partial}{\partial \kappa} \kappa^{1/2} \int_0^1 T^l(x; x') N^l(\kappa; x') \, dx' +$$

$$+ 2\kappa \frac{\partial}{\partial \kappa} \int_0^1 T_1(x; x') N_1(\kappa; x') \, dx' = 0 ,$$

$$2 \frac{\partial}{\partial \kappa} \kappa \int_0^1 T_1(x'; x) N^l(\kappa; x') \, dx' = \eta = 0 .$$

At fixed values of $\kappa$, the terms involved in Equations (11) and (12) behave differently
as functions of the variable $x$. This means that the equalities (11) and (12) can be satisfied, in general, not on the entire interval $0 \leq x \leq 1$ but only at some values of $x_i = x_i(\kappa)$. It is on these lines $x_i(\kappa)$ which are called 'rays' in Breizman et al. (1973), where the functions $N^I$ and $N_1$ are non-zero.

When solving the system of Equations (11) and (12), it is convenient to consider first the situation when electromagnetic waves with frequency $\omega \simeq \omega_p$ are absent. In this case the last term in Equation (11) can be discarded, and for the Langmuir spectrum we obtain a solution of the form

$$N^I(\kappa; x) = 2\Gamma_0 A(\kappa) \delta(x - 0),$$

$$A(\kappa) = \begin{cases} \frac{a}{\kappa^{1/2}} \left[ \left( \frac{1}{\kappa} + 1 \right) \exp \left( -\frac{1}{2\kappa} \right) + \frac{\eta}{2\Gamma_0 a} \kappa^{1/2} - C_1 \right] & \text{for } \kappa_* \leq \kappa \leq \kappa_0, \\ 0 & \text{outside the interval } (\kappa_*; \kappa_0). \end{cases}$$

Here $\kappa_0$ is the upper bound of the wave excitation region defined as the major root of the equation

$$2\Gamma(\kappa; 0) - \eta = 0.$$  

Under conditions when the instability growth rate exceeds greatly the collision damping rate, $\Gamma_0/\eta \gg 1$,

$$\kappa_0 \approx \left( \frac{2\Gamma_0 a}{\eta} \right)^{2/3} - 1.$$  

The constant $C_1$ is determined from the condition that the function $A(\kappa)$ becomes zero at point $\kappa_0$:

$$C_1 = \frac{\eta}{2\Gamma_0 a} \kappa_0^{1/2} \left( \frac{\kappa_0 + 1}{\kappa_0 - 1} \right).$$

When $\Gamma_0/\eta \gg 1$,

$$C_1 \approx 1 + \frac{3}{2} \left( \frac{\eta}{2\Gamma_0 a} \right)^{2/3}.$$  

The form of the function $A(\kappa)$ for different values of $\eta/2\Gamma_0$ is shown in Figure 3. A maximum of the spectral function $N^I_1$, as follows from the figure, corresponds to $k^I \approx \omega_p/V_h$, and the width of the spectrum $\Delta k^I \sim k$.

The spectrum of Langmuir waves (13) is concentrated in a plane perpendicular to the axis of the trap. While coalescing, these waves are able to produce electromagnetic emission near the double plasma frequency. The probability of a three-wave interaction $l + l' \rightarrow t(2\omega_p)$ is given, for example, in a paper by Pustovalov and Silin (1972) and in

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Fig. 3. The function $A(\kappa)$ is calculated at the following values of the parameters: $E = 100$ keV, $T = 100$ eV, and different $\eta/2T_0$: 1 = 0.01, 2 = 0.1, and 3 = 0.2.

a book by Tsytovich (1972). Under typical conditions of coronal loops, the escape time of the emission with frequency $2\omega_p$ from the loop, which, on order of magnitude, equals $R/c$, is small compared with a typical decay time:

$$
\frac{R}{c} \ll \frac{1}{\omega_p} \frac{nmc^2}{W^1} \left( \frac{mc^2}{E} \right)^{1/2}.
$$

Therefore, for emission at the second harmonic of plasma frequency, the loop may be considered optically thin. The intensity of electromagnetic waves near the double plasma frequency, $I(\omega; x) = k^2 \omega^4(k)N_k/(2\pi)^3$, is determined from the equation

$$
\frac{dI}{dS}(\omega; x) = a(\omega; x) - \mu(\omega)I(\omega; x)
$$

in which the emissivity $a(\omega; x)$ and the absorptivity due to Coulomb collisions $\mu(\omega)$ are given by the following expressions:

$$
a(\omega; x) = \frac{2\pi^5 e^2}{m^2 c \omega_p} \frac{\omega^2}{(\omega^2 - \omega_p^2)^{1/2}} \int \frac{(k_1^2 - k_2^2)^2}{k_1^2 k_2^2} [k_1 \times k_2]^2 \times
$$

$$
\times \delta(k - k_1 - k_2)\delta(\omega - \omega_1 - \omega_2)N_{k_1}'N_{k_2}' \frac{dk_1 dk_2}{(2\pi)^6},
$$

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\[ \mu(\omega) = \frac{v}{c} \frac{\omega_p}{(\omega^2 - \omega_p^2)^{1/2}} , \]  

and \( S \) is a coordinate along the ray. In a homogeneous plasma the solution of Equation (19) is well known:

\[ I(\omega; x) = \frac{a(\omega; x)}{\mu(\omega)} \left( 1 - e^{-\mu(\omega)x} \right) . \]  

In coronal loops with plasma density \( n \approx 10^8 \text{ cm}^{-3} \), temperature \( T \approx 100 \text{ eV} \), and transverse size \( R \approx 10^8-10^9 \text{ cm} \), the collisional absorption of waves can be neglected. The intensity of the emission leaving the loop then is

\[ I(\omega; x) = a(\omega; x)R . \]  

For calculating the emissivity \( a(\omega; x) \), we shall do an integration in expression (20) over azimuthal and polar angles, by taking into account the axial symmetry of the problem and the ray-type form of the spectral functions \( N'_k \). As a result of integration, one obtains:

\[ \int \delta(k - k_1 - k_2) \delta(x_1 - 0) \delta(x_2 - 0) \, dx_1 \, dx_2 \, d\varphi_1 \, d\varphi_2 = \]

\[ = \frac{2}{k} \frac{\delta(x - 0)}{\sqrt{4k_1^2k_2^2 - (k^2 - k_1^2 - k_2^2)^2}} . \]  

The wave vectors of electromagnetic waves are, obviously, perpendicular to the trap’s axis; therefore, the angular dependence of the quantity \( a(\omega; x) \) has the form of a delta-function (24). On substituting into formula (20) the spectral functions of Langmuir waves (13) and performing an integration over \( k_2 \), we obtain the following expression for emissivity:

\[ a(\omega; x) = \frac{1}{(2\pi)^3} \left( \frac{3}{2} \right)^3 \frac{\pi}{8a^2} \left( \frac{T}{E} \right)^2 \left( \frac{M}{m} \right)^2 \left( \frac{n}{n^1} \right)^2 nTF(\Omega)\delta(x - 0) , \]  

in which \( \Omega = \omega/\omega_p \) is a dimensionless frequency of electromagnetic waves. The function \( F(\Omega) \), which at its maximum reaches a value of order unity, specifies the form of the emission line:

\[ F(\Omega) = \frac{\Omega^2}{\Omega^2 - 1} \int \frac{2k - b}{\kappa(b - \kappa)} \sqrt{4\kappa(b - \kappa) - (d - b)^2} \times \]

\[ \times A(\kappa)A(b - \kappa) \, d\kappa , \]  

\[ b = \frac{2}{3} \frac{E}{T} (\Omega - 2) , \quad d = \frac{E}{mc^2} (\Omega^2 - 1) . \]

Integration is done here over an interval in which the radicand is positive. A plot of the function \( F(\Omega) \) as calculated on a computer for different values of \( \eta/\Gamma_0 \) is given in
Figure 4. When $\eta/2\Gamma_0 \ll 1$, a typical width of the spectral line $\Delta \Omega \approx T/E$. Note that the electromagnetic emission spectrum is somewhat displaced with respect to $\Omega = 2$ towards higher frequencies. This is caused by the fact that the spectrum of Langmuir waves terminates in the long-wavelength region, without reaching the point $\kappa = 0$ (see Figure 3). The brightness temperature of emission $T_b$ from an optically thin loop at the second harmonic of plasma frequency, calculated for a maximum intensity of the spectral line, is (formulae (23) and (25))

$$T_b \sim \frac{\pi m e^2}{120 \epsilon} \frac{T}{E} \left( \frac{M}{m} \right)^2 \left( \frac{n'}{n} \right)^2 \frac{R}{r_D} \left( r_D^3 n \right) F T.$$

(27)

In this expression $F = \max \{ F(\Omega)/(\Omega^2 - 1) \}$.

### 3. Fundamental Plasma Emission

The assumption made in Section 2 about the absence in the loop of electromagnetic waves with frequency near $\omega_p$, is, generally speaking, unjustified. The point here is that the solution (13) is unstable to an excitation of electromagnetic waves. This becomes obvious if the spectrum (13) is substituted into Equation (8): in the domain of the variables $\kappa$, defined by the inequality

$$\left( \frac{1}{\kappa^2} + 1 \right) e^{-1/2 \kappa} > C_1,$$

(28)

the stability condition (10) is violated.
However, the regime of stabilization of the loss-cone instability treated in Section 2 can, nevertheless, be realized, provided that electromagnetic waves escape from the generation region, without being able to grow. A typical growth time of t-waves is of the order of the time of l- scattering and, therefore, of the order of the inverse loss-cone instability growth rate. The escaping time of t-waves with frequency \( \omega \approx \omega_p \) from the loop can be estimated as \( R/v_g \) (\( v_g \) being the group velocity of t-waves), and then the condition for their absence in the system is

\[
\gamma < \frac{v_{Te}}{2R} \left( \frac{3mc^2}{E} \right)^{1/2} .
\]  

(29)

On the other hand, the loss-cone instability growth rate must, nevertheless, exceed the frequency of Coulomb collisions. The combined fulfilment of these two conditions places constraints on admissible values of the parameter \( \eta/\Gamma_0 \), at which the regime described in Section 2 is realized:

\[
\frac{R v}{v_{Te}} \left( \frac{E}{3mc^2} \right)^{1/2} < \frac{\eta}{2\Gamma_0} < 1 .
\]  

(30)

As is apparent from this inequality, under conditions of the solar corona the range of variation of the parameter \( \eta/\Gamma_0 \) is not very broad: for example, when \( R = 10^8 \) cm, \( T = 100 \) eV, \( E = 100 \) keV, and \( n = 10^8 \) cm\(^{-3} \), we obtain

\[
0.2 < \eta/2\Gamma_0 < 1 .
\]

A corresponding value of \( F \) does not exceed 0.12 and the ratio \( n'/n \leq 2.8 \times 10^{-7} \). Hence, the brightness temperature of the emission on the second harmonic of plasma frequency, as follows from formula (27), is bounded by the value of \( T_b \approx 2 \times 10^4 \) T \( \approx 2 \times 10^{10} \) K. Note that the left-hand term of (30) decreases with increasing temperature \( \sim T^{-2} \). For example, when \( T = 200 \) eV, the domain of the parameter \( \eta/2\Gamma_0 \), in which the regime under consideration is realized, is given by the inequality \( 0.05 < \eta/2\Gamma_0 < 1 \), and the brightness temperature can reach a value of \( T \approx 6 \times 10^{11} \) K. A maximum value of the ratio \( n'/n \), at which the inequality (29) is satisfied, increases proportionally with \( T^{1/2} \), and when \( T = 200 \) eV, \( n'/n = 4.0 \times 10^{-7} \).

Under conditions when the inequality (29) is not satisfied, the solution of the systems (11) and (12) becomes more complicated. The calculations are quite similar to those performed in a paper by Breizman (1975); therefore, we give here only the result. The stable solution of Equations (11) and (12), of interest here, has the following form.

1. \( \kappa > \kappa_0 \). In this region the instability growth rate is below the collisional threshold; therefore,

\[
N'(\kappa; x) = N_1(\kappa; x) = 0 .
\]  

(31)

2. \( \kappa_1 \leq \kappa \leq \kappa_0 \). When \( \kappa < \kappa_0 \), there appears a ray of l-waves:

\[
N'(\kappa; x) = 2\Gamma_0 A(\kappa) \delta(x - 0) ,
\]  

(32)
and t-waves are absent as before. The spectrum (32) extends to the point \( \kappa_1 \), at which \( 2\Gamma_0 A(\kappa_1) = \eta \). When \( \eta/2\Gamma_0 \ll 1 \),

\[
\kappa_1 \approx \frac{1}{3} \left( \frac{2\Gamma_0 a}{\eta} \right)^{2/3} - 1. \tag{33}
\]

(3) \( \kappa_2 \leq \kappa \leq \kappa_1 \). At the point \( \kappa_1 \) there appears a ray of electromagnetic waves that is directed along the trap’s axis:

\[
N_1(\kappa; x) = 2\Gamma_0 B(\kappa)\delta(x - 1 + 0), \tag{34}
\]

\[
B(\kappa) = 2a \left[ (1 + 2\kappa) \frac{e^{-1/2\kappa}}{\kappa^{3/2}} - \sqrt{2\pi} \text{erf} \left( \frac{1}{\sqrt{2\kappa}} \right) + C_2 \right], \tag{35}
\]

\[
C_2 = \sqrt{2\pi} \text{erf} \left( \frac{1}{\sqrt{2\kappa_1}} \right) - (1 + 2\kappa_1) \frac{e^{-1/2\kappa_1}}{\kappa_1^{3/2}},
\]

and the density of Langmuir waves is constant in the interval \( \kappa_2 < \kappa < \kappa_1 \):

\[
N'(\kappa; x) = \eta \delta(x - 0). \tag{36}
\]

At the point \( \kappa_2 \) the function \( B(\kappa) \) goes to zero.

(4) \( \kappa_3 < \kappa < \kappa_2 \). Electromagnetic waves are absent here, and \( N'(\kappa; x) \) decreases to zero at the point \( \kappa_3 \):

\[
N'(\kappa; x) = 2\Gamma_0 \frac{a}{\kappa^{1/2}} \left[ C_3 - \left( \frac{1}{\kappa} + 1 \right) e^{-1/2\kappa} - \frac{\eta}{2\Gamma_0 a} \kappa^{1/2} \right], \tag{37}
\]

\[
C_3 = \frac{\eta}{2\Gamma_0 a} \kappa_2^{1/2} + \left( \frac{1}{\kappa_2} + 1 \right) e^{-1/2\kappa_2}.
\]

Figure 5 illustrates the solution of the system of Equations (11) and (12) under conditions when

\[
\frac{vR}{\nu T_e} \left( \frac{E}{3mc^2} \right)^{1/2} > \frac{\eta}{2\Gamma_0} \quad \text{for} \quad \eta/2\Gamma_0 = 0.1.
\]

Calculations show that \( \kappa_3 > 0 \); therefore, the sink of Langmuir waves into the condensate is absent. Note that the energy density of electromagnetic waves is estimated as \( \Gamma_0/\eta \) times exceeding that of Langmuir waves, i.e., in the regime considered, stabilization of the instability occurs due to the \( l \)-scattering and the subsequent collisional absorption of electromagnetic waves. The intensity of electromagnetic emission near \( \omega_p \) is specified by the following expression:

\[
I(\omega; x) = \frac{1}{2a} \left( \frac{3}{2\pi} \right)^{3/2} \left( \frac{T}{E} \right)^{3/2} \frac{c}{\omega_p} \frac{M}{m} \frac{n'}{n} \epsilon^{1/2} B(\epsilon)nT\delta(x - 0 + 1). \tag{38}
\]
Here

\[ \varepsilon = \frac{2}{3} \frac{E}{T} \left( \frac{\omega}{\omega_p} - 1 \right). \]

The width of the spectral emission line \( \Delta \omega \approx \omega_p T/E \), and the brightness temperature calculated for a maximum intensity of the line, is

\[ T_b = \sqrt[3]{\frac{3}{2}} \frac{\pi^{3/2}}{a} \left( \frac{mc^2}{T} \right)^{3/2} \left( \frac{E}{T} \right)^{1/2} \frac{M}{m} \frac{n'}{n} nr_D^3 TB, \]

\[ B = \max \left\{ \frac{B(\varepsilon)}{\varepsilon^{1/2}} \right\}. \]

Note that the electromagnetic emission in this case is directed along the magnetic field of the loop (see formula (34)). The brightness temperature of emission near \( \omega_p \) by formula (39) is estimated as \( T_b \approx 10^{10} \text{T} \approx 10^{16} \text{K} \). So high a brightness temperature does not appear to be surprising, if it is taken into consideration that by neglecting the carrying-away of the emission, we are considering a homogeneous optically thick source. Of course, the emission spectrum includes also the second harmonic of plasma frequency, and the emission with \( \omega = 2\omega_p \) is directed perpendicularly to the loop axis. But the intensity of the second harmonic is small because coalescence \( l + l' \rightarrow t(2\omega_p) \) is a second-order process with respect to the energy density of \( l \)-waves (and, hence, proportional to \( (n'/n)^2 \)) and, besides, the energy density of \( l \)-waves in this case is \( \Gamma_0 / \eta \) times smaller than that of \( t \)-waves.
4. Discussion

Let us now consider the applicability conditions of the solutions obtained.

