SCIENTIFIC OBJECTIVES OF THE SOLAR-B MISSION

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ABSTRACT

Our view of the solar corona has been revolutionized by Yohkoh. Yohkoh has shown that the hot corona is extremely dynamic, with magnetic reconnection, rapid heating, and mass ejection being common phenomena. The next vital step is to understand the magnetic origins of coronal dynamics and heating. Solar-B, Japan’s next solar physics mission, is designed to establish the connection of the dynamics and heating observed in the corona into the magnetic field at the photosphere. This paper presents Solar-B scientific instruments and makes discussions on scientific objectives of Solar-B. Simultaneous observations at La Palma with Yohkoh is also presented as a preview of Solar-B.

Key words: Yohkoh; Solar-B; magnetic field; photosphere; corona; high resolution.

1. INTRODUCTION: YOHKOH VIEWS THE SUN

A lot of interesting results from Yohkoh motivated us to plan the Solar-B mission with the current design concept. Yohkoh is a guide to Solar-B science. Before we present the Solar-B mission and its scientific instruments (§2) and make discussions on its scientific objectives (§3), we briefly summarize scientific findings by Yohkoh.

The Yohkoh satellite launched in August 1991 has made significant advances in understanding solar flares and corona and revolutionized our view of the hot corona. Yohkoh has shown that the hot corona is extremely dynamic, with rapid heating, plasma ejections, and coronal restructuring being common phenomena. Yohkoh also discovered several pieces of evidence which support the idea that magnetic reconnection plays a vital role of energy release in solar flares. Some findings by Yohkoh regarding solar flares are summarized below:

1. Hard X-ray sources in solar flares show a strong tendency to occur in simultaneous pairs. The double sources match the photospheric footpoints of a flaring loop, establishing that non-thermal electrons transport the impulsive-phase energy along the flare loops (Sakao et al. 1992; Hudson et al. 1992, 1994; Canfield et al. 1992)

2. A cusp-shaped soft X-ray structure was found in long duration flares (Figure 1). The SXT temperature map shows the tendency for highest temperatures to occur in the periphery of the cusp structure, suggesting that magnetic reconnection takes place far above the cusp (Tsuneta et al. 1992; Tsuneta 1996; Forbes and Acton 1996).

3. A hard X-ray source was discovered above a flaring loop of an impulsive flare (Figure 2). This finding suggests that some impulsive flares have configurations similar to that of long duration flares with a cusp-shaped soft X-ray structure. A reconnection site in the corona above the soft X-ray flaring loop drives a rapid outflow, which impinges on denser material in the underlying magnetic loop and creates the hard X-ray source (Masuda et al. 1994, 1995).

4. Many flares show traces of ejection of hot material seen in soft X-rays (Shibata et al. 1995; Ohyama and Shibata 1997).

5. Simultaneous X-ray and radio observations showed that at least two loops are involved in the majority of impulsive flares (Hanaoka 1996; Nishio et al. 1997). Typical sizes of the two loops are different from each other; one is compact, typically less than 20 arc sec.
Figure 2. A hard X-ray source above a flaring loop and double sources at the photospheric footpoints of the loop. Soft X-ray image of the 13 January 1998 flare at the solar limb with hard X-ray (33-53 keV) image contours superposed. This finding suggests that a newly emerging flux is involved in the energy release of flares.

6. The separation between hard X-ray double footpoint sources increases during the impulsive phase for half of solar flares, whereas some of flares show decreasing footpoint separation (Sakao, Kosugi, and Masuda 1998). The magnetic field configuration inferred from the former class of flares suggests a picture in which magnetic reconnection takes place above a flaring loop. The latter class of flares suggests a picture in which magnetic reconnection takes place between a newly emerging flux and a pre-existing flux. New views of the corona in which the corona is extremely dynamic are illustrated with the following dynamical phenomena which were first found with Yohkoh:

1. Transient brightenings of compact loops occurring in active regions (Figure 3). Their energy is at the small end of flare size \((10^{28} \sim 10^{29} \text{ ergs})\), qualifying as microflares and close to qualifying as nanoflares (Shimizu et al. 1992; 1994). Transient events are also found in X-ray bright points and quiet region networks (Strong et al. 1992; Krucker et al. 1997).

2. X-ray coronal jets (Shibata et al. 1992, 1994; Shimojo et al. 1996). Jets are accompanied with microflares or flares, and can be well explained by magnetic reconnection between a newly emerging magnetic flux and a pre-existing flux (Yokoyama and Shibata 1996). Some of type III bursts are associated with coronal jets (Kundu et al. 1995).

