CORONAL PHYSICS WITH THE SOLAR AND HELIOSPHERIC OBSERVATORY

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If we look back at the development of Solar Physics in the last ten years, it is quite evident that major steps forward have been made with the use of X-ray and UV instruments on board rockets and satellites. Partly, this has been a consequence of the obvious increase of knowledge one gets every time a hitherto unexplored spectral region is opened up to observations. However, even more importantly, this progress has been mainly a result of the fact that X-ray and UV instrumentation has reached a degree of spatial and spectral resolution approaching that obtainable with optical observations from the ground.

Let me briefly summarize some of the major results obtained over the last decade by a very successful series of rockets and satellites, which include Skylab, OSO-8, the Solar Maximum Mission, the High Resolution Telescope and Spectrograph (HRTS), and many others. X-ray and UV images obtained from Skylab in 1973-74 showed for the first time that the solar corona is highly structured, and that the basic structural elements are arch-shaped features (so called "loops") tracing magnetic field lines (Withbroe and Noyes 1977, Vaiana and Rosner 1978). The loops arch between regions of opposite magnetic polarity, which are brighter at chromospheric levels in Lyα and in other UV lines of low-ionization stage ions. Although the overall structure of an active region may remain unchanged for several days, substantial

(*) Invited paper at the 8th European Regional Astronomy Meeting, Toulouse, France, September 1984. Other aspects of the SOHO project were presented at the same meeting by C. Frohlich (solar oscillations) and C. Harvey (solar wind experiments). Given the interest expressed by the Italian solar physics community for the SOHO project, the text of the talk is reproduced here with only minor changes.

(**) The author is currently a member of the Solar System Working Group of the European Space Agency.
Variations of individual features occur on time scales as short as a few hours (Vaiana 1973). Occasionally, rapid brightenings (flares) occur in active region loop structures. The most important result of these observations has been the demonstration of the essential role played by magnetic fields not only in shaping coronal structures, but also in heating the plasma (Rosner et al. 1978, Ionson 1978, Heyvaerts and Priest 1983). Recently this conclusion has been enforced by observations of transition regions and coronae in nearby stars by the International Ultraviolet Explorer and the Einstein Observatory (Vaiana et al. 1981, Linsky 1983).

Let us consider in somewhat more detail the problem of coronal heating. As is well known, the temperature in the outer solar atmosphere jumps abruptly from values of the order of $10^6$ K in the chromosphere to values in excess of $10^6$ K in the corona. The very narrow interface region, the transition region (TR), plays a crucial role in the heating process, and it is extremely important to determine the physical conditions in this region with the greatest possible accuracy. The best way to do that is to observe ultraviolet spectral lines, each of them formed over a very narrow temperature range, in such a way as to sample the transition region at different heights. An example of this technique is provided by the series of simultaneous spectroheliograms in various UV lines obtained by the Harvard experiment on Skylab (see e.g. Withbroe 1976, Pallavicini et al. 1981). These observations, although invaluable for obtaining a first order description of the region at different heights, were obtained with a spatial resolution of 5 arc sec, which is barely sufficient to show the coarser structures, but totally inadequate to resolve the very important fine details.

Images of quiet regions obtained with the same instrument on Skylab (Withbroe 1976) show the presence of the chromospheric network which persists throughout the transition region, but eventually disappears at coronal (Mg X) levels. This is presumably due to the diffusion of magnetic field lines when passing from a region where the plasma $\beta$ factor ($\beta = 8\pi P_g/B^2$) is of the order of $\approx 1$, to a region where $\beta \ll 1$ (Gabriel 1976). Observations at higher spatial and spectral resolution obtained with the Naval Research Laboratory HRTS instrument on rockets have shown the existence of a very complex pattern of dynamic phenomena in the transition region and in the corona, over spatial scales of the order of $\sim 1$ arc sec and with velocities of up to 500 km s$^{-1}$, far in excess of the sound speed at the same levels (Brueckner 1981, Brueckner and Bartoe 1983, Dere 1984). In particular, the observations of high energy jets which carry a total amount of energy comparable with the coronal radiative losses, may have very important consequences for the mechanism of coronal heating as well as for the acceleration of the wind.