When describing the plasma oscillations, we have everywhere neglected the dispersion corrections associated with the magnetic field. This is possible only if the magnetic field of the loop does not have any essential influence upon the motion of suprathermal electrons in the electric field of the oscillations, i.e., when the condition

$$\frac{\omega_B}{\omega_p} < \left(\frac{3T}{E}\right)^{1/2} \tag{40}$$

is satisfied. Another constraint on the magnitude of the magnetic field is associated with the fact that in the initial equations (7) and (8) we have neglected the influence of the magnetic field upon the motion of background plasma ions in the electric field of beatings, by assuming that

$$\omega_1 - \omega_2 = kv_T \gg \omega_B, \tag{41}$$

($v_T$ and $\omega_B$ being, respectively, the thermal velocity and the gyrofrequency of the ions). When $T_i \approx T_e$, this condition does not impose additional (as compared with (40)) constraints:

$$\frac{\omega_B}{\omega_p} \ll \left(\frac{M}{m}\right)^{1/2} \left(\frac{T}{E}\right)^{1/2}. \tag{42}$$

The next condition refers to the process of quasi-linear relaxation of suprathermal electrons. In Sections 2 and 3 it has been assumed that stabilization of the loss-cone instability occurs due to an induced scattering of waves off the ions and the influence of the waves upon hot electrons has been neglected. A typical time of variation of the distribution function of hot electrons due to induced emission and absorption of waves $\tau_q$ in order of magnitude is $\tau_q \approx \gamma^{-1} \Lambda$, where $\Lambda$ is the logarithm of the ratio of the energy density of waves to that of thermal noise, and $\gamma$ is the loss-cone instability growth rate. The energy density of waves during a quasi-linear relaxation $W_q \approx n'E/\Lambda$ (see Breizman, 1986). However, taking account of nonlinear terms in the equation for waves leads to a limitation of the wave energy density at the level $W' \ll W_q$. By estimating the inverse time of differential transfer of plasmons during the $li$-scattering off ions as $\omega_p(m/M)(E/T)(W/nT)$ and comparing it with the instability growth rate $\gamma \sim 0.1 \omega_p n'/n$, we find

$$W' \approx 0.1 \frac{n'}{n} \frac{M}{m} \frac{T}{E} nT, \tag{43}$$

so that

$$W_q/W' \approx (10/\Lambda) (m/M)(E/T)^2 \gg 1.$$
A typical time of variation of the energetic particle distribution in this case is $W_q/W'$ times larger than the quasi-linear time and is estimated as

$$
\tau_h \approx 100 \omega_p^{-1} \frac{n}{n'} \frac{m}{M} \left( \frac{E}{T} \right)^2 \approx 10^3 \; \text{s},
$$

(44)

which greatly exceeds typical times of the processes considered above. Note that in the regime considered in Section 3, when $W'/W' \sim \Gamma_0/\eta$, this time $\tau_h$ increases still $\Gamma_0/\eta$ times. So slow a relaxation of hot electrons allows us to consider sufficiently correctly the stationary solutions of Equations (7) and (8) during time $\gamma^{-1} \ll t \ll \tau_h$.

Finally, we shall give an estimate of the thickness of the rays. The question of the actual thickness of rays in $k$-space is investigated in a paper by Breizman et al. (1973) as well as in some other papers (for example, Malkin, 1982). Assuming that a broadening of the rays occurs on account of a four-plasmon interaction of Langmuir waves, for a typical thickness of the ray $\Delta x$ we obtain the following estimate (Breizman et al., 1973):

$$(\Delta x)^2 \approx 10 \left( \frac{m}{M} \right)^{1/2} \left( \frac{E}{T} \right)^{3/2} \left( \frac{W'}{nT} \right)^2 \frac{n}{n'} (\Delta x_0)^2.
$$

(45)

Here $\Delta x_0$ is the angular width of the instability growth rate. In the example considered here $\Delta x_0 \approx 1$ (see Figure 1) and $(\Delta x)^2 \approx 10^{-3}$.

It must be emphasized in conclusion that the solutions obtained in this paper for spectra of Langmuir and electromagnetic waves differ from those reported earlier not only quantitatively but also qualitatively: the emission directions near the plasma frequency and its second harmonic are different. The singular character of these solutions is determined by the structure of Equations (7) and (8) rather than by a specific form of the growth rate chosen only to simplify the calculations. With a different excitation source of the waves, the number of rays and their form will, generally speaking, be different. It is important, however, that the observed (Kosugi, 1985) directivity of the type IV burst emission can be associated precisely with an essentially anisotropic generation of electromagnetic waves in the source rather than with propagation effects.

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STUDIES ON A VERY FLARE-ACTIVE $\delta$ GROUP: PECULIAR $\delta$
SPOT EVOLUTION AND INFERRED SUBSURFACE MAGNETIC
ROPE STRUCTURE

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Abstract. The complex subsurface magnetic rope structure of a very flare-active isolated $\delta$ group (McMath 13043, July 1974) is studied by means of high-resolution evolutionary data from BBSO magnetic and velocity data. This group showed unusually fast evolution accompanied by a number of intense flares occurring on the neutral line of a $\delta$ spot, and provided an excellent opportunity to study the inherent relation of flare occurrence to changes of the magnetic configuration. We first examine the abnormal evolution of this group started by formation of a large, compact, reversed $\delta$ spot by squeezing of multipole. The $\delta$ configuration was deformed by penetration into the opposite polarity umbra and its subsequent disappearance, decaying by rapid shear motions. Strong transverse fields over 4000 G were detected in the penumbrae and some umbral components.

Combining these data with the August 1972 region, the evolution of these isolated $\delta$ groups is shown to decompose into two flare-associated elementary modes: (A) shearing produced by spot growth and (B) reduction of shear as spots disappear. We propose a model of an emerging twisted magnetic knot to explain the two modes and apply realistically to the present evolution. The inferred magnetic topological structure of this region consists of tightly twisted (sheet-like) knots and a long-winding twisted rope with an internally reversed loop and a hooked bottom structure. Their consecutive emergences are suggested to explain the abnormal evolution of this $\delta$ group. This result indicates that the origin of the concentrated flare activity in these isolated $\delta$ groups may be traced to internal magnetic activity responsible for forming anomalous magnetic ropes.

1. Introduction

The $\delta$ configuration, defined as umbrae of opposite polarity lying in a common penumbra, has been known as the most active spot configuration (Kunzel, 1960; Ellison, McKenna, and Reid, 1960; Bruzek, 1960; Warwick, 1966; Zirin and Werner, 1967; McIntosh, 1969, 1970; Sawyer and Smith, 1970; Sakurai, 1972; Zirin and Tanaka, 1973; Tanaka, 1980; Hagyard et al., 1984; Zirin and Liggett, 1987). Tanaka (1980) showed that 90% of $\delta$ groups with inverted polarity produced great flares (or great geomagnetic storms) in the period 1917–1974. Zirin and Liggett (1987) surveyed 25 $\delta$ groups in recent data and deduced the general properties and formation. They classified $\delta$ in 3 categories, concluding that $\delta$ groups are responsible for almost all great

† The author died on January 2, 1990. This paper, prepared for publication at the time of his death, was edited by Professor H. Zirin.


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flares and that the most intensive activity has occurred in isolated large δ groups. Tang (1983) examined δ formation due to collision of two groups. The δ configuration generally shows a polarity order inverted from the Hale–Nicholson law with normally preceding polarity following. There is a tight structure between the two polarities with strong magnetic shear and motion along the shear line. This suggests an abnormal magnetic rope (bundle of magnetic field lines) structure as compared to the normal bipolar structure. However, little is known about the details and origin of anomalous evolution and activity. The most active isolated δ group survives only for the order of a week, so high-resolution observations of the whole life of such a region which happen to coincide with its disk transit is extremely rare. After a quick survey of such groups over two maxima (1973–1982) since the August 1972 region (Zirin and Tanaka, 1973), McMath 13043 (July 1974) proved to be one of the best regions that fit this condition. It showed unusually violent evolution accompanied by very high activity, almost continuous flaring (59 intense flares) occurring right on the δ site with clear-cut relations to rapid changes of underlying magnetic morphology. High-resolution observations were obtained at BBSO during the whole life of this group from June 28 to July 10, together with some magnetic data at Okayama and Kitt Peak, and velocity data at Mt. Wilson. Based upon these invaluable data this series of papers* study the origin of the δ group and flare occurrences inherent in the δ configuration, aiming to explore the ultimate flare origin as a product of subsurface magnetic activity. This paper seeks complex magnetic rope structures under the surface as inferred from detailed evolutionary data. (Further analyses were planned on quantitative relations between flare occurrences and δ evolution (Paper II), and on development and origin of two kinds of flares that occurred on July 4 and July 5 (Papers III and IV).)

2. Abnormal Evolution and Structure of the δ Group McMath 13043

The δ spot as completed on July 3 (Figure 1(b)), has a really extraordinary shape. A large p spot on the right (east) is surrounded by f spots, from west and north (down), across a narrow light bridge of L-shaped penumbra. The light bridge has a constant width of about 2.5″–3″, coinciding exactly with the inversion line, and showing thin penumbral filaments almost parallel to it, thus extremely high magnetic shear. At the south side of the NS inversion line $f_4$ is located immediately west of a p umbra with a 180° polarity inversion, while lower down (N), where the neutral line is horizontal, the polarity inversion is 90°. On the following day (July 4) this δ collapses dramatically. Figure 1(c) shows a sudden penetration of the completely inverted $f_4$ into the middle of the p umbra which split into two small p spots $p_4$ (small) and $p_2$. It changed the pattern of the light bridge but retained its narrowness. Between the invading $f_4$ and the invaded $p_3$, short direct connections, totally unsheared, appeared, and at the final stage the entire $f_4$ and $p_2$ spots had disappeared. After this peculiar spot disappears, the whole δ shape elongated east–west (July 5; Figure 1(d)), due to rapid eastward shear motions.

* To our regret, the following papers planned by the deceased author will not appear.
of $f_1$ and $f_2$ which occurred in contact with a remaining $p_1$, and $f_1$ departed the $\delta$ (July 6).

This outline indicates that rapid evolution occurred consecutively in about 6 days, clearly being divided into three phases: $\delta$ formation, deformation, and decay. Throughout the three phases, a number of intense flares continue to occur, showing different shapes and developments corresponding to the underlying magnetic configurations (later papers). This short lifetime is typical of highly active spots. We now describe more details of each phase of this $\delta$. 
Phase 1 ($\delta$ formation)

This large but compact $\delta$ spot was actually formed by a gathering of $p$- and $f$-poles born separately. From June 28 to July 1 more than 7 EFR's appeared in a spotless area near the east limb. Motions and growth started immediately, with spots of each polarity leaving their counterpart, the $p$ spots moving west, $f$ spots east. Only $p_1 - f_1$, originally born as a tight $\delta$ at the central region with axis oriented NS, remained and grew as the core of a large $\delta$ spot. Other poles flowed to this pair and merged (Figure 1(a)). The most striking motion was the rapid (800 m s$^{-1}$) approach of $p_2$ from the far east on leave of $f_2$. There can be seen, by July 1 (Figure 1(a)), two aligned belts of $p$- and $f$-poles growing and approaching $p_1$ and $f_1$, respectively. Each belt consisted of many small threaded poles in the north–south direction, which may suggest bundles of magnetic sheets (umbrae) aligned NS. By July 3 the threaded umbrae collided and coalesced to form a large $p$ umbra and surrounding elongated $f$ umbra ($f_1-f_2-f_3$) (Figure 1(b)).

The formation of a key $f$-spot ($f_4$) is mysterious. It was absent from any pair of EFR on July 1, but when $p_2$ merged with $p_1$ tightly on July 2–3, it suddenly appeared immediately west of the narrow light bridge. Its structure is remarkable. An underexposed print (Figure 2) clearly shows that the $f_4$ umbra consists of two thin threads parallel to the inversion line or penumbral filaments. This could not be due to a height effect as we used H$\alpha \pm 1$ Å off-band photos. Polarimeter spectra of a photospheric line

![Diagram](https://via.placeholder.com/150)

**Fig. 2.** Underexposed photo of July 3 showing fine structures of $p$ and $f$ umbrae. Note that a large $p$ umbra consists of three parts: $p_1, p_2, p_4$, and $f_4$ consists of elongated thread-like features. Shown also are four components of polarization spectra of 6303 Å taken at Okayama Observatory and their slit position (parallel to $f_4$ threads). A high transverse field of 4300 G is detected in these spectra.
6303 Å at four polarizations obtained at Okayama (also shown in Figure 2) present Zeeman splitting patterns indicating a very strong transverse field of 4300 G along the f4 threads (the slit was parallel to them), though weaker longitudinal fields were also present (note that this region was near the center of the disk). Figure 2, further, indicates that the compact large p shows fine structure components, large p2, curved p1 and small p4, reflecting its formation process. The timing of the appearance of p4 is not so clearly observed as the birth of f4. So the companion of f4 may be p4. In a model presented later, the sudden appearance of f4 and fine structure of p provides a key clue to understanding whole magnetic rope topology constituting this δ spot.

The flares at this stage were first associated with eruptions of many EFR’s; before the departure of p2 a large two-ribbon flare occurred at the p2 – f2 pair (July 2 8 UT). The first large flare associated with the completion of the large δ occurred in a (N–S) vertical portion of L(f4 – p) at July 3, 08:30 UT.

Phase 2 (δ deformation)

After the completion of the δ, this configuration remained remarkably stable for half a day. This coincides only with a quiet span in the continued activities of this region. The stillness was suddenly broken and dramatic activities began by the start of the penetration of f4 into p as mentioned before. Figure 3 shows a whole sequence of evolution on July 4. As soon as f4 squeezed p, the inversion line bent and a small p4 split and moved rapidly south (up in Figure 3(b)). The f4 penetration started at 3 UT and continued with a very constant speed of 180 m s⁻¹ throughout the day. This caused an intense flare there first at 06:30 UT and 13:50 UT (white-light flare), and after f4 entered in the middle of p4 and p2, almost continuous flaring was seen at the rim (p side) of the sheared inversion line connecting f4 to p4 and behind f4 (see arc emissions in Figure 3(d)).

By the penetration of f4, remarkable changes happened in the high shear seen in the original light bridge. From the single sheared penumbral connection parallel to the inversion line seen in Figure 3(a), the connection between f4 and p umbrae became double: one sheared connection from south of f4 to p4 which was split southward from the main p umbra and the other totally unsheared connection from the north side of f4 to the large spot p2 crossing the narrow light bridge (Figure 3(c)). This division indicates that the f4 – p4 and f4 – p2 connections actually existed, presumably under the surface, even though no apparent connections were seen above the surface when p4 was included in the large p. Livingston (1974) found high transverse fields of 4130 G on this unsheared light bridge around 17 UT (at the time of Figure 3(c)) and much weaker longitudinal fields (1700 G) in the umbrae (f4 and p2). After 20 UT (Figure 3(e)) these short filaments cut into the umbrae themselves, and f4 and p2 became threaded north–south. The threading proceeded steadily, and extended to the whole f4 and p2, showing AFS-like (Bruzek, 1967) connections (Figure 3(f)). The f4 and p2 disappeared completely, together with their penumbral connection around 22–24 UT. Absolute magnetic fields measured visually at Mt. Wilson (Mr T. Cragg) weakened to 2900 G (probably transverse field) at this phase. Velocity measurements made during 22:40–24:40 UT.
at Mt. Wilson (5250 Å) (courtesy of Dr B. LaBonte) indicate perfect coincidence of the whole threaded umbral region with an island of high upflow (0.3–1.2 km s⁻¹). Figure 4 shows the correspondence of velocity maps and disappearing umbrae. This location (W 14°, S 16°) was so close to the disk center that the observed velocities were mostly rising. In view of the nearly horizontal structure of the threads of this peculiar structure,
Fig. 4. Comparisons of Hz off-band photo of late July 4 (22.2 UT) (a) and its sketch (b) with Mt. Wilson fine scan maps (2.42°-EW x 4.85°-NS resolution) of the same region: (c) longitudinal magnetic field, (d) velocity (dashed - blue shift, solid - red shift) at 22.7-22.8 UT, and (e) velocity at 23.8-24.7 UT. The region of the threaded umbra (P, and L) is indicated by squares. Note that this region coincides with a high-velocity blue-shifted island. Four levels of velocity (-0.3, -0.6, -0.9, and -1.2 km s⁻¹) correspond respectively to φ = 0, -0.6, and -1.2 km s⁻¹. (Courtesy of Dr. B. LaBonte.)
the umbral threading and disappearances can be viewed as the emerging process of magnetic bundles that were almost flat or concave to the surface. This is just opposite to the formation of a normal bipolar spot pair where longitudinal field spots appear as the result of emergence of a magnetic bundle convex to surface. Gradual weakening of the longitudinal field may support this idea. This abnormal phenomenon suggests the emergence of a hooked part \( (f_4 - p_2) \) of the magnetic rope. \( p_4 \) was left behind by the disappearance of \( f_4 \), but some violent reconnections and an associated flare happened, producing a new connection from \( p_4 \) to another \( f(f_3) \) above the chromosphere (Paper III).

**Phase 3 (\( \delta \) decay)**

On July 5 (Figure 1(d)), the \( \delta \) region shrank by disappearance of a major part of \( p \) and \( f_4 \). Obviously the region was decaying. But fast eastward shear motions of 50 to 100 m s\(^{-1}\) began by the \( f \) spot \( (f_1 \) and a part of \( f_5 \) in contact with the remaining umbra \( (p_1) \), and furthermore the approach of a new inverted \( (90^\circ) \) pair \( (p_5 - f_5) \) resulted in a very elongated inversion line, upon which a very low, active filament developed. There were two homologous large two-ribbon flares that occurred \( (15:10 \text{ UT and 21:40 UT}) \), with the second flare being very eruptive and energetic. It is of interest that the largest flare occurred in the decaying phase of the \( \delta \) group. The polarimeter measurement at Okayama showed a high transverse field (3500 G) in \( p_1 \) and \( f_1 \) umbrae as well as in shearing penumbral filaments. Peculiar arc structures extending from the edge of the \( p_1 \) umbra (Figure 1(d)) is also suggestive of horizontal magnetic structure. In general, transverse fields must have been particularly strong and in some cases dominant in the umbrae constituting this \( \delta \) group. Rapid shear motions of \( f \) spots continued until July 7 further producing two homologous flares on July 6, and \( f_1 \) departed from the \( \delta \) on July 6.

### 3. Discussion and Model

The present results have revealed the following remarkable facts about this extraordinary \( \delta \) group.

(a) A large, still compactly reversed \( \delta \) was formed by gathering and squeezing of several growing poles of opposite polarity.

(b) The light bridge (inversion line) passing through the whole \( \delta \) configuration was very narrow \( (2.5'' - 3'') \), of constant width, and consisted of highly sheared penumbral fibrils.

(c) The \( \delta \) group showed continued violent motions, switching consecutively from collision \( (\delta \text{ deformation}) \) and finally to shearing \( (\delta \text{ decay}) \) during its relatively short life (one week).

(d) All motions were directed so as to return to normal orientation of polarity (i.e., \( p \) spots moved west, \( f \) spots east).