3. Slowly expanding active-region loops with velocity of a few to a few tens of km/s (Uchida et al. 1992). Their morphology distinguishes them from coronal mass ejections (CMEs), suggesting a different physical origin.

4. Coronal restructuring frequently occurs from large scale to small scale. Large-scale coronal restructuring events appear to be X-ray counterparts of steamer disruptions (Tsuneta et al. 1992; Hiei, Handhausen, and Sime 1993; McAllister et al. 1996). With capability of estimating physical parameters of coronal loops, Yohkoh has given some hints in understanding the heating of the corona. Some findings regarding the coronal heating are listed as follows:

1. The frequency distribution of microflares (transient brightenings) is well represented by a power-law function with an index of 1.5 - 1.6 (Shimizu 1995). This indicates that microflares are just flares at the smaller end of normal flares (Gary, Hartl, and Shimizu 1997; Nitta et al. 1998), suggesting that microflares do not contribute significantly to coronal heating of active regions.

2. Multi-temperature structures in the corona are revealed with joint observations with SOHO, sounding rocket experiments, and ground-based coronagraphs (Ichimoto et al. 1995; Yoshida et al. 1995).
3. The temperature maps deduced from SXT images show that the temperature structure is far different from the spatial distribution of soft X-ray intensity (Figure 4) (Yoshida and Tsuneta 1996). The active region corona consists of two components; one is cooler, quasi-steady structures with 3–5 MK, and the other is hotter (>5 MK), transient structures such as cusp-shaped features and multiple loop structures due to microflares (Sterling, Hudson, and Watanabe 1997).

4. The temperature of coronal holes may be similar to that of quiet regions (Hara et al. 1992). In these regions, the temperature of the corona appears to slightly increase with height (Sturrock, Wheatland, and Acton 1996; Foley, Culhane, and Acton 1997).

5. A deep survey of nanoflare events was made with temporal sequences of high sensitive SXT images (Shimizu and Tsuneta 1997). Short timescale variability fainter than transient brightenings (microflares) is found almost everywhere in active regions and X-ray bright points, whereas no significant variability is found in quiet regions.

6. The distributions of physical parameters along coronal loops have been studied to learn about the heating mechanisms (Kano and Tsuneta 1995; Klimchuk and Porter 1995). The temperature is higher at the apex than at the footpoints of coronal loops. The "RTV" scaling law among the maximum temperature, gas pressure, and length of loops was confirmed with Yohkoh.

7. Soft X-ray imaging observations have been continuously made for more than 6 years since 1991. Long-term changes of the heating in different coronal regions have been monitored from the solar maximum over the solar minimum (Figure 5).

Table 1 Overview of Solar-B

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Orbit</td>
<td>600 km Sun-synchronous polar orbit</td>
</tr>
<tr>
<td>Weight</td>
<td>~700 kg (dry) + ~170 kg (thruster gas)</td>
</tr>
<tr>
<td>Launch</td>
<td>February 2004</td>
</tr>
<tr>
<td>Lifetime</td>
<td>&gt;3 years</td>
</tr>
<tr>
<td>Attitude control</td>
<td>3-axis stabilized body control with tip-tilt mirrors for optical telescope</td>
</tr>
<tr>
<td>Data rate</td>
<td>~500 kbps</td>
</tr>
<tr>
<td>Amount of data</td>
<td>~4 Gbits per orbit</td>
</tr>
<tr>
<td>Telemetry rate</td>
<td>~5 Mbps</td>
</tr>
</tbody>
</table>

2 SOLAR B INSTRUMENTATION

Yohkoh has made great advances in understanding dynamics of the corona and flares. The next vital step is to understand the magnetic origin of coronal dynamics and heating. Solar-B, which is Japan's next solar physics mission under preparation for its launch in February 2004, is designed in order to establish the connection of the dynamics and heating observed in the hot corona into the
magnetic field at the photosphere; simultaneous observations are made over a range of different heights and temperatures, i.e., from photosphere (6,000 K) to hot corona (> 2 MK). Solar-B will have a coordinated set of instruments:

(1) A 50 cm optical telescope equipped with a narrowband filter imager and a spectro-polarimeter to make accurate measurements of vector magnetic and velocity fields at ~ 0.2 arcsec resolution.

(2) An X-ray telescope to image coronal plasma in the range of 0.7 - 10 MK at ~ 1 arcsec resolution.

(3) An EUV imaging spectrometer to measure velocity fields in the corona and transition region.

Since the conference focuses on scientific discussions about future space observations, the paper does not intend to give technical details for the design of Solar-B (Figure 6). Instead we give only those closely relating to Solar-B science. The overview of Solar-B is summarized in Table 1 and specifications of the three telescopes are listed in Table 2 and Table 3. Note that details of the specifications are not finalized at this stage.