One of the most important results of Skylab observations was the discovery that a fundamental distinction must be made between regions of closed magnetic fields (loops) and regions of open magnetic fields (coronal holes). In X-ray images, coronal holes appear as dark areas of reduced density and of a somewhat lower temperature (Zirker 1981).
The amount of non-thermal energy supplied at chromospheric levels in quiet regions and coronal holes is approximately the same in the two cases (Withbroe and Noyes 1977), suggesting that in one case the non-thermal energy goes mostly into heating the plasma, while in the other it goes mostly into accelerating the wind. Extrapolations of the photospheric magnetic fields show that the field lines in coronal holes are open to the interplanetary medium, thus allowing the solar wind to escape freely. We now know that high velocity wind streams (with V up to 800 km s\(^{-1}\)) originate in coronal holes (Krieger, Timothy and Roelof 1973), a fact which is difficult to explain with the standard model of a thermally driven wind accelerated by the pressure gradient in a medium heated by thermal conduction. It appears that additional energy and/or momentum, possibly by Alfvén waves, must be supplied in coronal holes to produce the high velocity wind streams (Kopp 1981, Hollweg 1981). At the same time, the region of origin of the slow speed wind (V ~ 400 km s\(^{-1}\)) remains unknown.

Comparisons of X-ray photographs of the inner corona projected on the disk with optical images of the corona at the limb, show that the structures seen in X-rays extend far out in the corona. Most of our knowledge of the outer corona has been obtained in recent years by means of coronographs mounted on Skylab and the Solar Maximum Mission (Rust and Hildner 1980, Wagner 1984). Among the many structural features observed, of particular interest are the large scale coronal streamers which appear to overlie regions of closed magnetic fields. It has been speculated that the slow speed wind may be associated with these streamers, although the precise region where the acceleration occurs and the mechanism of acceleration itself remain largely unknown. Time sequences of coronal observations by coronographs in space have shown that coronal transients, i.e. large-scale dynamic phenomena in the outer corona, are quite common and are associated with disturbances in the interplanetary medium as seen at 1 A.U. (Schwenn 1983).

After this brief overview of the main results in coronal physics obtained in the last decade, let me indicate here some of the key problems which may be addressed quite effectively by a future space mission such as the proposed Solar and Heliospheric Observatory (SOHO). The following list does not aim to be complete, but rather to point out a few problems for which substantial progress can be expected from a mission as SOHO. As known, SOHO has been proposed to the European Space Agency and is currently under Phase A Study. For a general description of the SOHO project, the reader is referred to the results of the Assessment Study, published by ESA in September 1983. For a detailed discussion of the scientific motivations of the SOHO mission see also Malinovsky-Arduini and Frohlich (1984).

The first fundamental problem which can be addressed by SOHO is the heating of the solar corona. We know at present that heating by magnetic processes is more likely than purely acoustic heating (Kuperus, Ionson and Spicer 1981, Pallavicini 1984), but we do not know which of the many proposed mechanisms (e.g. MHD waves, DC currents, magnetic reconnection) is more important in the coronal case. We do
not even know whether the heating is steady or whether it results from
the superposition of a large number of discrete pulses. Determina-
tion of physical conditions (temperature, density, velocities) in the
transition region and low corona at the smallest possible spatial sca-
le is essential for tackling the heating problem.

Another fundamental problem, which is intimately related to the
previous one, is understanding the mechanism of wind acceleration,
both inside and outside coronal holes. In this respect, it is neces-
sary to obtain information on the mass outflow as close to the Sun as
possible, in particular in the region within a few solar radii, where
most of the acceleration is believed to take place.

Next, it is important to determine the structure and dynamics of
transition region and coronal features, in particular of loops which
are the building blocks of the solar corona. The equilibrium and sta-
bility of these structures is still a matter of controversy. It is
essential to determine the longitudinal and radial dependence of
thermodynamic quantities \( (T_e, N_e) \) in these structures, as well as the
presence and amount of flows.

Finally, it is of importance to determine the relationship between
phenomena observed in the wind (slow streams, fast streams, plasma wa-
ves etc.) and phenomena observed in the corona (holes, streamers,
transients etc.). It is extremely advantageous to observe from the
same satellite (as can be done by SOHO) both the disturbances in the
wind and their parent phenomena in the corona.