(e) Remarkable motions (e.g., \( f_4 \) invasion, \( f_1 - f_5 \) shear motions) were confined to one polarity no matter how close \( (2.5'') \) the opposite polarity occurred.

(f) Throughout the rapid changes of the \( \delta \) configuration intense flares continued to
occur on the $\delta$ site, clearly demonstrating that these changes represented by apparent spot motions caused the flare occurrences.

(g) Some (probably most) umbral magnetic structures were transverse showing threadlike features and their intensities are strong over 4000 G in some phases. This result establishes for the first time that the elongated umbrae common in $\delta$ spots are the site of strong transverse fields.

(h) The $f_4$ umbra, with very high transverse field, mysteriously appeared at the completely (magnetic) reversed position in contact with the large $p$ spot, probably its counterpart being included in the large $p(p_4)$.

(i) $f_4$ invaded a $p$ umbra, splitting $p$ into two parts ($p_4$ and $p_2$) and the original highly sheared connection $p - f_4$ changed in two ways: one totally unsheared connection to $p_2$ at north side of $f_4$ and the other sheared connection to the split $p_4$ from the south side of $f_4$, which proved that $f_4$ was connected to these two spots.

(j) The umbral ($f_4$) penetration ended by a peculiar threading and the unusual disappearances of the penetrating ($f_4$) and penetrated ($p_2$) spot pair, accompanied by a high rising velocity, suggesting the $f_4 - p_2$ connection to be a hooked bottom of a rising magnetic rope.

These characteristics evidently differ not only from normal bipolar spots but also from other common complex spot groups with or without partial $\delta$ configurations, and probably are inherent to particularly active isolated $\delta$ groups. During the whole evolution, the spots appeared in a spotless region, increased their area rapidly, and after the violent changes, shrank rapidly. Therefore, the whole process may well represent the continued emergence of a complexly intertwined magnetic flux rope(s). The aim of this discussion is to infer such topology so that emergence of such ropes can explain the above results as closely as possible.

It is possible that all motions are due to surface flows. However, it would be difficult to explain fact (e) because such a narrow stream confined only to one polarity would be hydrodynamically unbelievable. Furthermore, the pressure balance problem would be difficult in that hypothesis. If the motions that squeeze umbrae of the same polarity (a), as seen in the initial coalescences, and force penetration into opposite polarity umbra (i), were due to pressing by surface flows, the dynamic pressure $\rho v^2$ ($\sim 10$ dyne cm$^{-2}$) is 5 orders of magnitude smaller than the magnetic pressure ($\sim 10^6$ dyne cm$^{-2}$) with $v \sim 100-500$ m s$^{-1}$, $\rho \sim 10^{-7}$ g cm$^{-3}$, $B \sim 3000-4000$ G. We need the density at depth $r \sim 0.8 R_o$ to balance this magnetic pressure. The compactness of the region and magnetic fine structures in which only one polarity moved may exclude the effect of horizontal flows at such a deep level.

The fact (b) that the width of the light bridge separating opposite polarities with transverse field was constant, but not narrower than 2.5", might indicate that the observed width may be the limit of approach of two spots of opposite polarity. The magnetic rope structure would inevitably produce strong transverse fields to intercept the two polarities and maintain magnetic pressure, thereby avoiding direct contact of two opposite polarity spots beneath or at the photospheric level. If such contact happened violent (sub)-photospheric reconnection and flares should occur.
Though peculiar evolution may be predominantly associated with abnormal magnetic rope topology under the surface and with this rope emergence, some additional forces must have affected the emerging part(s) of rope(s) and caused dynamical effects in each flux rope. Magnetic tension at the photospheric interface or in subsurface intertwined structure would occur during the emergence process in addition to magnetic buoyancy, Hale–Nicholson force (Zirin, 1988) and others. Studies of such dynamical flux emergence of a complex rope would require theoretical simulations and are far beyond the scope of the present paper. I, therefore, discuss the flux emergence based on a quasi-stationary configuration. However, the fact that (d): motions are directed to return to normal $p - f$ orientation may reasonably be attributed to the effect of the Hale–Nicholson force which is related to the tension of underlying toroidal fields linked to the complex ropes (in emergence of a normal pair the $p$ spot tends to move west due, presumably, to this force; Zirin, 1988).

Comparison with the complex evolution in the 1972 region, another isolated $\delta$ group studied in detail (Zirin and Tanaka, 1973) reveals some similarities though the evolutionary speed was much faster in the July 1974 region. In the Appendix I classify all evolutionary patterns in flare-associated phases of the two groups and deduce the

Fig. 5. Two elementary evolutionary patterns responsible for great flare occurrence deduced from the August 1972 and July 1974 groups (see Appendix), and their explanations by an emerging twisted knot model. Mode A (a, b) is a shearing process with growth of spots and Mode B (c) is an unshearing process with disappearances of spots. (a) A bundle of toroidal magnetic field lines (left) is twisted in a clockwise direction by right hand, which forms a magnetic knot (middle), and its photospheric intersections at two successive times: $t_1, t_2$ show photospheric cross sections representing mode A evolution as seen in the August 1972 case (right). (b) Mode A but in case of counter-clockwise twisting by right hand. Mode A evolutions seen in the July 1972 case are realized. Note that the north–south orientation of two polarities and direction of the penumbral shear are reversed compared to case (a). (c) A model of mode B in the case of clockwise twisting. Emergence of the bottom part of the rope explains a new connection of one of the sheared poles ($p_1$) with the third spot ($f_2$) and their shrinkings or disappearances.
following two rather simplified elementary modes which show common or similar characteristics (shown by enclosure in the Appendix and schematically in Figure 5).

Mode A: two poles of opposite polarity appear and grow with a north–south oriented axis, and shear (and whirl structure) develop in the penumbra in between and surrounding the umbrae together with a shearing motion.

Mode B: there already exists high shear between a developed spot pair in the middle stage of its evolution, a third originally unconnected spot approaches one sheared pole of opposite polarity and a new sheared connection appears between the two poles, and gradually the shear weakens or disappears. Finally the two spots shrink or disappear.

Modes A and B are considered respectively as the shearing and unshearing processes in which great flares occur, common in active isolated δ groups and in some others as well. A simplified model to explain the two modes phenomenologically would be to assume an emerging process of a tightly twisted magnetic knot out of the surface as shown in Figure 5. It is presumed that such twisted knots are formed in the convection zone by forces analogous to twisting a rubber band followed by quasi-stationary lifting to the surface. Intersections of the knot with a photospheric surface plane at successively lower parts of the knot would produce the apparent photospheric evolution of a δ group. Shown in Figure 5(a) is the case of a knot realized by clockwise twisting by the right hand of a toroidal bundle of field lines (seen from forward of the bundle). In mode A, emergence of the top portion of the knot to the photospheric plane (t1) shows the p-pole located north of the f-pole (90° inverted to the Hale–Nicholson law) and rather smooth connections between the two. Further emergence of successively lower twisted parts (t2) would gradually show up, at the photospheric intersection, as an increase of whirl patterns in the penumbrae surrounding to two umbræ in the clockwise direction, reflecting right-hand twisting of the rope and sheared penumbral connections in the same sense between the two poles. At the same time, the p and f poles apparently shift west and east, respectively, following the shape of the knot whose deeper parts are linked to the toroidal rope. This would be interpreted as the shear motion. As can easily be seen, these features apply to the August 1972 case (Appendix). In the case of a knot formed by counter-clockwise right-hand twisting by right hand from in front (or clockwise twisting by left hand from behind) shown in Figure 5(b), its successive emergences would result in a configuration of f north of p and counter-clockwise whirl structure (S-shaped penumbral connections) but the shear motion would have the same direction as the above case. This case accords with the observed four mode A evolutions in the July 1974 group (Appendix). Note that relative north–south orientation of p and f spots and direction of the whirl structure or the shear in the magnetic knot model depend on the direction of twisting of the magnetic fields, twisting as can be seen from the rubber band analogy, and the observed cases in the two groups actually obeyed these rules.

Mode B is a case of a knot having one more turn at the bottom concave to the upper surface, which may be realized in twisting a more extended portion of a rope. Emergence of such a knot (in the case of clockwise twisting by right hand) at the middle phase (t1), shown in Figure 5(c), results in an appearance of a third pole (f2) originally unconnected to the sheared poles (p1 – F1) at the side of the sheared penumbra and with further
emergence \( t_2 \), \( f_2 \) approaches \( p_1 \) and a new connection would appear. This connection may be less sheared compared to \( p - f_1 \), because it represents smooth fields near the bottom of the concave rope, and, gradually becomes shortened and straight \( t_3 \), finally emergence of the bottom of the rope concave to the surface results in disappearance of the \( f_2 - p_1 \) pair totally out of the photosphere. This explains quite well the evolutionary details from August 5 to August 9 in the 1972 region (Appendix) as well as essential changes of spot invasion accompanied by spot disappearance on July 4, 1974.

The important consequence of the emergence of a twisted knot would be that as soon as the twisted part appears at the surface, intense flare(s) occurs at the edges of twisted umbrae (see Appendix), presumably, due to a supply of energy included in twisted rope to the low-\( \beta \) atmosphere. But more detailed discussions of the emergence-flare relation will be given in later papers.

Finally, we consider a more realistic topological connection of magnetic rope structure to explain details of the July 1974 observation. There must have been two key twisted magnetic ropes (A and B). Figure 6 shows the successive emergences of these ropes as superposed in the observed spot configurations presented in Figure 1. Dashed parts represent the rope(s) under the surface before emergence, and twisted field structures are roughly shown. (Other EFR ropes such as \( p_1 - f_3 \) knot are neglected). Actual shapes of these ropes must be more sheet-like as elongated conic sections are

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Fig. 6. Topological structures of two representative magnetic ropes (A, B) whose emergences explain evolutions of the presently studied \( \delta \) group as shown in Figure 1. Subsurface portions of the ropes are shown by dashed lines and ropes’ photospheric intersections (i.e., spots) are indicated, together with rough structure of twisted fields. (See text for explanation.)
found, particularly in $f$ spots. The initial appearance of north–south inverted $p_1 - f_1$ (July 1) and final shear motion of $f_1$ (July 5) would be explained by the emergences of, respectively, the top part, and after some stationary span, a very shallow, low-inclination tail of left-hand twisted rope(s): A (mode A-type with sheet-like cross section). Another rope, B (modified mode B-type), has an internally reversed twisted loop and hooked bottom structures as shown in Figure 6(b). Whether the two ropes are interconnected inside topologically or not cannot be inferred from the present observations. The initial birth of $p_2$ far apart from the main region and subsequent rapid approach to $p_1$ may trace a very fast shift of its photospheric intersection at the emergence of a very shallow rope at the top of B (a). The birth of transverse-dominant $f_4$ without its counterpart as a normal bipolar pair (h) would be understood as an emergence of a reversed loop of B (Figure 3(b)). This loop must be highly twisted and lie in a nearly horizontal plane, so the $f_4$ umbra itself has a large transverse component (g, h). $f_4$ and $p_4$ would be the intersections of this reversed loop, thereby realizing complete magnetic inversion. $p_4$, $p_2$, and $p_1$ must be so closely located at the surface intersections respectively of the ropes B, and A on July 3, thus showing a large coalesced single-looking umbra but fine structure showed their separations (Figure 2). The peculiar penetration of $f_4$ into $p$ (i) and subsequent disappearances of $f_4$ and $p_2$ (j) would result from an emergence of a concave (hooked) bottom portion of B connecting $f_4$ to $p_2$ (Figure 6(b, c)). It must have accompanied some dynamical motions of the reversed loop and probably the whole rope, B, due presumably to the changes of tension which should occur when such an intricate structure of magnetic rope starts to appear in the low-$\beta$ atmosphere. This would have disturbed the stationary emergence of the rope B and caused a rapid southward shift of $p_4$ and eastward shift of $f_4$ intersections, realizing a constant invasion of $f_4$. This dynamics needs to be studied further theoretically and experimentally. Anyway, emergences of the looped and hooked portion of B explain the appearance of double connections of $f_4$ to $p_4$ and $p_2$ at least topologically by the present model. $f_4$ is connected southward to $p_4$ by the twisted reversed loop, so with high shear, justifying the occurrence of continuous flaring associated with this connection. $f_4$ is also connected northwards to $p_2$ without shear, probably reflecting a rather smooth short bundle of field lines shaping the bottom of the rope. This is characteristic of the late phase of mode B evolution (see August 1972 case in the Appendix).

The present model hypothesizes that flare occurrences on the evolving $\delta$ spots are due to the emergence of twisted parts of the magnetic ropes. The current included in such a twist, which has been stably flowing under the balanced condition of high pressure in the high-$\beta$ region, may break the balance and become unstable as soon as the twisted part (the current) emerges out to the low-$\beta$ corona. Actually the flares have occurred at the edges of evolving (moving ) spots. The new kinds of flares were clearly initiated by the start of new motions which are interpreted as emergences of the different twisted part of the ropes in the present model. Precise agreement of energy outputs and inputs in this model will be demonstrated in Paper II (see footnote on p. 134).

The above-introduced topology of magnetic ropes might not be unique, though other topologies considered could not explain the evolution better. Of course there may be a
completely different approach such as to consider dynamical subsurface reconnection(s) between the magnetic ropes. Present work may be primitive, but is the first attempt to explain the evolution of the complex isolated δ group based only upon the complex magnetic rope topology under the surface. Similarities in the two great isolated δ groups may encourage further studies in similar groups, which may lead to common rope(s)-shaped characteristics of these particularly active groups, and provide clues to infer the active intertwined rope formations in the convection zone inherent to great flare activity. What causes these complex rope structures (twisting and looping) is a different, but obviously important problem. If the rather short (one week) evolution in the isolated δ group is considered as a continuous emerging process of the complex rope(s) assembly with a vertical speed of the order of observed translational motions (50–200 m s\(^{-1}\)), its depth would be 10\(^5\) km, located near the bottom of the convection zone. The birth of an isolated δ group may be related to complicated magnetic rope formation due to activity at the bottom of the convection zone or due to fluctuating (spatial and temporal) changes of solar rotation at the intersection of large scale flows (like global convection, supergranulation). Such information must await very precise and long-term studies of helioseismology.

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Appendix

Evolutionary similarities between the August 1972 (Zirin and Tanaka, 1973) and the present July 1974 region are illustrated here in Figures A1 and A2 by showing fine tracings of umbral outlines and penumbral fine filaments. Enclosed squares represent portions where particular evolutionary patterns (modes A and B) occurred sequentially. Great flares occurred in these squared portions. Flare kernels are shown by smeared regions in the August 1972 group. Note that the coordinate system is rotated by 180° in the July 1974 region, so north is up in the 1972 region and south is up in the 1974 region. Mode A is a shearing process accompanied by spots growing, and mode B is an unshearing process accompanied by spots shrinking and/or disappearances. In the August 1972 group \(p_1\) grows north of \(f_1\) and until August 4 \(p_1\) moves west relative to \(f_1\), increasing shear and clockwise whirl structure. This is a typical mode A evolution, while starting August 4, the spot \(f_2\) (3 small spots), whose counterpart is missing, approaches the whirled part of \(p_1\) from west and is connected to \(p_1\) on August 7, whereupon a great flare occurs on the rims of \(p_1\) and \(f_2\), then \(f_2\) is connected to \(p_1\) with less shear on August 8 and disappears, together with \(p_1\) shrinking, on August 9–10 (Mitaka data). Further photos were unavailable due to the group passing the limb. But
probably \( p_1 \) also disappeared. This mode B pattern also produced a large flare in the beginning. For the July 1974 group detailed descriptions are given in the text. Differences from the August 1972 group are (1) evolution was much faster, (2) the \( f \) spot grew north of \( p \) spot (note 180° rotation in the coordinate axis), (3) due to closeness of the two spots the shear is higher and the whirl structure is less clear but is certainly counterclockwise. Four mode A evolutions occurred at different regions (A1 and A3 at similar place). In

**1972 August Group**

![Diagram of the 1972 August group](image)

Fig. A1. The 1972 August group.
only one mode B evolution on July 4 clear disappearances of unshearing $f_4$ and $p_2$ spots were witnessed. Large flares occurred at the beginning of mode B and in the middle of mode A, common in both regions. Flare kernels change so rapidly in the July 1974 activities that they are not shown here. The directions of the spot motions were the same in the two groups.
References

Ellison, M. A., McKenna, S. M. P. and Reid, J. H.: 1960, Observatory 80, 149.
STABILITY OF PROMINENCES EXPOSING HELICAL-LIKE PATTERNS

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Abstract. The internal structure of prominences appearing as twisted tubes was studied. The sample embraced 15 stable and 13 eruptive prominences, exposing patterns which possibly reflect a helical configuration. The equivalent pitch angles ($\vartheta$) of twisted fine structure features were measured. In some cases the evolution of the internal structure was followed and 49 independent measurements of the parameter $\vartheta$ were performed in total. The results are presented in the plane relating the parameter $\vartheta$ and the normalized prominence height. The eruptive prominences occupy the region characterized by $\vartheta > 50^\circ$ and $h > 0.8d$, where $h$ and $d$ are the prominence height and the footpoint half-separation, respectively. All prominences characterized by $h < 0.6d$ or by $\vartheta < 35^\circ$ were stable. Such a result is in good agreement with an order of magnitude treatment of the forces acting in a curved magnetic tube, anchored at both ends in the photosphere.

1. Introduction

Cold and dense prominence plasma provides an insight into the structure of the inner parts of the arcade-like coronal magnetic fields embedded in prominences (Martin, 1990). Unfortunately, present magnetic field measurements in prominences cannot provide information at a fine spatial scale and, moreover, the interpretation of the measurements is far from being straightforward (Leroy, 1989; Kim, 1990). The observations indicate that the prominence plasma fills up (due to the small scale-height) the regions characterized by a horizontal field which is necessary to support the dense plasma against gravity (Priest, 1990). The angle between the field vector and the axis of the prominence is usually small (Leroy, 1989). On the other hand, observations of the prominence morphology provide fine structure details. However, the interpretation of such observations is based on the assumption of a frozen-in condition. Moreover, only the projection of the structure in the plane of the sky is available.