Let us consider now some of the features of SOHO which make it
particularly suitable for addressing the above mentioned problems. The
advantages offered by SOHO with respect to previous and planned satel-
lites include:

- the possibility of continuous, uninterrupted observations of the
  solar corona and solar wind, offered by its location near the
  inner Lagrangian point.
- Substantially improved spatial and spectral resolution (up to 1
  arc sec and 10 mÅ at ~1000 Å, respectively).
- Instruments operating in a spectral region (~100 - 1000 Å) which
  has not been adequately investigated so far. This is a very in-
  teresting region, which contains a large number of UV lines sui-
  table for the application of sophisticated plasma diagnostic
  techniques for material at temperatures between ~10^5 and ~10^6 K
  (Dere and Mason 1981).
- High sensitivity to velocities, both in the transition region
  and low corona (from observations of line profiles) and in the
  region of wind acceleration (by means of the Doppler dimming
  technique).
- Possibility of relating unambiguously phenomena observed in the co-
  rona to wind properties measured in situ by particle and field
instruments onboard the same satellite.

- Possibility of measuring coronal magnetic fields by the Hanle effect, if magnetic fields $\geq 10$ Gauss exist at coronal levels.

SOHO addresses coronal physics by means of an optimized set of six instruments which may be grouped in three subsets of two instruments each (Table I). The first couple of complementary instruments is constituted by a Grazing Incidence Spectrometer and a Normal Incidence Spectrometer which measure physical quantities ($T_e$, $N_e$, $V$) in the chromosphere, transition region and low-corona with high spatial and spectral resolution. The second set is composed of imaging instruments, i.e. a couple of EUV Imaging Telescopes operating at two different wavelengths and a Soft X-ray Telescope, to image structures in the upper chromosphere and low corona as a function of time, and to locate the features to be resolved spectroscopically with the two spectrometers. The third set of instruments include an UV Coronagraph and a White-light Coronagraph to investigate the structure and dynamics of the region between 1.4 and 6 $R_\odot$, where most of the wind acceleration probably occurs and where coronal transients affecting the conditions in the interplanetary medium are first accelerated. The details of the proposed instruments, as envisaged in the Assessment Study and in subsequent on-going studies, are shown in Table II.

The Grazing Incidence Spectrometer operates in the spectral band 65 - 1700 Å, with moderate spectral resolution ($\sim 0.1$ Å) and high spatial resolution (1.5 arc sec). The spectrometer provides stigmatic spectra over a slit 1.5 arc sec wide and 6 arc min long which can be moved in a raster pattern across the solar surface. The main purpose of this instrument is to derive electron temperatures and densities using plasma diagnostic techniques for UV lines over the temperature range $\sim 10^4 - 10^6$ K. Selected spectral regions within the same wavelength interval will be observed at higher spectral resolution by the Normal Incidence Spectrometer which has a spectral resolution of $\sim 10$ mÅ allowing accurate measurements of line profiles and the detection of velocities as low as $\sim 1$ km s$^{-1}$. The slit is 1 arc sec wide and 4 arc min.

<table>
<thead>
<tr>
<th>Solar Corona Observations</th>
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<tbody>
<tr>
<td>Grazing Incidence Spectrometer</td>
</tr>
<tr>
<td>Normal Incidence Spectrometer</td>
</tr>
<tr>
<td>EUV Imaging Telescopes</td>
</tr>
<tr>
<td>Soft X-Ray Telescope</td>
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<tr>
<td>UV Coronal Spectrometer</td>
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<tr>
<td>White-Light Coronagraph</td>
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TABLE I. SOHO - MODEL PAYLOAD

Mem. S.A.It., 1984

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<table>
<thead>
<tr>
<th>Instrument</th>
<th>Wavelength Range</th>
<th>Spectral Resolution</th>
<th>Spatial Resolution</th>
<th>Field of View</th>
<th>Parameters measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRAZING INCIDENCE SPECTROMETER</td>
<td>65-1700 Å</td>
<td>0.1 Å</td>
<td>1.5&quot;</td>
<td>1.5&quot;x6'</td>
<td>T_e, N_e</td>
</tr>
<tr>
<td>NORMAL INCIDENCE SPECTROMETER</td>
<td>584-625 Å</td>
<td>14 mA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>770-835 Å</td>
<td></td>
<td>1&quot;</td>
<td>1&quot; x4'</td>
<td>N_e, V</td>
</tr>
<tr>
<td></td>
<td>904-1300 Å</td>
<td></td>
<td>10 mA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EUV IMAGING TELESCOPES</td>
<td>304 Å (HeII)</td>
<td>~20 Å</td>
<td>10&quot;</td>
<td>4R_0 x4R_0</td>
<td>TR+coronal structures</td>
</tr>
<tr>
<td></td>
<td>284 Å (FeXV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOFT X-RAY TELESCOPE</td>
<td>2-100 Å</td>
<td>broad-band</td>
<td>5&quot;</td>
<td>20'x20'</td>
<td>inner coronal structures, T_e, N_e</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1&quot;</td>
<td>3'x3'</td>
<td></td>
</tr>
<tr>
<td>UV CORONAL SPECTROMETER</td>
<td>HI:1025 Å, 1216 Å</td>
<td>80mA</td>
<td>10&quot;-1'</td>
<td>10&quot;x30'</td>
<td>V, T_ion, B</td>
</tr>
<tr>
<td></td>
<td>OVI:1032 Å, 1037 Å</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WHITE-LIGHT CORONOGRAPH</td>
<td>4000-7000 Å</td>
<td>2000 Å</td>
<td>1'</td>
<td>6R_0 x6R_0</td>
<td>outer coronal structures, N_e</td>
</tr>
</tbody>
</table>
long and can be rastered over the solar features of interest. The spectra are stigmatic so as to allow spatial information to be recorded along the slit with a resolution of 1 arc sec.

The EUV Imaging Telescopes operate in two different spectral lines, the He II line at 304 Å, which is formed in the upper chromosphere, and the Fe XV line at 284 Å, which is formed in the low corona. Together, they allow imaging of the full sun in two different temperature regimes with a spatial resolution of 10 arc sec. Higher spatial resolution (as high as 1 arc sec) over smaller fields of view can be obtained with a Soft X-ray Telescope which has been added to the model payload during the Phase A Study. The soft X-ray telescope records broad-band X-ray images and provides a detailed description of coronal structures, while allowing estimates of effective temperature and emission measure along the line of sight.

A very important instrument on SOHO is the UV Coronal Spectrometer which is capable of measuring the outflow of the wind in the region between 1.4 and 5 R⊙. With a f.o.v. of 10 arc sec x 30 arc min which can be positioned in all radial directions around the solar disk, it will provide essential information on the acceleration of the wind both inside and outside coronal holes. The flow velocity is measured by means of the Doppler dimming of the resonance scattered component of UV lines (Kohl and Withbroe 1982, Withbroe et al. 1982). Lyα will give information on flow velocities in the range ~100 – 300 km s⁻¹, while the use of OVI lines at 1032 and 1037 Å will allow the measurement of flow velocities in the range ~30 – 100 km s⁻¹. The spectral resolution of 80 mÅ allows the determination of ion temperatures from the Doppler broadening of the lines. The same instrument can be used to measure the vector magnetic field in the corona by the Hanle effect, i.e. through the modification of the polarization characteristics of spectral lines by magnetic fields (Bommier, Leroy and Sahal-Brechot 1981, Sahal-Brechot 1981, Bommier and Sahal Brechot 1982). Model calculations show that, for the Lyα and OVI lines observed by the instrument, the range of magnetic fields which could be detectable is ~10 – 450 Gauss. Alternatively, the failure to detect magnetic fields by this method will put sensitive upper limits to the magnetic field strength at coronal heights.

Finally, the SOHO model payload includes a White-light Coronagraph which is an updated version of similar instruments flown on Skylab, SMM and the P78-1 satellites. It provides information on column densities along the line of sight (necessary to analyze the observations from the UV Coronal Spectrometer) as well as providing detailed information on outer coronal structures and coronal transients. This instrument is particularly useful for relating coronal phenomena to the in situ measurements of solar wind properties performed by the particle and field experiments on SOHO.

To conclude, even without taking into account the equally important helioseismology and solar wind experiments, the set of instruments on SOHO devoted to coronal studies appear to be capable of al-
Following substantial progress to be made in fundamental areas of solar physics. The possibility of having a European space mission such as SOHO is a unique opportunity which the solar physics community in Europe should seize without delay, if solar physics research in Europe has to maintain the high level which it has had until the present time.

REFERENCES


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