Generally, quiescent prominences show a slab-like geometry characterized by vertical fine structure threads (Engvold, 1979). Twisted, helical-like patterns are more frequent in active-region prominences, but sometimes can be found also in quiescent prominences (Rompolt, 1975, 1988, 1990). Such patterns can show up in various magnetic configurations, e.g., like the one proposed by Hirayama (1985) or van Ballegooijen and Martens (1990). However, all these configurations basically can be represented by an axial current and so are equivalent to a simple twisted magnetic flux tube. Occasionally,
rotational plasma motions are observed in prominences (Liggett and Zirin, 1984; Schmieder, Raadu, and Malherbe, 1985) indicating an intrinsic cylindrical geometry.

In the eruption phase, the morphology of a prominence often changes dynamically and can be very intricate (Rompolt, 1975, 1990) as illustrated by the eruptive prominence of May 17, 1989 in Figure 1(a). However, in the late phases of eruption, usually a rather simple arch remains, frequently exposing helical-like patterns (Tandberg-Hanssen, 1974; Schmahl and Hildner, 1977; House and Berger, 1987; Moore, 1988; Vršnak et al., 1990a; Rušin, 1989). The configuration can sometimes be quite regular, as in the case of the famous eruptive prominence of December 19, 1973 (Figure 1(b)). Generally, most of the events follow a rather similar scenario: the eruption is preceded by a slow rising motion of the prominence, which is accompanied by a gradual morphological evolution from an initially intricate structure into an apparently toroidal shape, exposing sometimes twisted patterns, most often prominent in the legs of the prominence. At a certain critical height a fast acceleration begins and the internal structure ‘relaxes’ into a rather simple form appearing as an expanding bundle of loops, or helically-twisted threads. De-twisting and rotational motions are frequently reported (Engvold, Malville, and Rustad, 1976; Schmahl and Hildner, 1977; Ruždjak and Kleczek, 1977; Vršnak, 1980; House and Berger, 1987; Moore, 1988; Vršnak, 1990a), also indicating an intrinsic cylindrical geometry. Ejections of cold prominence plasma can sometimes be followed, even in the outer corona, up to 10 solar radii where twisted patterns still can be identified (Athay and Illing, 1986; Illing and Hundhausen, 1986; House and Berger, 1987; Rompolt, 1990).

In spite of the complicated internal structure, prominences are usually modelled either in a slab or cylindrical geometry (see Priest, 1990, and references therein). Various MHD instabilities can appear in such configurations and cause the prominence eruption (Priest, 1982, 1985). An order of magnitude treatment involving only basic physical concepts provides a simple one-dimensional description of prominence equilibrium and stability, as presented by Kuperus and Van Tend (1981), Demoulin and Priest (1988), Steele and Priest (1989), or Vršnak (1990b, c). The eruption is comprehended in terms of the forces acting in a curved, current-carrying magnetic tube. The process of the eruptive instability can be preceded by some resistive 3-D instability involving reconnection within the tube, as such processes have a lower threshold (Priest, 1985). Resistive instabilities develop on a rather slow time scale. They can explain the apparent structural change from a slab to cylindrical geometry, and, moreover, the appearance of helical threads (Waddell et al., 1978). The development of such an instability can cause the initial evolution during the pre-eruptive phase, and so could be an ouverture which causes an ideal eruptive instability.

In an attempt to establish empirical criteria for the onset of an eruptive instability, we studied the internal structure in prominences, exposing patterns which we interpret as helically shaped fragments of twisted flux tubes.
Fig. 1. (a) The eruptive prominence of May 17, 1989, showing an extremely complex structure. (b) Famous eruptive prominence of December 19, 1973, exposing a very regular structure.
2. Observations

2.1. The studied sample of prominences

We have analyzed a sample of 28 prominences with fine structure patterns appearing as helical threads. The sample was selected from a larger set containing about a hundred prominences showing helical-like patterns. The main criterion was a sufficient spatial resolution which had to be at least 2". Furthermore, we chose prominences with an internal structure as simple as possible, so that helical-like patterns could be identified and the corresponding pitch angles measured. Most of the prominences were observed at Hvar Observatory and the Astronomical Observatory of Wrocław University, but we also have used material from other observatories (see Table I and Rompolt, 1975).

In Table I we list the prominences of our sample where we divided the prominences into stable (S) and eruptive (E). We introduced two additional classes for the eruptive prominences: ON – eruptive prominences at the onset of eruption, and PE – eruptive prominences in the post-acceleration phase (Table II). Some of the prominences were observed during extended periods of time, and in these cases changes in the internal structure were followed. The numbers assigned to each prominence in the first column are used for identification in Table II. The number of evaluated independent filtergrams used to follow the evolution of the prominence is denoted as \( n \). In total, we studied 49 independent filtergrams. In the last column the references for the already published cases are given. In the case of prominences No. 5, 11, and 16 we used the values determined by Tandberg-Hanssen and Malville (1974), Moore (1988), and Malville and Schindler (1981), respectively.

2.2. Classification of helical patterns

We suppose that the \( \text{H}_\alpha \) material is ‘frozen’ in the field lines, as the magnetic Reynolds number is very large and the diffusion across the field lines can be neglected on the time scale of a thread lifetime. Therefore, we assume that the \( \text{H}_\alpha \) fine structure threads outline parts of the magnetic field configuration (Vršnak, 1990a). Helical-like patterns of different classes can be found in the structure of prominences (Rompolt, 1975). In Figure 2 we present schematically a simplified classification of the most frequently observed patterns. We denote as class-A the pattern where the threads are apparently twisted around the prominence cylinder axis. Such features are common in active region prominences with small pitch angles of threads (Vršnak et al., 1988) and in dynamical dispersitio brusques of quiescent prominences (especially in the legs) when the intricate initial structure transforms into a rather simple pattern. Twisted features sometimes consist of several finer threads also resembling a helically twisted bundle. The class-B pattern is typical for huge quiescent prominences which have a sharp lower edge shaped as an arc from which a number of twisted threads extend upwards making the upper edge diffuse (see, e.g., Rompolt, 1975, 1990; Engvold, 1979). The class-C pattern is frequently observed as a ‘cross-like’ structure in the legs of quiescent as well as eruptive prominences. Finally, the class-D pattern is a helical thread which is twisted around an axis parallel, but not coinciding with, the axis of the prominence.
TABLE I
List of prominences

<table>
<thead>
<tr>
<th>No.</th>
<th>Date</th>
<th>Class</th>
<th>$n$</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>1</td>
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<td>E</td>
<td>3</td>
<td>Tandberg-Hannsen, 1974</td>
</tr>
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<td>S</td>
<td>1</td>
<td>Rompolt, 1975</td>
</tr>
<tr>
<td>3</td>
<td>29 Jan., 1957</td>
<td>S</td>
<td>4</td>
<td>Rompolt, 1975</td>
</tr>
<tr>
<td>4</td>
<td>12 Sept., 1966</td>
<td>S</td>
<td>1</td>
<td>Valniček, 1968</td>
</tr>
<tr>
<td>5</td>
<td>22 Oct., 1968</td>
<td>S</td>
<td>1</td>
<td>Tandberg-Hannsen and Malville, 1974</td>
</tr>
<tr>
<td>6</td>
<td>Nov., 1969$^a$</td>
<td>S</td>
<td>1</td>
<td>Rompolt, 1975</td>
</tr>
<tr>
<td>7</td>
<td>13 Nov., 1969</td>
<td>S</td>
<td>1</td>
<td>Rompolt, 1975</td>
</tr>
<tr>
<td>8</td>
<td>23 Nov., 1969</td>
<td>E</td>
<td>1</td>
<td>Rompolt, 1975</td>
</tr>
<tr>
<td>9</td>
<td>2 Oct., 1970</td>
<td>S</td>
<td>1</td>
<td>Rompolt, 1975</td>
</tr>
<tr>
<td>10</td>
<td>30 Aug., 1971</td>
<td>E</td>
<td>1</td>
<td>Sakurai, 1976</td>
</tr>
<tr>
<td>11</td>
<td>19 Dec., 1973</td>
<td>E</td>
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<td>Schmahl and Hildner, 1977; Moore, 1988</td>
</tr>
<tr>
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<td>S</td>
<td>1</td>
<td>Rompolt, 1975</td>
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<tr>
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<td>8 June, 1974</td>
<td>E</td>
<td>1</td>
<td>Engvold, Malville, and Rustad, 1976</td>
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<td>Vršnak and Ruždjak, 1982; Vršnak et al., 1988</td>
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<tr>
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<td>2</td>
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<td>E</td>
<td>1</td>
<td>Vršnak et al., 1988</td>
</tr>
<tr>
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<td>S</td>
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<td></td>
</tr>
<tr>
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<td>5 May, 1980</td>
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<td>House and Berger, 1987</td>
</tr>
<tr>
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<td>29 July, 1980</td>
<td>S</td>
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<td>Vršnak, 1985; Vršnak et al., 1988</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td>Rušin and Rybansky, 1982; Athay et al., 1983;</td>
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<td></td>
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<td></td>
<td>Athay and Illing, 1986; Illing and Hundhausen,</td>
</tr>
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<td></td>
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<td>1986</td>
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<td>7 Oct., 1981</td>
<td>S</td>
<td>1</td>
<td>Pant, 1984</td>
</tr>
<tr>
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<td>5 Apr., 1982</td>
<td>E</td>
<td>1</td>
<td>Zodi et al., 1988</td>
</tr>
<tr>
<td>24</td>
<td>26 May, 1982</td>
<td>S</td>
<td>1</td>
<td>Vršnak, 1984; Vršnak et al., 1988</td>
</tr>
<tr>
<td>25</td>
<td>16 Aug., 1988</td>
<td>E</td>
<td>4</td>
<td>Vršnak, 1990a, b</td>
</tr>
<tr>
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<td>11 Sept., 1988</td>
<td>E</td>
<td>1</td>
<td>Vršnak et al., 1990</td>
</tr>
<tr>
<td>27</td>
<td>23 June, 1989</td>
<td>E</td>
<td>3</td>
<td>Rompolt, 1990</td>
</tr>
<tr>
<td>28</td>
<td>15 Sept., 1989</td>
<td>E</td>
<td>1</td>
<td>Korobova, 1989; Rybansky and Noonoy, 1990</td>
</tr>
</tbody>
</table>

$^a$ Date unknown (see Rompolt, 1975; p. 59, Figure 3(a)).

$^b$ Date unknown (see Rompolt, 1975; p. 68, Figure 16).

In our study we analyzed only the prominences exposing clearly the class-A pattern. Several examples from our sample are presented in Figures 3–6 where we indicated helical-like patterns. Special attention was paid to the eruptive prominence of August 18, 1980 (Figure 3), one of the most extensively studied eruptive prominences (Ruždjak and Vršnak, 1981; Vršnak et al., 1988; Rušin and Rybansky, 1982; Athay et al., 1983; Athay and Illing, 1986; Illing and Hundhausen, 1986). Detailed observations of the magnetic field vector on August 15 and 16, are presented by Athay et al. (1983). The inferred magnetic field was predominantly horizontal, i.e., the cold prominence plasma was concentrated in the dips of the magnetic field structure. However, we would like to note that several deviations from the horizontal direction (possibly related to fine structure elements with a non-horizontal field, dynamically filled with
plasma) could be found in the results presented. One has to have in mind that the magnetic field measurements are characterized by low spatial resolution ($3.8'' \times 10''$) and long time integration (1.5–2 min) which can easily mask the transient effects of dynamical fine structures, characterized by a time scale of a few minutes (Jensen, 1990).

The magnetic field vector in the prominence was predominantly orientated at a large angle $\phi^*$ (as denoted in Athay et al., 1983) with respect to the prominence axis. It was typically between 100° and 120°, i.e., it was inclined only by 10° to 30° from the normal to the prominence axis which is usual for stable prominences (Leroy, 1989). Later it will be shown that these results are consistent with our measurements of the 'pitch angle', presented in Section 3. The azimuthal angle of the field vector was characterized by a considerable dispersion of values; the parameter $\phi^*$ was in extreme cases as low as 24° and as high as 132°. Such a dispersion could also be caused by fine structure elements which showed rather intricate patterns (Figure 3(a)). Finally, let us stress that one has to take into account the so-called ‘180° ambiguity’ in the azimuthal angle. Moreover, as the results of the magnetic field measurements depend on the reduction procedure (as well as on the applied physical assumptions), the same observations can lead to different final results (compare results by Landi Degl’Innocenti and V. Bommier presented in Athay et al., 1983).

2.3. Measurements

The measured parameters are denoted in Figure 6 where one twisted thread is indicated in Figure 6(b) by an arrow. We want to stress that the helical-like patterns usually were
Fig. 3. The eruptive prominence of August 18, 1980. (a) Pre-eruptive phase (08:01 UT): the indicated helical-like patterns were also identified in plasma motions by Rušín and Rybansky (1982). (b) Onset of the eruption (10:14 UT). (c) The phase of fast acceleration (11:32 UT): note the helical-like patterns on the right-hand side of the prominence. (d) Late phases of eruption observed by the coronagraph onboard SMM satellite (13:16 UT) showing 'relaxed' fine structure. The values of the parameter $\beta_0$ presented in Table II are extrapolated values at the edge of a cylinder assuming a uniform twist configuration.

not completely regular and they only approximately follow the ideal form. Moreover, often only a part of a prominence showed helical patterns. The prominence axis height is denoted by $h$ and the footpoint separation by $2d$. We define a normalized height as $Z = h/d$. In Figure 6(c) we present an idealized cylindrical prominence as a twisted
magnetic flux tube. The pitch angle of a helical thread is denoted by $\theta$. It is related to the radius of the ‘coil’ $r$ and the pitch length $\lambda$ as

$$\tan \theta = \frac{2\pi r}{\lambda}.$$  

(1)

We have measured the values of $d$ and $h$ on each analyzed filtergram, and approximating the shape of the axis by a circular arc, one obtains for its length:

$$l = R(\pi + 2\zeta).$$  

(2)

The parameter $\zeta$ is the angle between the solar surface and the line connecting one footpoint and the center of curvature (Figure 6(c)) and is negative if the center is below the surface. The radius of curvature of the prominence axis $R$ can be related to $h$ and $d$ as

$$R = \frac{d}{\cos \zeta} = \frac{(h^2 + d^2) / 2h}{\lambda(r) and r$, where $\theta$ is given by Equation (1).

We performed a series of independent measurements for each parameter and determined the mean value and the associated standard deviation. The largest relative standard deviations were for the pitch angles $\theta$, which were measured with an accuracy of typically 5°, although the error can amount up to 20° in cases with complicated structure (see Figure 7). Once a helical pattern of an individual thread is identified, the main source of error is the uncertainty of the prominence axis direction. We determined the direction of the prominence axis and the direction of the thread independently in each individual measurement. Measurements in active region prominences were more reliable than in the more complicated patterns appearing in quiescent and eruptive prominences.

The value of $\theta$ depends on the angle $\delta$ between the plane of the prominence and the
Fig. 5. (a) Eruptive prominence of June 4, 1946. (b) Eruptive prominence of September 15, 1989. The value of the parameter $\theta_0$ was determined by measuring the pitch length and the radius of the 'coil'.
heliographic meridian, since the pitch length projection is $\lambda = \lambda_0 \cos \delta$, while $r$ does not depend on this angle. The correction for the central meridian distance is negligible when the prominence is close to the limb. The prominences in our sample were chosen to have
a small tilt \( \delta \). To illustrate typical values of errors caused by this effect let us consider a tilt of \( 30^\circ \). The error has a maximum for \( \delta = 45^\circ \) and the measured value would be \( \delta' = 49^\circ \) which is still within the accuracy of the measurements. For, e.g., \( \delta = 80^\circ \) one finds \( \delta' = 81^\circ \), a negligible error. However, a tilt of prominences can cause a systematic increase of the \( \delta \) values and related parameters, but only within the above-mentioned limits.

A tilt of the prominence axis also affects the value of the normalized height, \( Z \), since we 'see' the footpoint separation, \( d \), in projection. For a tilt of \( \delta = 30^\circ \) the value of the parameter, \( Z \), will be apparently larger by 15%. The central meridian distance of a prominence affects the value of the parameter, \( Z \), only when the prominence footpoints are far from the limb, and so the value of the parameter, \( h \), has to be corrected for the part 'obscured' by the limb.

From the measured values of \( \delta, l, r, \) and \( d \) one can define the parameters

\[
X(r) = \tan \delta(r), \tag{4}
\]

\[
\Phi = lX/r, \tag{5}
\]

and the ratio \( \Phi/D \). These parameters are useful for comparison with predictions of various models. The parameter \( X \) is related to the projected ratio of the azimuthal and axial component of the magnetic field in the tube at a given distance from the prominence cylinder axis:

\[
X = B_{\phi}/B_{\parallel}, \tag{6}
\]

assuming that the threads follow the field lines of a cylindrically-symmetric magnetic tube. The parameter \( \Phi \) represents an effective twist of the field line, for a uniform value of the parameter \( X \) along the prominence axis. It can be related to the real twist \( \Phi_0 \) (Vršnak, 1990a) which is an important parameter, defined by the number of turns \( (N) \) of the coil as \( \Phi_0 = 2\pi N \). The value of \( \Phi_0 \) does not depend on the projection effects.

Since the pitch angle in principle depends on \( r \) (Vršnak et al., 1988) the parameters \( X \) and \( \Phi/D \) are functions of \( r \) and we define the parameters \( X_0 = Xr_0/r \) and \( \Phi/D_0 = \Phi r_0/Dr \) which correspond to the values of \( X \) and \( \Phi/D \) at the edge of the cylinder under the assumption of the uniform-twist configuration (Vršnak et al., 1988). However, most often the measured thread depicted the surface of the prominence cylinder and the value of \( r \) corresponded to the value of \( r_0 \). Finally, it is important to note that the values of the parameters were measured close to the prominence summits and not in the legs, which is essentially different from some previous studies (Engvold, Malville, and Rustad, 1976; House and Berger, 1987; Rušin, 1989).

### 3. Results

In Table II we present the measured values of the parameters \( Z, R, \) and \( \delta \). Prominences are divided according to classes and are numbered according to Table I. We marked the independent filtergrams, taken at successive times, by series of small letters in all the cases when we followed the prominence evolution.
<table>
<thead>
<tr>
<th>No.</th>
<th>Class</th>
<th>Z</th>
<th>R</th>
<th>θ (deg)</th>
<th>No.</th>
<th>Class</th>
<th>Z</th>
<th>R</th>
<th>θ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>S</td>
<td>0.32</td>
<td>0.17</td>
<td>55</td>
<td>25b</td>
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<tr>
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<td>0.35</td>
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Fig. 7. Measured values presented in the (Z, θ) plane. Dots represent stable prominences (class S), open circles the prominences at the onset of eruption (class ON), black triangles the prominences in the phase of acceleration (class E), and the squares represent prominences in the post-acceleration phase (class PE). Error bars represent standard deviations of independent measurements and are omitted if smaller than the symbols used. Dotted lines indicate the evolution of prominences, where the evolution of the prominence eruption on August 18, 1980 is indicated by (21).
Fig. 8. (a) Deduced parameters for the studied prominences presented in the plane \((Z, X_0)\). The symbols have the same meaning as in Figure 7. (b) Region of the eruptive instability onset after Vršnak (1990c).

Fig. 9. (a) Deduced parameters for the studied prominences presented in the plane \((Z, \phi/D_0)\). The symbols have the same meaning as in Figure 7. (b) Region of the eruptive instability onset after Vršnak (1990c).
The results of the measurements are presented in the plane \((Z, \phi)\) in Figure 7, where the error bars represent standard deviations of a series of independent measurements. Full circles represent stable prominences (S), open circles eruptive prominences at the onset of the instability (ON), black triangles eruptive prominences in the acceleration phase (E), and squares denote eruptive prominences in the post-acceleration phase. The thin lines connect the values corresponding to the same prominence when the values of the parameters were changing. The results presented in the planes \((Z, X_0)\), \((Z, \phi)\), and \((Z, \phi/D_0)\), are shown in Figures 8(a), 9(a), and 10(a), respectively.

Fig. 10. (a) Deduced parameters for the studied prominences presented in the plane \((Z, \phi)\). The symbols have the same meaning as in Figure 7. (b) Region of the eruptive instability onset after Vršnak (1990c).

Figures 7, 8(a), 9(a), and 10(a) disclose a systematic trend. A stable region is separated from the eruptive region by a belt filled with the prominences at the onset of the eruption, or the prominences in the post-acceleration phase. The cloud of the representatives forming this belt traces the 'hyperbolic-type' curve defined by \(Z \approx \text{const.}\) for \(0.6 < Z < 0.8\) and \(X \approx \text{const.}\) for \(Z > 1\).
4. Discussion

In Figures 8(b), 9(b), and 10(b) we present the regions in which an ideal MHD instability onset should be expected according to the simple 1-D model by Vršnak (1990c) for a wide range of parameters which can be found in prominences. The model describes the eruptive instability (Priest, 1984) in terms of forces acting at the summit of the curved prominence axis. According to this model, the threshold for the eruption depends on the parameters $X_0$ and $Z$. The eruption starts at a critical height, after a phase of slow rising motion caused either by mass loss, reconnection below the prominence, emerging or merging flux process, or by development of some internal 3-D resistive instability. The resistive instability could cause the transformation of the prominence shape from a slab to cylindrical geometry, as well as the appearance of helical threads caused by the formation of X-type and O-type helicoidal neutral lines.

Comparing Figures 8(a) and 8(b), 9(a) and 9(b), 10(a) and 10(b), one finds a good correspondence between the predicted instability region and the empirically established one. The ON-class prominences fill up the vertical branch of the instability onset area and, moreover, the PE-class prominences fill up the horizontal branch of the border between stable and unstable regions at large values of $Z$. On the other hand, stable prominences situated close to the instability-onset belt showed a significant activity and a tendency of decreasing value of the parameter $X_0$ (Vršnak and Ruždjak, 1982; Vršnak et al., 1988). Some of the prominences depicted in Figures 8(a), 9(a), 10(a) were characterized by rather large values of the parameter $X_0$ (as well as $\Phi$ and $\Phi/D_0$) but were below $\zeta_{\text{crit}}$ and were stable. Of course, they could be unstable to some resistive instability, developing on a much slower time scale. Such an instability can cause a rather slow and nonviolent evolution and can eventually lead to an eruption if the critical conditions are fulfilled. We did not find any eruptive prominence characterized by $Z < 0.6$ or $X_0 < 1$, $\Phi < 2\pi$ and $\Phi/D_0 < \pi$. A simple treatment of the forces acting at the prominence summit is consistent with this empirically established threshold for the onset of eruption and also the behaviour in the post-acceleration phase. Another important point is that the total twist $\Phi_0$ in such a model, which neglects the reconnection below, above, or within the prominence, remains constant through the eruption. Several reported observations (Engvold, Malville, and Rustad, 1976; House and Berger, 1987; Vršnak, 1990a) indicated such a behaviour.

5. Conclusion

The basic assumption of this study is that the twisted Hα patterns in the internal structure of the prominences studied really reveal elements of helical structure and cylindrical geometry. So, one should keep in mind that the measured parameter $\zeta$ has the meaning of a pitch angle only if this assumption holds. However, even if the observed twisted patterns appear due to some other kind of configuration (e.g., the one proposed by Hirayama, 1985), $\zeta$ still has a physical meaning which is supported by the systematic trend in the results (Figure 7).
Although the accuracy of the measurements is limited by several factors described in Section 2.3, the results presented in the plane \((Z, \theta)\) reveal a clear distinction between parameters describing stable and unstable prominences. The ON and PE prominences occupy the corridor between stable and eruptive prominences, indicating critical values of the parameters \(X_0\) and \(Z\). In the case of the prominence of August 18, 1980 we followed the changes of the internal structure from the onset of eruption till the late phases of eruption. The main characteristic of the eruption was ‘detwisting’, i.e., decrease of the parameter \(\theta_0\). However, no change of the total twist could be detected within the accuracy of measurements (Figure 10(a)). The coronograph observations reveal a further ‘relaxation’ of the internal structure in the late phases of eruption (Figure 3(d)). The measured value of the parameter \(\theta_0\) at the onset of the eruption was about 70°, i.e., some 20° from the normal to the prominence axis. This is consistent with the magnetic field measurements in the pre-eruptive phase (Athay et al., 1983) as the field vector was inclined by only 10°–30° from the normal to the prominence axis.

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References

THE INTERACTION EFFECT OF FAST AND SLOW SOLAR WIND STREAMS IN INTERPLANETARY SPACE ON WIND CHARACTERISTICS AT THE EARTH’S ORBIT

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Abstract. By analyzing observational data, it has been possible to determine quantitative relationships that represent the role of the interaction of fast and slow solar wind (SW) streams in the formation of characteristic SW properties at the Earth’s orbit.

It is shown that maximum values of magnetic field $B^M$ and density $n^M$ peaks in the neighbourhood of the sector boundary (SB) at the base of the high-speed stream front are associated with solar wind characteristics such as the SW minimum velocity near the SB, $V_m$, the maximum velocity in the central part of the fast stream, $V_M^f$, and the slope $\beta$ of the magnetic field neutral line to the solar equatorial plane at $R = 2.5 R_\odot$ ($R_\odot$ is the solar radius).

It is concluded that enhancements of absolute values of the z-component of the magnetic field, $|B_z|$, recorded at the Earth’s orbit, are largely attributable, at sufficiently large values of $\beta$, to the interaction of different-velocity SW streams.

1. Introduction

Substantial progress might be anticipated as regards the understanding of the formation of peculiarities of solar wind (SW) quasi-stationary streams which are recorded at the Earth’s orbit, provided that it will become possible to separate the influence of the processes accompanying the SW acceleration near the Sun (at distances of up to 20 solar radii) and the subsequent SW evolution in interplanetary space.

A typical feature of the time variation of parameters of quasi-stationary SW streams at $R = 1$ AU is the regular increase of the particle density $n$ and magnetic field $B$ in the neighbourhood of sector boundaries (SB) with maxima $n$ at the base and $B$ approximately in the middle of the velocity front $V(t)$ of a fast SW stream as well as the relatively steep frontonts and extended backfronts on $V(t)$-profiles (King, 1983, 1986).

There are different views of the nature of such a SW structure at the Earth’s orbit. Almost immediately after the detection of long-lived solar wind streams made by the Mariner 2 spacecraft in 1962, such a behaviour of $n$, $B$, and $V$ near the Earth was regarded as a consequence of the arising (due to the solar rotation) interaction of SW plasma flows propagating in interplanetary space with different velocities (Parker, 1963; Snyder and Neugebauer, 1964; Dessler, 1967). There emerged various quantitative models for such an interaction (Carovillano and Siscoe, 1972; Siscoe and Finley, 1969, 1970; Matsuda and Sakurai, 1972; Pizzo, 1982). These models all lent support to the view that the observed SW structure at the Earth’s orbit can be determined by the SW evolution in interplanetary space.

According to an alternative approach based on analyzing experimental data,
increased values of \( n \) and \( B \) observed at the Earth’s orbit in the slow wind region merely reflect the variation of these parameters in the corona near the Sun. Borrini et al. (1981), by analyzing helium and hydrogen SW structures, identified two classes of events. In some cases density peaks in the neighbourhood of sector boundaries lie in the region of weak changes of plasma velocity before the velocity of the nearest fast SW stream begins to increase. This class of events was referred to by the authors as ‘stream-free’, and they suggested that in this case the observed SW density peaks are carried to the Earth’s orbit from the solar corona. In other cases (‘stream-associated’ events) when density peaks were located at the base of high speed flows in the region of increasing velocity, Borrini et al. (1981) did not negate the role of the interaction of fast and slow SW streams for the formation of such a wind structure. Eselevich and Filippov (1988), by analyzing SW parameter measurements obtained at distances \( 1 \text{ AU} > R > 0.3 \text{ AU} \) by the HELIOS spacecraft, also arrived at the conclusion that the density and magnetic field enhancements in the region of the heliospheric current sheet (HCS) are attributable to coronal streamers with increased values of \( n \) and \( B \) propagating into interplanetary space. These conclusions are also supported by the hypothesis reported by Gosling et al. (1978) that such a structure in the vicinity of the sector boundary as an ‘interface’ extends earthward from the solar corona.

Calculations made by Kaigorodov and Fainshtein have shown that both the carrying away of the characteristic features in the plasma parameter distribution from the solar neighbourhoods as far as the Earth’s orbit and the interaction of fast and slow solar wind streams in interplanetary space are able to make a comparable contribution to the formation of the SW structure observed at the Earth’s orbit. In this case the effectiveness of such an interaction depends substantially on the character of the distribution of \( n \), \( B \), and \( V \) in the vicinity of the Sun.

So far, there is no direct experimental evidence for the decisive role of the interaction of different-velocity SW streams for the formation of the SW structure at \( R = 1 \text{ AU} \). Therefore, the search of such facts as well as of indirect experimental evidence in favour of the effectiveness of such an interaction remains a challenging problem.

Recently, Eselevich and Fainshtein have demonstrated that there exists a high correlation between maximum values of density and magnetic field in the vicinity of the sector boundary at \( R = 1 \text{ AU} \) and characteristics such as the neutral line (NL) slope of the magnetic field on the source surface \( (R = 2.5 R_{\odot}) \) to the solar equatorial plane and azimuthal gradients \( \partial V/\partial \phi \) at points \( n^M \) and \( B^M \) at \( R = 1 \text{ AU} \). These dependences can be regarded as supporting the existence of an effective interaction of different-velocity SW streams in interplanetary space.

This paper continues the study of experimental data that characterize the interaction effect of fast and slow solar wind streams on its properties at the Earth’s orbit. An attempt is made to intercompare these data with simplified physical models for the solar wind evolution in interplanetary space.
| No. | Date      | \(B^M\) | \(n^M\), \(\text{cm}^{-3}\) | \(B^M\), \(\gamma\) | \(V^M\), \(\text{km s}^{-1}\) | \(V^M/V^M\), \(\text{km s}^{-1}\) | \(\beta\), \(\text{deg}\) | \(T_r(n^M) \times 10^{-3}, \text{K}\) | \(T_r(B^M) \times 10^{-3}, \text{K}\) | \(V(n^M), \text{km s}^{-1}\) | \(V(B^M), \text{km s}^{-1}\) | \(|B_z|^M\), \(\gamma\) |
|-----|-----------|---------|-----------------|------------------|------------------------|------------------------|----------------|-----------------------------|-----------------------------|------------------|------------------|-----------------|
| 1   | 22 Dec.   | 36.5    | 17.2            | 320              | 490                    | 1.53                   | 51            | 213                         | 337                         | 369              |                   |                 |
| 2   | 19 Jan.   | 39.8    | 17.9            | 340              | 510                    | 1.5                     | 31            | 234                         | 346                         | 489              |                   |                 |
| 3   | 6 Mar.    | 27.9    | 17.9            | '320'            | 470                    | 1.47                    | 218           | 318                         | 425                         | 480              |                   |                 |
| 4   | 19 Mar.   | '56.8'  | 21.8            | 360              | 770                    | 2.13                    | 55            | 346                         | 355                         | 594              |                   |                 |
| 5   | 23 July   | 39.6    | 12.4            | 360              | 510                    | 1.42                    | 55            | 174                         | 389                         | 418              |                   |                 |
| 6   | 28 May    | 35.1    | 12              | 330              | 490                    | 1.48                    | 33            | 249                         | 349                         | 500              |                   |                 |
| 7   | 10 June   | 30.5    | 19.1            | 370              | 760                    | 2.05                    | 199           | 619                         | 542                         | 569              |                   |                 |
| 8   | 22 Aug.   | 26.2    | 10.9            | 380              | 570                    | 1.5                     | 60            | 60                          | 407                         | 407              |                   |                 |
| 9   | 26 July   | 30.4    | 19.3            | 430              | '630−770'              | 1.67                    | 130           | 395                         | 449                         | 574              |                   |                 |
| 10  | 20 Aug.   | 38.9    | 9.5             | 300              | 440                    | 1.47                    | 36            | 36                          | 333                         | 333              |                   |                 |
| 11  | 15 Sep.   | 21.8    | 10.5            | 335              | 570                    | 1.7                     | 264           | 301                         | 421                         | 445              |                   |                 |
| 12  | 5 Nov.    | '32.9'  | 10.4            | '320−350'        | 580                    | 1.73                    | 38            | 177                         | 349                         | 427              |                   |                 |
| 13  | 13 Nov.   | 20.7    | 10.4            | 370              | 480                    | 1.3                     | 39            | 150                         | 385                         | 454              |                   |                 |
| 14  | 24 Nov.   | 26.7    | 18.2            | 330              | '700'                  | 2.12                    | 100           | 230                         | 412                         | 475              |                   |                 |
| 15  | 28 Dec.   | '22.5'  | 11.9            | 400              | '580'                  | 1.45                    | 234           | 112                         | 499                         | 436              |                   |                 |

**December 1972–1973**

<p>| No. | Date      | (B^M) | (n^M), (\text{cm}^{-3}) | (B^M), (\gamma) | (V^M), (\text{km s}^{-1}) | (V^M/V^M), (\text{km s}^{-1}) | (\beta), (\text{deg}) | (T_r(n^M) \times 10^{-3}, \text{K}) | (T_r(B^M) \times 10^{-3}, \text{K}) | (V(n^M), \text{km s}^{-1}) | (V(B^M), \text{km s}^{-1}) | (|B_z|^M), (\gamma) |
|-----|-----------|---------|-----------------|------------------|------------------------|------------------------|----------------|-----------------------------|-----------------------------|------------------|------------------|-----------------|
| 16  | 15 Jan.   | 18.5    | 14.7            | 390              | 665                    | 1.7                     | 98            | 216                         | 466                         | 543              |                   |                 |
| 17  | 25 Jan.   | 67      | 25.2            | 315              | 760                    | 2.4                     | 366           | 587                         | 422                         | 534              |                   |                 |
| 18  | 21 Mar.   | '13.4'  | 13.4            | 590              | 750                    | 1.27                    | '343'         | '343'                       | '383'                       | '582'            |                   |                 |
| 19  | 18 Apr.   | 30.6    | 14.8            | 300              | '500'                  | 1.67                    | 41            | 57                          | 328                         | 394              |                   |                 |
| 20  | 3 May     | '25.7'  | 15.8            | 420              | 585                    | 1.38                    | 134           | 184                         | 420                         | 527              |                   |                 |
| 21  | 31 May    | 21      | 19.8            | 370              | 760                    | 2.05                    | 113           | 450                         | 501                         | 628              |                   |                 |
| 22  | 23 July   | '56.9'  | 22.3            | 330              | 810                    | 2.45                    | 92            | 412                         | '458'                       | 604              |                   |                 |
| 23  | 19 Aug.   | 40.9    | '16.4'          | '330−350'        | 630                    | 1.78                    | '54−103'      | 103                         | 405                         | '348'            |                   |                 |
| 24  | 29 Aug.   | 36.4    | 10.6            | 430              | 560                    | 1.3                     | 59            | 71                          | 494                         | 483              |                   |                 |
| 25  | 24 Oct.   | 59.7    | '17.5'          | ?                | 320                    | 1.2                     | 238           | 99                          | 447                         | 465              |                   |                 |
| 26  | 7 Dec.    | 34.9    | 9.0             | 360              | 430                    | 1.2                     | 29            | 82                          | 370                         | 398              |                   |                 |
| 27  | 17 Dec.   | '34.8'  | 14              | '500'            | '670'                  | 1.34                    | 37            | 122                         | 402                         | 510              |                   |                 |
| No. | Date   | $B^M$, cm$^{-3}$ | $n^M$, $B^M$, $\gamma$ | $V_m$, km s$^{-1}$ | $V_M$, km s$^{-1}$ | $V_M/V_m$ | $\beta$, deg | $T_p(n^M) \times 10^{-3}$, K | $T_p(B^M) \times 10^{-3}$, K | $V(n^M)$, km s$^{-1}$ | $V(B^M)$, km s$^{-1}$ | $|B_\perp|^M$, $\gamma$ |
|-----|--------|------------------|-----------------|-------------------|------------------|-----------|--------|-----------------|-----------------|----------------|----------------|----------------|
| 28  | 13 Jan. | 25.5             | 14.2            | 480               | '650'            | 1.35      |        | 146             | 120             | 429            | 483            | 7.7            |
| 29  | 10 Feb. | 38.3             | '14.1'          |                   |                  |           |        | 41              | 156             | 467            | 430            | 6.3            |
| 30  | 27 May  | 41.9             | 10.2            | 390               | 470              | 1.21      |        | 82              | 165             | 368            | 500            | 8.1            |
| 31  | 12 June | 21.5             | 14.4            |                   |                  |           |        | 82              | 165             | 368            | 500            | 8.1            |
| 32  | 20 Aug. | 28.7             | '12.1'          | '330'             | '600'            | 1.82      |        | 55              | '49–155'        | 398            | 411            | 7.8            |
| 33  | 27 Sep. | 28.8             | 11.3            | 380               | 530              | 1.39      |        | 19              | 165             | 368            | 500            | 8.1            |
| 34  | 29 Nov. | 37               | 19.9            | 320               | '720'            | 2.24      |        | 45              | 250             | 350            | 446            | 7.2            |</p>
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Table I(a) (continued)

| No. | Date      | \( n^M \), \( \text{cm}^{-3} \) | \( B^M \), \( \gamma \) | \( V_m \), \( \text{km s}^{-1} \) | \( V_M \), \( \text{km s}^{-1} \) | \( V_M/V_m \) | \( \beta \), deg | \( T_p(n^M) \times 10^{-3} \), K | \( T_p(B^M) \times 10^{-3} \), K | \( V(n^M) \), \( \text{km s}^{-1} \) | \( V(B^M) \), \( \text{km s}^{-1} \) | \( |B_z|^M \), \( \gamma \) |
|-----|-----------|------------------|--------------|-----------------|-----------------|-------------|---------|-----------------|-----------------|-----------------|-----------------|-----------------|---------|
| 52  | 3 Aug.    | 43.4             | 13           | '207'           | '450'           | 1.67        | 75      | 27              | 83              | 326             | 365             | 8.4    |
| 53  | 25 Aug.   | 33.9             | 9.6          | 300             | 365             | 1.22        | 25      | 14              | 86              | 306             | 339             | 7.6    |
| 54  | 18 Oct.   | 42.7             | 15.8         | 345             | 470             | 1.36        | 47      | 62              | 99              | 388             | 393             | 9.7    |
| 55  | 18 Dec.   | 46               | 24.8         | 385             | '670'           | 1.74        | 73      |                 |                 |                 |                 |        |
|     |           |                  |              |                 |                 |             |         |                 |                 |                 |                 |        |
| 1979|           |                  |              |                 |                 |             |         |                 |                 |                 |                 |        |
| 56  | 21 Apr.   | 30.2             | 14.7         | 330             | 520             | 1.58        | 88      | 22              | 154             | 336             | 407             | 10.6   |
| 57  | 5–6 May   | 14.4             | 10.6         | 300             | 420             | 1.4         | '80'    | 61              | ?               | 344             | 341             | 8      |
| 58  | 18 May    | 19.2             | 10.2         | 355             | 450             | 1.27        | 77      | 21              | 86              | 355             | 385             | 8.7    |
| 59  | 15 June   | 22.9             | 9.1          | 340             | 470             | 1.38        | 63      | 22.9            | 26              | 341             | 416             | 6.9    |
| 60  | 13 July   | 22.8             | 13.1         | 330             | 520             | 1.58        | 70      | 57              |                 | 371             |                 | 8.7    |
|     |           |                  |              |                 |                 |             |         |                 |                 |                 |                 |        |
| 1980|           |                  |              |                 |                 |             |         |                 |                 |                 |                 |        |
| 61  | 25 Apr.*  | 26.7             | 8.2          | 300             | 340             | 1.13        | 45      | 30              | 48              | 308             | 309             | 7.2    |
| 62  | 5 May     | 22.5             | 8.8          | 315             | 380             | 1.21        | 79      | 20              | 21              | 341             | 347             | 6      |
| 63  | 11 July   | 13.7             | 9.8          | 340             | 465             | 1.37        | 55      | 14              | '83'            | 339             | '400'           | 5.1    |
|     |           |                  |              |                 |                 |             |         |                 |                 |                 |                 |        |
| 1981|           |                  |              |                 |                 |             |         |                 |                 |                 |                 |        |
| 64  | 26 Jan.   | 30               | 9.5          | 340             | 440             | 1.29        | 53      | 36              | 41              | 358             | 370             | 6      |
| 65  | 23 Feb.   | '32'             | '12.8'       | 310             | 410             | 1.32        | 80      | 61              | 117             | 350             | 404             | 8      |
| 66  | 15 June   | 28.8             | '10'         | '300'           | 400             | 1.33        | 71      | 29              | 35              | 322             | 322             | 5.9    |
| 67  | 11 July   | 63.2             | 14.5         | 315             | '460'           | 1.6         | 63      | 30              | 61              | 341             | 365             | '7.8'  |
| 68  | 3 Sep.    | 28               | 15           | 320             | '455'           | 1.58        | 73      |                 |                 |                 |                 | '11'   |
| 69  | 29 Sep.   | 38               | 16.5         | 300             | 480             | 1.6         | 68      |                 |                 |                 |                 | '8'    |
| 70  | 8 Oct.    | 29.2             | 13           | 360             | 490             | 1.38        | 63      | 36              | 54              | 373             | 381             | 10.6   |
|     |           |                  |              |                 |                 |             |         |                 |                 |                 |                 |        |
| 1982|           |                  |              |                 |                 |             |         |                 |                 |                 |                 |        |
| 71  | 25 Feb.   | 39.1             | '17'         | 380             | 650             | 1.71        | 62      | 14              | '59'            | 374             | '400'           | 11     |
| 72  | 9 May     | 29.6             | 9.4          | 310             | 400             | 1.32        | 52      | '40'            | '40'            | 330             | 339             | 8.5    |
| 73  | 28 Aug.   | 46               | 11.9         | 415             | 560             | 1.35        | 58      | 38              | '152'           | 416             | 439             | '8'    |
Table 1(a) (continued)

| No. | Date   | \(B^M\), cm\(^{-3}\) | \(n^M\), \(\gamma\) | \(V_m\), km s\(^{-1}\) | \(V_M\), km s\(^{-1}\) | \(V_M/V_m\) | \(\beta\), deg | \(T_p(n^M) \times 10^{-3}\), K | \(T_p(B^M) \times 10^{-3}\), K | \(V(n^M)_,\) km s\(^{-1}\) | \(V(B^M)_,\) km s\(^{-1}\) | \(|B_z|^M\), \(\gamma\) |
|-----|--------|---------------------|-------------------|------------------|------------------|----------------|-------------|------------------|------------------|------------------|------------------|------------------|
| 1983|        |                     |                   |                  |                  |                |             |                  |                  |                  |                  |                  |
| 74  | 18 Mar. | 12.6                | 11.6              | 430              | 580              | 1.35           | 68          | 53               | 103              | 454              | 539              | 7.2              |
| 75  | 24 Apr. | 74.1                | 19.4              | 355              | 600              | 1.69           | 88          | 75               | 362              | 487              | 560              | '11.5'           |
| 76  | 21 May  | '25'               | '19.3'            | 370              | '700'            | 1.89           | 78          | '29'             | '462'            | '462'            | '15.5'           |                  |
| 77  | 17 June | 13.9?               | 13.4              | 500?             | '650'            | 1.3            | 88          | 197              | 163              | 511              | 578              | 6                |
| 78  | 24 July | 21.4                | 18.2              | 415              | 560              | 1.35           | 88          | 166              | 162              | 412              | 420              | 12.5             |
| 79  | 29 July | '71.1'             | '19.5'            | 350              | 640              | 1.83           | 73          | 65               | 81               | 385              | 390              | 15.8             |
| 80  | 8 Sep.  | '50.7'             | 17.7              | 350              | 560              | 1.6            | 71          | '49'             | '35'             | 388              | '417'            | '11.5'           |
| 81  | 24 Sep. | 26                 | 17.1              | '315'            | 680              | 2.15           | 53          | 82               | 206              | 398              | 493              | 11.2             |
| 82  | 4 Oct.  | 38.4                | 23.6              | 370              | 530              | 1.43           | 82          | 36               | 30               | 382              | 384              | 16.9             |
| 83  | 28 Oct. | 58                 | '21.3'            | 300              | 570              | 1.9            | 75          | 40               | 92               | 354              | 379              | 14.4             |
| 84  | 2 Nov.  | '32'               | 24                | 360              | 660              | 1.83           | 63          | '268'            | '268'            | '438'            | '438'            | '438'            | 10.3             |
| 85  | 25 Nov. | 29.6                | 11.7              | 350              | 480              | 1.37           | 68          | 45               | 78               | 348              | '396'            | 6.2              |
| 86  | 12 Dec. | 15.8                | '14'              | 450              | 700              | 1.55           | 45          | 77               | '376'            | 458              | '558'            | 9.7              |

Column 1 – event number; 2 – date of maximum value of magnetic field peak; 3 – amplitude of density peak, \(n^M\); 4 – amplitude of magnetic field peak, \(B^M\); 5 – averaged minimum SW velocity in the sector boundary region, \(V_m\); 6 – averaged solar wind velocity in the central part of the fast stream, \(V_M\); 7 – value of the ratio \(V_M/V_m\); 8 – slope of the magnetic field neutral line to the solar equatorial plane at \(R = 2.5 R_\odot\) (Hoeksema and Scherrer, 1986); 9 – proton temperature at the top of the magnetic field peak; 11 – solar wind velocity at the top of the density peak; 12 – solar wind velocity at the top of the magnetic field peak; 13 – maximum value of the modulus of the \(z\)-component of the magnetic field in the neighbourhood of the sector boundary.

'\(P\)' – there is an uncertainty as regards the determination of the value of the parameter as a consequence of a data gap and for some other reasons. \(l(g)\) – histogram of distribution of events with different \(B^M\) in the range of velocities \(V(B^M) < 420\) km s\(^{-1}\). The arrows indicate the mean values of parameters determined from histograms.
TABLE I(b)

Horizontal heliospheric current sheet

<table>
<thead>
<tr>
<th>No.</th>
<th>Dates of central meridian plane passage by the horizontal portion of the neutral line at $R = 2.5 R_\odot$</th>
<th>Date of magnetic field maximum at $R = 1$ AU</th>
<th>$n$, cm$^{-3}$</th>
<th>$B$, $\gamma$</th>
<th>$T_p(n) \times 10^{-3}$, K</th>
<th>$T_p(B) \times 10^{-3}$, K</th>
<th>$V(n)$, km s$^{-1}$</th>
<th>$V(B)$, km s$^{-1}$</th>
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Column 1 – event number; 2 – date of central meridian passage by the horizontal portion of the neutral line at $R = 2.5 R_\odot$; 3 – date of magnetic field maximum in the region of the horizontal current sheet at the Earth's orbit; 4 – amplitude of density peak; 5 – amplitude of magnetic field peak; 6 – proton temperature at the top of the density peak; 7 – proton temperature at the top of the magnetic field peak; 8 – SW velocity at the top of the density peak; 9 – SW velocity at the top of the magnetic field peak.

2. Data

Our analysis has used the following data:

- characteristics of a quasi-stationary solar wind immediately before the passage ($\sim 1–2$ days) and during several days after the Earth had intersected the sector boundary during 1973–1983 (King, 1977, 1983, 1986). The events chosen for the analysis are presented in Table I(a);

- characteristics of a slow solar wind for periods when the Earth moved at small angles to the sector boundary located nearly horizontally (i.e., parallel to the solar
equatorial plane), deviating from it by an angular distance in excess of 5–7 (King, 1977, 1983), Table I(b). The selection rules for such events will be discussed below;

- solar wind parameters at distances of $0.3 \text{ AU} < R < 1 \text{ AU}$ according to the Helios spacecraft measurements for 1975–1976 (Burlaga et al., 1978).

When choosing events for the analysis (Tables I(a) and I(b)), the following factors were taken into account:

- during the time intervals considered, strong shock waves were not recorded near the Earth, and sudden storm commencements (SSC) were not observed on the ground;
- the sector boundary, as it was traversed by the Earth, was clearly observed, i.e., fluctuations of the magnetic field direction were absent; and
- events with considerable data gaps which made their analysis difficult, were not considered.

The events presented in Table I(b) were selected in the following way. From the catalogue by Hoeksema and Scherrer (1986) we took a nearly horizontal (parallel to the solar equatorial plane) NL portion located at the angular distance $< 5–7^\circ$ from the ecliptic plane, within which the angle $\beta$ between the line tangent to NL and the solar equatorial plane did not exceed $\sim 10^\circ$ (except for event No. 14 from Table I(b), where $\beta < 20^\circ$, whose inclusion in Table I(b) was justified by the behaviour $n(i), B(i)$, and $V(i)$ at $R = 1 \text{ AU}$).

Boundaries of the chosen portions of the NL were compared with those of corresponding slow wind portions at the Earth’s orbit through the relationships:

$$t_E = t_S + 4.5 \text{ days},$$

where $t_S$ is the moment of central meridian plane passage by the NL boundary point, and $t_E$ is the moment of passage by the Earth of the corresponding slow wind boundary at $R = 1 \text{ AU}$. On some occasions the values of $t_E$ determined in this way were corrected whenever the calculated time intervals near the Earth involved portions of the heliospheric current sheet preceding the passage of high speed SW streams, or the high-speed streams themselves. Within the boundaries of the horizontal portions of the heliospheric current sheet region, several peaks of $n^M$ and $B^M$ presented in Table I(b) were taken for the analysis.

And finally, in the analysis of observational data made below, some results of the analysis were compared with results of calculations of the coronal magnetic field (potential-field approximation). These calculations used synoptic maps of the magnetic field measured in the line of sight obtained at the Stanford observatory and usually published in Solar Geophysical Data.

3. Results

The interaction of fast and slow solar wind streams caused by the solar rotation must have the least effect on SW characteristics in the case of the horizontal location of the HCS (Eselevich and Fainshtein, 1990). Therefore, by comparing plasma parameters at $R = 1 \text{ AU}$ in the region of horizontal HCS portions (to which, as mentioned above, at
Fig. 1. Histograms of solar wind parameter distributions at the Earth's orbit in the neighbourhood of the sector boundaries. (I) In the absence of the interaction of fast and slow solar wind streams in the neighbourhood of horizontal portions of the sector boundaries. (II) In the region of interaction of solar wind streams of different velocities in the neighbourhood of inclined portions of the sector boundaries. $B^M$, $n^M$ – maximum values of peaks of magnetic field and of proton density at the front of a SW fast stream; $T_p(B^M)$, $T_p(n^M)$, is the proton temperature in the region with $B = B^M$ and $n = n^M$, respectively; $V(B^M)$ and $V(n^M)$ are the solar wind velocities in the region with $B = B^M$ and $n = n^M$. Ilg – histogram of distribution of events with different $B^M$ in the range of velocities $V(B) < 420 \text{ km s}^{-1}$. The arrows indicate the mean values of parameters determined from histograms.
$R = 2.5 R_\odot$ there correspond the slopes between the lines tangent to the NL and the solar equatorial plane $\beta < 10^\circ$) with SW parameters in the neighbourhood of the sector boundaries, to which NL portions with $\beta > 10^\circ$ correspond, it becomes possible to estimate the interaction effectiveness of SW streams of different velocities at the Earth's orbit. Such a comparison is made possible by Figure 1(I, II), showing the histograms of distributions of the various parameters in the region of the horizontal and inclined HCS. By analyzing this figure, one is led to draw the following conclusions:

- regions of the horizontal heliospheric current sheet as compared with that inclined to the solar equatorial plane are characterized, on the average, by lower values of $n^M$, $B^M$ (by a factor of 2) and of ion temperature $T_p$ at points, where (by a factor of 2) and $B = B^M$ (by a factor of 4) and by solar wind velocities at these points (here $n^M$ and $B^M$ are maximum values of magnetic field density peaks);

- for the inclined HCS, almost all histograms clearly show maxima in the distribution of events and a gradual decrease toward the region of the increasing parameter which was used to construct the histogram.

The histogram in Figure 1(II, g) gives an answer to the question: the conclusions formulated above after if the horizontal HCS is compared only with events in the inclined HCS, for which values of SW velocity at points $n^M$ and $B^M$ lie within the range of velocity variation in the horizontal HCS, i.e., for $V(B) < 420$ km s$^{-1}$. One can see that in this case the conclusions arrived at above remain qualitatively the same, although the $N(B^M)$ - distribution itself is deformed and the value of $B^M$, $\langle B^M \rangle$ average for this distribution, decreases.

Let us now consider the events related only to the inclined HCS which are supposed to carry information on the interaction of fast and slow SW streams. Many details of such an interaction can be understood if one establishes the relationship between the SW parameters which are determined by such an interaction (for example, $n^M$ and $B^M$) and by solar wind characteristics which change little in interplanetary space. Such characteristics are, for example, the minimum velocity between two high-speed streams in the region of the heliospheric current sheet $V_m$ and the maximum velocity $V_M$ in the central part of the contiguous high-speed stream that interacts with this HCS. The weak variation of $V_m$ and $V_M$ in the process of evolution of the solar wind in interplanetary space follows from numerous calculations of such an evolution (see Matsuda and Sakurai, 1972; Kaigorodov and Fainshtein, 1990). Besides, according to measurements aboard the Helios spacecraft during 1975–1976 (Schwenn, Muhlhauser and Marsch, 1978), the solar wind velocity changes little throughout the range of variation at distances $R = 0.3$–1.0 AU. A further SW characteristic that varies little in interplanetary space is the angle between the heliospheric current sheet and the solar equatorial (SE) plane in the HCS vicinities. Near the Sun, at $R = 2.5 R_\odot$ this angle coincides with the neutral line slope to the SE plane. The closeness of the value of $\beta$ at the Earth’s orbit to the value of $\gamma$ obtained by calculating the magnetic field in the corona (Hoeksema and Scherrer, 1986) is shown in a paper by Eselevich and Filippov (1988).

It will be shown here that the interaction effectiveness of different-velocity streams can depend on different combinations of $V_m$ and $V_M$: $V_M/V_m$, $V_MV_m/(V_M - V_m)$.
\( V_M - V_m \). Note that, in practice, values of \( V_m \) and \( V_M \) were determined using data reported by King (1977, 1983, 1986) by averaging \( V(t) \) over fast (with a typical period \( T < 10 \) hr) SW velocity variations. In view of the role of the subjective factor in such a procedure, the accuracy of determining \( V_m \) and \( V_M \) in this case did not exceed \( \sim 20 \) km s\(^{-1}\).

![Graph showing dependence of \( B^M \) on \( \beta \) for the greatest values of \( V_M/V_m > 1.7 \) (a) and for the smallest values of \( V_M/V_m < 1.3 \) (b).](image)

Figure 2 shows the dependence of \( B^M \) on \( \beta \) for the smallest values of \( V_M/V_m < 1.3 \) and for the largest values of \( V_M/V_m > 1.7 \). It is evident that at small values of \( V_M/V_m \) the value of \( B^M \) depends little on the angle \( \beta \), and at the greatest values of \( V_M/V_m \) such a dependence exists. Points with intermediate values of \( V_M/V_m \), not shown in Figure 2, fill the 'space' between the two sets of points, characterizing curves (a) and (b).

By analyzing the data from Table I(a), it is easy to see that almost the same events form the (same as in Figure 2) dependences of \( B^M \) on \( \beta \) for the largest values of \( V_M - V_m > 200 \) km s\(^{-1}\), \( (V_M V_m/(V_M - V_m))^{-1} > 1/(900 \) km s\(^{-1}\)\) and for the smallest values of \( V_M - V_m < 100 \) km/s, \( (V_M V_m/(V_M - V_m))^{-1} < 1/(1650 \) km s\(^{-1}\)\). There exists also a correlation between \( B^M \) and \( V_M/V_m((V_M - V_m), V_M V_m/(V_M - V_m)) \). On the average, with an increase of these parameters, the value of \( B^M \) increases. This is evident, for example, from Figure 3(a), showing the dependence of \( B^M \) on \( V_M/V_m \) as well as from Figure 3(b) which presents the relationship of \( B^M \) with \( (V_M - V_m) \) for the events from Table I with \( \beta > 55^\circ \) for the period 1976–1983. If events with higher values of \( \beta > 70^\circ \) are chosen, this does not decrease substantially the spread of points.

Similar dependences can also be constructed for \( n^M : n^M = n^M(\beta, P) \), where \( P \) is one of the combinations of \( V_M \) and \( V_m \) considered above. These dependences are not given here in order not to congest the paper with figures. Qualitatively, they are similar to the dependence \( B^M(\beta, P) \) but are characterized by a larger spread of points.
Fig. 3. The relationship of $B^M$ with $V_M/V_m$ (a) and $V_M - V_m$ (b) for events with $\beta > 55^\circ$ (●, ◆) and $\beta > 70^\circ$ (○).
From Figures 1–3, hence, it follows that the value of \( B \) at the Earth's orbit near the sector boundary is determined, to a significant extent (and for large values of \( \beta \) and \( P \), mainly), by the interaction of fast and slow SW streams in interplanetary space.

This conclusion permits us to come close to ascertaining the physical nature of the enhancement of the \( z \)-component of the magnetic field \( (B_z) \) which is usually recorded in the vicinity of the sector boundary near the peaks of magnetic field \( B^M \) and plays an important role in the process of energy exchange between the solar wind and the magnetosphere.

![Diagram](image)

Fig. 4. The relationship of the maximum value of the modulus of the \( z \)-component of the magnetic field in the neighbourhood of the sector boundary with the value of \( B^M \): \( \bullet - \beta > 70^\circ; \) \( \bullet - 55 \leq \beta < 70^\circ; \) \( \bullet - 10^\circ \leq \beta < 55^\circ \).

From Figure 4 it is evident that between \( B^M \) and \( |B_z| \) there exists a relatively high correlation on the average, with increasing \( B^M \), there is an increase of the maximum value of \( |B_z|^M \) in the vicinity of the sector boundary. In this case, to events with \( B_z \) there correspond events with predominance of both \( B_z > 0 \) and \( B_z < 0 \) (Figure 4 is constructed according to data from King (1977, 1983, 1986)). Circles in Figure 4 indicate events with \( \beta > 70^\circ \). It is evident that in this case the spread of points decreases slightly.

Thus, from Figure 4, in view of Figures 1–3, it follows that the value of \( B_z \) near the sector boundary at \( R = 1 \) AU is also determined by the interaction of SW streams of different velocities.

It is known that the predominant sign of \( B_z \) in the sector boundary region (along with
the value of $|B_z|$ plays an important role in the process of energy input from the solar wind to the magnetosphere. Periods, during which near the Earth $B_z < 0$, are usually more geoeffective than those with $B_z > 0$. As opposed to the amplitude, the predominant direction of $B_z$ in the vicinity of the sector boundary seems to be determined by the situation near the Sun.

$$B_{2,1,0}^M, x$$

\[ -26 -22 -18 -14 -10 -6 -2 2 6 10 \]

\[ B_{1}^M, \text{ rel. un.} \]

Fig. 5. The correspondence between the greatest peak of $|B_z|^M$ near the sector boundary at the Earth's orbit and the components of the calculated magnetic field at the distance $R = 1.8 R_\odot$ ($R_\odot$ is the solar radius).

- $\triangle - B_\perp^M = B_\odot$;
- $\times - B_\perp^M = B_\odot$;
- $\bullet - B_\perp^M = B_\odot + B_\odot$.

Figure 5 shows a correspondence between the value and sign of the largest peak of the $B_z$-component after the sector boundary passage by the Earth and the values of $B_\theta$, $B_\phi$, and $B_\theta + B_\phi$, determined by calculating the magnetic field in the potential approximation in the ecliptic plane at distance $R = 2.5 R_\odot$ eastward of the intersection point of the NL with the ecliptic plane at $\sim 13.3^\circ$. From this figure it is evident that the best correlation exists between the signs of $B_\theta + B_\phi$ and of the predominant direction of $B_z$ near the sector boundary (the maximum of $B_z$ is shifted, on the average, with respect to the sector boundary by an angle $\sim 13.3^\circ$). Calculations of the magnetic field in this case were performed for Carrington rotations 1707–1709 by a method reported by Adam and Pneuman (1976) in collaboration with A. P. Kaigorodov. Note that the possible correlation between the amplitude of $B_\theta$ and the value of $B_z$ at the Earth's orbit was also pointed out by Ponyavin and Pudovkin (1982).
4. Discussion

A large number of factors can have an influence upon the character and effectiveness of the interaction of fast and slow solar wind streams in interplanetary space.

In accordance with calculations reported by Matsuda and Sakurai (1972) and Kaigorodov and Fainshtein (1990), an important role in such an interaction is played by details of the azimuthal distribution of solar wind parameters at relatively long distances from the Sun. In order to ascertain the contribution of the most substantial factors that determine the SW evolution in interplanetary space as well as to be able to intercompare the experimental dependences that characterize the interaction of SW streams of different velocities with calculated ones, we will examine a simplified model of such an interaction.

In a coordinate system connected with the rotating Sun, in the approximation when the SW is regarded as a two-dimensional (dependent only on radius $R$ and on azimuth $\phi$) flux of noninteracting particles, the magnetic field is assumed zero, the azimuthal convection is neglected, and the stationary solar wind flow can be described by the following equivalent system of nonlinear equations (Matsuda and Sakurai, 1972):

\begin{equation}
V_r \frac{\partial V_r}{\partial r} + \frac{\partial V_r}{\partial r} = 0
\end{equation}

\begin{equation}
\frac{\partial \rho}{\partial r} + \frac{\partial (\rho V_r)}{\partial r} = 0
\end{equation}

where $V_r = \tilde{v}_r/\tilde{v}_r^0$, $\rho = \tilde{\rho}/\tilde{\rho}_r^0$, $\tilde{v}_r$ is the SW radial velocity, $\tilde{\rho}$ is the SW density, $\tau = -(\tilde{v}_r^0/\Omega_0 R_0)\phi$, $\tilde{v}_r^0$, $\tilde{\rho}_r^0$ is a typical SW radial velocity and SW density at distance $R_0$, and $\Omega_0$ is the angular rate of solar rotation, $r = R/R_0$.

An analog of the boundary-value distributions of $V_r(\phi, r_0)$ and $\rho(\phi, r_0)$ are the relationships

\begin{equation}
V_r^0 = V_r^0 \quad (r = 1, \tau_0),
\end{equation}

\begin{equation}
\rho^0 = \rho^0 \quad (r = 1, \tau_0).
\end{equation}

Equations (1) and (2) with nonstationary boundary conditions (3) and (4) can be solved in the general form:

\begin{equation}
r = 1 + V_r^0(\tau_0)[\tau - \tau_0],
\end{equation}

\begin{equation}
V_r(r, \tau) = V_r^0(\tau_0(r, \tau)),
\end{equation}

\begin{equation}
\rho(r, \tau) = \rho^0(r_0(r, \tau)) \frac{V_r^0(\tau_0(r, \tau))}{V_r^0(r_0(\tau_0(r, \tau)))} \frac{\partial V_r^0}{\partial \tau_0}(\tau - \tau_0).
\end{equation}

Here the function $\tau_0(r, \tau)$ is the inverse for the function $r = r(\tau_0, \tau)$ from (5).
For the subsequent analysis, we will examine one of the simplest cases:

\[ V_r^0(\tau_0) = \begin{cases} V_m + \frac{V_M - V_m}{\Delta \tau_0} \tau_0, & 0 \leq \tau_0 \leq \Delta \tau_0, \\ V_M, & \Delta \tau_0 < \tau_0, \end{cases} \]  

(8)

\[ \rho^0(\tau_0) = \rho^0 = \text{const}. \]  

(9)

By analyzing, using Equations (5)–(7), the velocity and density behaviour of the flux of non-interacting particles in the case of nonstationary boundary conditions (8)–(9), one can arrive at the following conclusions:

- with distance from the boundary \( r = 1 \) \((R = R_0)\), the velocity gradient \( \partial V_r / \partial r \) in the region of the velocity front (the difference of \( V_r \) from \( V_M \) to \( V_m \)) will increase;
- simultaneously, in this region there will be an increase of the density peak, whose maximum value is \( \rho^M \):

\[ \rho^M = \rho^0 \frac{V_m \Delta \tau_0}{\Delta r}; \]  

(10)

- at some distance \( R^* \) the spatial velocity gradient becomes infinite: the fastest particles of the flux with velocity \( V = V_M \) there overtake the slowest with \( V = V_m \). In this case \( R^* = \Delta \tau_0 (V_M V_m/(V_M - V_m)) \).

For rough estimates, the parameter \( R^* \) can be used as the measure of the expected density enhancement in the region of the velocity front at a given distance \( R < R^* \). That is, by comparing flows with different values of \( R^* \), we anticipate that at a distance \( R < R^* \), when the velocity front traverses that location, the greater the value of \( \rho^M \) that is recorded, the smaller is the parameter \( R^* \). For constructing empirical relationships which establish a connection between \( \rho^M \) at the Earth’s orbit and other SW characteristics, it is convenient to use the quantity \( VMV_m/(V_M - V_m) \) as the parameter (in terms of the given model) because values of \( V_M \) and \( Vm \) can be determined from King (1977, 1983, 1986), while the front width \( \Delta \tau_0 \) (an analog of the angular width \( \Delta \phi_0 \)) is a characteristic unknown for many fast SW streams.

In order to determine more exactly \( \rho^M \), we will estimate the spatial width of the velocity front \( \Delta r \) at the moment of time when particles traverse this place \( R_m \) with velocity \( V_m \) at the front base:

\[ \Delta R = R_m \left( 1 - \frac{V_m}{V_M} \right) + V_M \Delta \tau_0. \]  

(11)

Hence, in this case we have

\[ \frac{\rho^M}{\rho^0} = \frac{\Delta \tau_0}{V_m \Delta \tau_0 - \frac{r_m}{V_m} \left( \frac{V_m}{V_m} - 1 \right)}. \]  

(12)
From (12) it is evident that the relation of $\rho^M/\rho^0$ to $V_M$ and to $V_m$ is a more complex one than that following from the rough estimates given above. The combination of $V_M$ and $V_m$: $V_M/V_m$ can be taken as the parameter. It is easy to see that at a fixed value of $r_m/V_m \Delta t$, with increasing $V_M/V_m$ (to the value of $V_M/V_m = (V_M/V_m)^*$, at which $\rho^M/\rho^0 \to \infty$) $\rho^M/\rho^0$, according to (12), increases.

Using a more complex technique for describing the solar wind flow in interplanetary space, magnetohydrodynamical, in the two- or three-dimensional approximation, in view of the effective viscosity, etc., only complicates the search for the solution, but qualitatively, the main results in this case are similar to those obtainable from the simple model considered above. In the two-dimensional approximation, calculations show that also in this case the amplitudes of density $n^M$ and magnetic field $B^M$ depend on $V_M$, $V_m$, $\Delta \varrho_0$, $\rho_0(\varphi)$, and on $r$ (Marsuda and Sakurai, 1972; Kaigorodov and Fainshtein, 1990).

In the three-dimensional approximation, the character of the SW flow begins to be affected by different geometrical factors. Detailed quantitative investigations of the role of such factors have not yet been carried out. It might be anticipated that $n^M$ and $B^M$ will depend on the NL slope to the solar equatorial plane because the compression force of a slow wind as it interacts with a fast wind perpendicular to the heliospheric current sheet, depends on this angle. In the case $\beta \approx 0$ the fast stream virtually does not interact with the slow stream because there is no ‘collision’ of these streams arising due to the solar rotation.

Thus, the above empirical relationships (Figures 2 and 3) between $B^M$ at the Earth’s orbit and $V_M/V_m$ and $V_M - V_m/V_M V$, agree with existing physical conceptions and with quantitative models of the interaction of SW streams of different velocities.

At the same time, from (12) it follows that, strictly speaking, density amplitudes (and accordingly, magnetic field amplitudes) depend on several parameters, and this may be one of the main reasons for the relatively large spread of points in Figures 2 and 3. It has become possible to compare, for some events from King (1977), the observed amplitudes $n^M$ at the base of the velocity front of a fast SW stream near the sector boundary with the ratio $\Delta \varrho_0/\Delta \varrho_E \sim \Delta \varrho_0/\Delta \varrho_E$, where $\Delta \varrho_0$ is the angular width of the velocity of the fast stream near the Sun, and $\Delta \varrho_E$, at the Earth’s orbit. The value of $\Delta \varrho_E$ was determined directly from the dependence of the SW velocity on time $V(t)$ at $R = 1$ AU: $
abla E \simeq \Delta \varrho_E(\text{days}) \times 13.3^\circ$, where $\Delta \varrho_E$ is the time width of the forefront of the fast SW stream. The value of $\Delta \varrho_0$ was determined from the relationship

$$
\Delta \varrho_0 = \Delta \varrho_E^b - R_E \frac{V_M - V_m}{V_M V_m} \frac{13.3^\circ}{8.64 \times 10^4},
$$

where $\Delta \varrho_E^b$ is the angular width of the backfront of the high speed SW stream, $\Delta \varrho_E^b \simeq \Delta \varrho_E^b(\text{days}) \times 13.3^\circ$ (see Figure 6(a)), $R_E = 1.5 \times 10^8$ km (1 AU), and $V_M$ and $V_m$ are defined in units of km s$^{-1}$. The results are presented in Figure 6(b). One can see that the three events considered of 24 November, 1973, 31 May, 1974 and 23 July, 1974 (dates of $n^M$ are indicated here) are concentrated near the straight line $n^M \sim \Delta \varrho_0/\Delta \varrho_E$. 

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As has already been pointed out, direct evidence for the increase of $n^M$ and $B^M$ from the neighbourhood of the Sun to the Earth’s orbit, accompanied by a steepening of the velocity front of a fast SW stream, has not yet been reported. Figure 7 shows the time behaviour of $n(t)$ and $V(t)$ for several events at different distances from the Sun: at $R = 1$ AU according to the data from King (1977) and at $0.3 \text{ AU} < R < 1 \text{ AU}$ for the same SW streams according to measurements of SW characteristics aboard the HELIOS spacecraft (Burlaga et al., 1978).

![Image of Figure 6](image.png)

Fig. 6. The influence of the angular width of the fast stream front in the neighbourhood of the Sun $\Delta \phi_0$ upon the value of amplitude $n^M (R = 1 \text{ AU})$ as a consequence of the interaction of this stream with a slow wind. 1 – 24.11.73; 2 – 31.05.74; 3 – 23.07.74.

By comparing the amplitudes of the two different density peaks in the vicinity of the sector boundary (one of them can, possibly, be referred to as the class of ‘stream-associated’ ones, and the other, as the class of ‘stream-free’ ones, according to the definition given by Borrini et al. (1981)), as well as the steepness of the velocity increase in the fast stream front, we arrive at the conclusion that in the events considered, the amplitude of the density peaks at the base of the velocity of the fast (‘stream-associated’) stream increases with increasing distance from the Sun as compared with the amplitude of an earlier (‘stream-free’) peak, and this is accompanied by an increase in maximum steepness of velocity $V(t)$ at the fast stream front. For the events of 8–10 February, 1975 and 24–25 March, 1976, the Earth and the spacecraft at the time of measurement of SW parameters were located at about the same heliolongitude, and for the events of 6–8 April, 1975, at different heliolongitudes. Hence, Figure 7 can be regarded as the first experimental evidence for the existence in interplanetary space of an effective interaction of fast and slow SW streams which has a substantial influence upon solar wind characteristics at the Earth’s orbit.
The above analysis of the relationship of the z-component of magnetic field $B$ with other SW characteristics allows us to draw an important conclusion, namely the maximum values of $|B_z|^M$ recorded at the Earth's orbit in the region of the sector boundary, $|B_z|^M \sim 15$–25 $\gamma$ (in the case $(B_z) < 0$, it is such events that the strongest geomagnetic disturbances are associated with) are attributable to the interaction of fast and slow solar wind streams in interplanetary space. In this case, as has already been stressed, we are dealing with geomagnetic disturbances unassociated with sporadic SW flows (shock waves, magnetic clouds, etc.). The enhancements of the $B_z$-component observed in the neighborhood of the sector boundaries are associated, primarily, with an increase of $B$ in these regions.

To conclude this section, we will give a further dependence which permits us to emphasize some properties of the formation of SW structures at the Earth's orbit as a consequence of the interaction of SW streams of different velocities. Figure 8(a) shows
the relationship between amplitude $B^M$ and solar wind velocity $V$ at the point where $B = B^M$. One can see that there is a correlation between the variation of these parameters, though a large spread of points forming this dependence is observed. A tendency for the mean value of $B^M$ to increase with increasing $V$ is clearly seen. For comparison, Figure 8(b) gives the relationship between $B$ in the central part of the high-speed stream, with the mean solar wind velocity here equal to $V_M$. This dependence qualitatively differs from that given in Figure 8(a). In this case, with increasing $V_M$, the magnitude of the magnetic field $B$ in the stream changes little, on the average, showing a slight tendency to decrease.

5. Conclusions

The physical processes that determine the behaviour of quasi-stationary solar wind flows observed at the Earth’s orbit remain largely unclear. It is believed that an important role in the formation of these peculiarities is played by the nonlinear solar wind evolution in interplanetary space which reflects the intrinsic interaction of fast and slow SW streams as a consequence of the Sun’s rotation. This conclusion is based mainly on the fact that the SW structure observed at 1 AU is similar to that obtained from model calculations of solar wind flow, with proper account of the interaction of SW streams of different velocities. There is also some indirect experimental evidence for the decisive role of such an interaction in the SW structure formation at the Earth’s orbit.

In this paper, by analyzing observational data, it has been possible to determine quantitative relationships which reflect the role of the nonlinear SW evolution in the formation of characteristic properties of the solar wind at the Earth’s orbit. For the first time, direct evidence for the existence of spatial changes in some SW characteristics has been presented, in agreement with the physical understanding of the interaction of fast and slow SW streams due to the Sun’s rotation.

It has been shown that maximum peak values of magnetic field $B^M$ and density $n^M$
in the neighbourhood of the sector boundary at the base of the high-speed stream front are associated with solar wind characteristics such as the minimum SW velocity near the sector boundary, \( V_m \), the maximum velocity in the central part of a fast stream, \( V_M \), as well as the slope \( \beta \) of the neutral line of the magnetic field to the solar equatorial plane at \( R = 2.5 R_\odot \). At sufficiently large \( V_M/V_m > 1.7 \) the value of \( B^M \) increases approximately linearly with increasing \( \beta \), and at small \( V_M/V_m < 1.3 \) the angle influences weakly the value of \( B^M \). Accordingly, when \( \beta > 55^\circ \) an increase of \( V_M/V_m \) is accompanied by a nearly linear increase of \( B^M \). The relationships between \( n^M \) and \( V_M/V_m \), \( \beta \) show a similar behaviour.

In this paper a comparison has been made of statistical properties of the solar wind in the vicinity of the sector boundary for cases when the interaction of SW streams plays also a significant role for events where such an interaction is unimportant. This occurs when considerable portions of the heliospheric current sheet are located nearly horizontally near the solar equatorial plane.

One of the most important conclusions drawn in this paper implies that enhancements of absolute values of the z-component of the magnetic field \( |B_z| \) recorded at \( R = 1 \) AU near the sector boundaries at rather large \( \beta \) are caused mainly by the interaction of SW streams of different velocities. The importance of this conclusion is justified by the fact that \( B_z \) has a substantial role in energy exchange between the solar wind and the Earth’s magnetosphere.

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DIAGNOSTIC FEATURES OF SUNSPOT REGIONS

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Abstract. Five-minutes \( p \)-mode oscillations are heavily attenuated in the active sunspot region. A
comparative study of wave modes and luminosity variations outside and inside the sunspot region is
found to depict certain diagnostic features of sunspot regions.

1. Introduction

The solar seismicity is orders of magnitude larger than the Earth’s seismic activity
and is known to generate \( p \)-mode waves. These waves propagate around the Sun
and are heavily attenuated in the sunspot region giving rise to modulation of optical
emissions. The generation and propagation of \( p \)-mode waves with a typical period
of five minutes is well known (Leighton, Noyes, and Simon, 1962; Lighthill, 1967;
McKenzie, 1971). A significant part of these waves is absorbed in passing through
the sunspot region (Braun, Duvall, and LaBonte, 1987, 1988; Braun and Duvall,
1990). The intent of this letter is to show that the waves trapped in the sunspot
region undergo a significant modification, and absorption of the incident \( p \)-mode
waves results into localized oscillations of photospheric gas. The analyses of optical
emissions in the sunspot region may provide diagnostics of dynamical features in
the photospheric and chromospheric regions as controlled by sunspots magnetic
field strength and its morphology.

2. \( P \)-Mode Wave Generation and Interaction with Sunspots Region

The solar seismic activity generates acoustic waves in the convection zone with an
energy input of \( 10^{7}-10^{9} \) ergs cm\(^{-2}\) sec\(^{-1}\). The frequency coverage of the dominant
\( p \)-mode wave is \( 2.5 \times 10^{-3} \) Hz to \( 3 \times 10^{-3} \) Hz. The stably stratified solar atmosphere
supports the Brunt-Väisälä frequency:

\[
N^2 = \left( \frac{g}{\rho_0} \frac{d\rho_0}{dz} + \frac{g^2}{V_s^2} \right),
\]

where \( \rho_0 \) is the undisturbed solar mass density decreasing with increasing altitude
\( z \), \( g \) is the solar gravity, and \( V_s \) is the acoustic wave speed. The Brunt-Väisälä fre-
cquency \( N^2 \) changes in the sunspot region because of changes in the stratification
and due to the presence of magnetic field. The process of \( p \)-mode wave transfor-
mation and its absorption in the sunspot region is rather complex, and observed
luminosity variations and dynamical features are not fully understood (Hollweg, 1988).
The magnetosonic wave velocity \( V_{ms}^2 = V_s^2 + V_A^2 \), where \( V_A \) is the Alfvén

velocity, enters in Equation (1) and plays an important role in the active sunspot region. For $\omega < N$, the acoustic wave propagates almost isotropically and for $\omega > N$ internal gravity waves are set in which propagate upwards in a cone. The globally propagating $p$-mode waves are attenuated in the sunspot region resulting into localized pressure oscillations. The consequent heating and cooling of the oscillating photospheric gas gives rise to a sinusoidal variation in the luminosity (Dollfus, 1990). The line intensity variations of Na$_1$D$_1$ (5895.94 Å) and Fe I (5930.191 Å and 5929.682 Å) and associated phase difference with oscillating photospheric gas has been used as a diagnostic measure of dynamical features (Deubner and Fleck, 1989). In addition, the line intensity ratios of some of the SV emissions in the EUV range, $R_4 = I(1199.1$ Å)/$I(786.9$ Å), show a significant decrease from 0.15 at $10^5$ K with increasing temperatures and also show an increase with decreasing temperatures (Keenan and Doyle, 1990). The emission measure $\phi(T)$ shows a fast decrease with increasing temperature as shown in Figure 1 (Lang, Mason, and Whister, 1990). At a constant temperature in the photospheric region, the envelope of eight overplots shows an insignificant spread. However, in the chromosphere-coronal transition and coronal regions the spread in $\phi(T)$ is seen to vary rather significantly. The emission measure is proportional to the emitted line intensity. The oscillatory nature of the photospheric luminosity has been measured using ACRIM aboard Solar Maximum Mission (Woodard and Hudson, 1983).

3. Conclusions

The detailed study of $p$-mode wave absorption and its transformation into magnetoacoustic waves in the active sunspot region is not yet fully carried out.
The wave-induced emission measures in the photospheric, chromospheric, and chromospheric-coronal transition regions show a sinusoidal variation with a typical phase change between oscillating photospheric gas and line intensity (Deubner and Fleck, 1989; Dollfus, 1990). The observations using ground-based Solar Luminosity Oscillation Telescope (SLOT) and the solar oscillation imager aboard SOHO may provide leading diagnostic information for $p$-mode wave transformation process and their absorption in the active sunspot region (Anderson et al., 1988; Jimenez et al., 1990).

References
A SOLAR MAGNETIC FIELD MODEL AND ITS 3-D BOUNDARY ELEMENT METHOD SOLUTION

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Abstract. A force-free magnetic field model with constant $\alpha$ is established, and a boundary element method is proposed to solve the problem. The procedure ensures a unique solution as well as a finite magnetic energy content. The proposed formulation is effective in solving magnetic fields above the solar surface, and the validity of our procedure is demonstrated by satisfactory agreement between calculated and observed magnetograms.

1. Introduction

There have been a number of analytical solutions to solar magnetic fields, such as Schmidt (1964), Nakagawa and Raadu (1972), Chiu and Hilton (1977), Seehafer (1978), and Chen et al (1986, 1989). Since boundary conditions are given in a discrete form such as magnetograph data, to meet the needs of these analytical procedures, it is necessary to convert the discrete data to a suitable form, as discussed by Yan, Yu and Kang (1991). Therefore how to verify the theoretical work with observational results remains a problem to solar physics.

During the past ten years or more, the boundary element method (BEM) has found wide applications in many fields (Mackerle and Brebbia, 1988). It is very suitable for treating problems such as open boundaries, materials extending to infinity, distant fields, or space between distant objects, etc. In this letter, we propose a force-free field model in terms of the magnetic induction $\mathbf{B}$ directly, based on Maxwell's equations and observational facts such that a unique solution and a finite energy content are ensured. Consequently, a BEM procedure is easily implemented so that the field are solved directly from measured magnetograph data; meanwhile, no additional data treatment is needed. Therefore, more accurate and more reliable results are likely obtained, as demonstrated by comparisons between calculated and observed magnetograms at the chromosphere.

2. Field Model and BEM Procedure

The magnetic field above the solar surface is assumed force-free. However, the field equation is expressed instead in terms of the magnetic induction $\mathbf{B}$ directly

$$\nabla^2 \mathbf{B} + \alpha^2 \mathbf{B} = 0$$

(1)

where $\alpha$ is considered constant. Obviously, this is a Helmholtz equation.

The boundary condition is

$$\mathbf{B} = \mathbf{B}_o \quad \text{on} \quad r = R_\odot \quad \text{surface}$$

(2)

where $\mathbf{B}_o$ denotes the known boundary value at the photosphere by observations, and $R_\odot$ is the solar radius.
In general all sources of the magnetic field are located within a finite distance of the origin and the field vanishes identically at infinity. Therefore it is reasonable to introduce the Sommerfeld condition to the above problem so that a unique solution and a finite energy content are ensured (Stratton, 1941, p.485)

\[ B \to 0 \quad \text{and} \quad r(\frac{\partial B}{\partial r} + j\alpha B) \to 0, \quad \text{when} \quad r \to \infty \quad (3) \]

It can be seen that the model proposed here is an exterior boundary value problem including the field equation (1), the Dirichlet condition (2), and the Sommerfeld condition (3), as shown in Figure 1.

![Figure 1. Model of the boundary value problem.](image)

The above exterior boundary value problem can be transferred into an integral form by Green's theorem so that a boundary integral equation is obtained (Stratton, 1941, p.460). By the BEM, the active region, \( \Gamma \), is first subdivided into a number of elements and then approximation functions are applied over each element. In our case the element dimensions are adequate to the spatial resolution, and 9-node bi-quadratic functions are employed there. Finally we obtain a discretized form of the above-mentioned boundary integral equation

\[ c_i B_i + \sum_{c=1}^{L} \int_{\Gamma_{c}} \frac{\partial F}{\partial n} \{N_1, N_2, \ldots, N_9\} \{\mathbf{B}_1, \mathbf{B}_2, \ldots, \mathbf{B}_9\}_e^T \, d\Gamma \]

\[ = \sum_{c=1}^{L} \int_{\Gamma_{c}} F \{N_1, N_2, \ldots, N_9\} \{\mathbf{Q}_1, \mathbf{Q}_2, \ldots, \mathbf{Q}_9\}_e^T \, d\Gamma \quad (4) \]

where \( c_i \) is a constant depending upon the location of point \( i \), \( B_i \) is the value of \( B \) at point \( i \), \( L \) is the total number of boundary elements, \( \mathbf{Q} \) denotes \( \partial B / \partial n \), \( \mathbf{B}_k \) and \( \mathbf{Q}_k \) are nodal values of \( B \) and \( \mathbf{Q} \) respectively, \( N_k \) are quadratic approximation functions, subscript \( e \) denotes the \( e \)th element, superscript \( T \) denotes the transpose, \( n \) is the unit inward normal direction of the solar surface \( \Gamma \), \( F \) is the fundamental solution of the Helmholtz equation in the 3-D case

\[ F = \frac{\exp(-j\alpha r)}{4\pi r}, \quad (5) \]

and \( \partial F / \partial n \) is the partial differential with respect to the normal. In the above, \( j \) denotes the imaginary unit, and \( r \) is the distance between the point \( i \) and a source point on \( \Gamma \).

In a system of Cartesian coordinates we assume that the space of our analysis is defined as \( \Omega = \{(x, y, z)|z \geq 0\} \), where \( z = 0 \) corresponds to the photosphere which we can observe. A magnetogram provides the boundary condition of \( B \) in a rectangular domain \( \Gamma = \{(x, y, z)|0 \leq x \leq L_x, 0 \leq y \leq L_y, z = 0\} \), and we assume \( B \equiv 0 \) when \( (x, y, 0) \not\in \Gamma \).
The influence of the coefficients in Equation (4) can be evaluated by a Gaussian quadrature rule (in our case 5 x 5 Gaussian points are adopted) as well as Cauchy’s integration of principal value, and the system of the BEM can be written as follows

\[ [H][b] = [G][q] \]  \hspace{1cm} (6)

where \([H]\) and \([G]\) are coefficient matrices, \([b]\) and \([q]\) are respectively the nodal vectors of \(B\) and \(Q\).

Substituting the Dirichlet boundary condition (2) we can see that the left side of Equation (6) is known, so it can be solved. \(\partial B/\partial n\) at each node is then obtained. As a result the magnetic induction \(B\) at any point above the solar surface can eventually be specified by employing Equation (4).

Though the above formulations are expressed in terms of \(B\), they also hold for the components: \(B_x\), \(B_y\), or \(B_z\). In the following we only use the longitudinal component \(B_z\) to show the validity. The transverse components \(B_x\), \(B_y\) can also be solved in the same way.

Figure 2 shows a \(B_z\) component magnetogram, which serves as the Dirichlet boundary condition. At present, only the area within the box in Figure 2 is considered. The unit length adopted here is 1370 kilometres, and a mesh with 27 x 21 nodes covering one quarter of the area is as shown in Figure 3, where numbers of nodes and elements are respectively 567 and 130. The equivalence principle has been applied to solve the problem (Yan et al, 1991).

![Fig. 2. Observed \(B_z\) component magnetogram at the photosphere on 3-May-1991 by Huairou Solar Station (Isomagnetic levels ranging from \(-1868.7\) Gs to \(1115.3\) Gs at a fixed interval).](image1)

![Fig. 3. Subdivisions of a quarter of the boundary area \(\Gamma\).](image2)

This field has been solved on a Micro-VAX/II computer, and calculated contours of the magnetic induction \(B_z\) at the solar chromosphere are given in Figure 4 (a), also in Figure 4 (b) is the measured contour at the chromosphere. It can be seen that the key features of the
exact distribution are represented properly by the calculated one, particularly the shape of isolines at the center of the sunspot. The CPU time elapsed was about 17 and 42 minutes for matrix generations and solving the equation respectively, and it took merely 2 seconds or so to calculate the magnetic induction at each field point. The measured maximum magnetic induction of the sunspot at the chromosphere is 532.6 Gs, compared with the calculated result 494.7 Gs for \( \alpha = 0.05 \). Aware that the spatial resolution may cover more than one thousand kilometers, this agreement is excellent.

(a) Calculated \( B_z \) magnetogram at Chromosphere  
(b) Measured \( B_z \) magnetogram at Chromosphere

Fig. 4. \( B_z \) component contours at the chromosphere: (a) \( \alpha = 0.05 \), (b) Measured (Isomagnetic levels are ranging from \(-200\) to \(490\) Gs at intervals).

3. Conclusions

In this letter a force-free magnetic field model with constant \( \alpha \) is established, and a BEM procedure is proposed to solve the problem. The validity of the proposed formulation is demonstrated by comparisons between calculated and observed magnetograms at the chromosphere. It shows that the BEM is a powerful tool to determine the distribution of magnetic fields in the solar atmosphere, and applications of the BEM in studying solar physical events appear prospective.

Acknowledgements

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References

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BOOK REVIEWS


The second volume of Reviews in Modern Astronomy published by Astronomische Gesellschaft contains review papers presented at the meeting of the AG at Friedrichshafen in April 1989 dedicated to ‘Astrophysics with Modern Technology – Space-based and Ground-based Systems’ and also at the AG meeting in Graz in September 1989. During the second meeting Martin Rees was awarded the Karl Schwarzschild medal and his lecture ‘Is there a Massive Black Hole in Every Galaxy?’ begins the book. Further follow 27 contributions covering a very broad range of topics. Starting from several comprehensive papers on the new research possibilities with new instrumentation, next generation of telescopes and future satellites, other topics such as extragalactic radio jets, spectroscopy of Supernova 1987A or chemically peculiar stars are treated in details. The book contains as well shorter reviews on, e.g., cosmic rays, accretion disks, stellar evolution, large-scale structures, and also solar physics. Two contributions could be of special interest for solar physicists: ‘A Correlation Tracker for Solar Fine Scale Studies’ by Th. Rimelele and O. von der Luhe and ‘The Sun’s Differential Rotation’ by M. Stix. The book will be interesting not only to the world-wide astronomical community but to any reader interested in new developments in modern astronomy.

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These proceedings contain review papers related to interstellar dust and give a good representation of the field at the time of the meeting. More than half of the book is devoted to general properties, especially to optics of grains either individually or in clouds, and to questions of the origin, distribution and evolution of the dust. Beside problems of sources and growth, destruction of grains is discussed in details as well as a number of physical processes such as electric charging and heating of grains. The following, about a hundred pages, contains chapters which deal with specific problems as, e.g., identification of PAH’s, interstellar absorption bands or hydrogen sticking and


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recombination on surfaces of interstellar grains. The last part deals mainly with cometary dust. As proceedings of a school, the book is valuable by the completeness of the treatment of respective chapters; they do not contain only basic phenomenological information and the basic methodological procedures for further study, but they also indicate the nature and extent of unsolved problems. Therefore, the book can be used by a very broad spectrum of readership – from students as an introduction to this field of research to experts in the field, and also by solar physicists interested in the dust component of the solar corona and in cometary impacts on the Sun.

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