Solar-B will be launched by an M-5 rocket into a 600-km circular polar sun-synchronous orbit. Such an orbit provides us with continuous viewing of the Sun for about 8 months in a year. Yohkoh has satellite night continuing for about 40 minutes every ~ 95 minutes' orbit, interrupting observations of X-ray phenomena of interest. Big flares often take place during night and Yohkoh has missed observations of such flares. At ground-based observatories, one can observe the Sun continuously for about 12 hours at maximum, but excellent seeing condition does not continue for more than tens of minutes. Thus, with continuous observations from space, great advances will be expected on studies of evolitional changes of magnetic and velocity fields.

For the optical telescope, a ~ 50 cm diameter telescope is proposed, which provides continuous series of ~ 0.2 arcsec images in the 390 - 660 nm wavelength range. The focal plane package of the telescope consists of a filter optics and a spectograph. The filter optics is used for high time resolution observations. In which the narrowband filter provides 2-D maps of magnetic and velocity fields and the interference filter provides high-quality images. The spectograph provides three components of the photospheric magnetic field with high accuracy by measuring Stokes I, Q, U, V profiles (Figure 7), although on relatively slow time scales.

The X-ray telescope is proposed to image coronal plasma in the range of 0.7 - 10 MK at ~ 1 arcsec resolution. Joint observations among SOHO EIT, Yohkoh, and sounding rocket experiments have shown different coronal structures from each other due to the difference in the tem-
Penumbra Stokes Spectra
Advanced Stokes Polarimeter
18 Jun 1992, μ=0.91, 630nm

I (ADU): 0.0
Q^{max} : 0.0492
U^{max} : 0.0492
V^{max} : 0.1506

Figure 7. Example of precision spectro-polarimeter observations. This is a set of polarisation images from the HAO/NSO Advanced Stokes Polarimeter (courtesy of Dr. B. W. Lites).

3. SCIENTIFIC OBJECTIVES

The main goal for the Solar-B mission is to comprehensively understand the corona and photosphere as a system. This goal widely covers many scientific areas in solar physics. Figure 8 summarizes the scientific objectives of Solar-B. Instruments necessary for understanding each topic are also indicated in the figure. In the following subsection, we discuss four selected major topics.

3.1 NATURE OF MAGNETIC FIELD IN THE PHOTOSPHERE

Weak (a few × 10 - a few × 100 gauss) magnetic fields in the corona which manifest themselves as coronal loops converge into localized areas with diameter of ~100 km at the photosphere. Studies using Stokes profiles of photospheric lines have revealed that the magnetic field at the photosphere is mostly strong (order of kilogauss). Strong magnetic fields, which are called thin magnetic flux tubes, thus have a discrete spatial distribution on
the solar surface. High spatial resolution observations in G band show that bright points with $\sim 100$ km size are also discretely distributed at the boundaries of granules (Figure 9). Since these bright points are co-spatially located with magnetic field regions observed with high spatial resolution magnetograms, they are believed to be the cross sections of thin magnetic flux tubes across the photosphere.

It is widely believed that the magnetic field of the Sun is formed and maintained by a dynamo process operating near the base of the convection zone. Magnetic field balloons up to the photosphere due to magnetic buoyancy and appears above the photosphere as newly emerging flux. The flux tubes just after the emergence are observed to have $\sim 500$ gauss (Brault 1983; Martínez Pillet, Lites, and Skumanich 1997), whereas most flux tubes at the photosphere have strength of greater than $1000$ gauss (e.g., Steenbock 1994). It has been proposed theoretically that the magnetic field of flux tubes is strengthened by convection at the photosphere (convective collapse).

The physical processes involved in the emergence of magnetic field, the formation (also diffusion) of strong thin flux tubes, and the dynamics of flux tubes have not been observed in detail because of lack of continuous high-spatial resolution observations. The Solar-B optical telescope has $0.2$ arcsec resolution which is comparable to the size of thin flux tubes, enabling us to directly observe physical processes involved in flux tubes. Measurements of Stokes profiles with high precision also provide physical condition inside thin flux tubes, although the spatial resolution of the telescope may not be enough to completely resolve the structure inside tubes.

Since the formation and diffusion of thin flux tubes is closely associated with convective motions on and below the photosphere, understanding convective motions is also a major objective of Solar-B. Three scales of convective motions have been observed; granulation in $\sim 1000$ km, meso-granulation in $\sim 10,000$ km, and supergranulation in $\sim 30,000$ km. The convective motions are complicated and anomalously shaped granules are frequently observed. Considering the complicated behavior of convective motions, we can imagine that magnetic flux tubes also have complicated dynamics. Such motions of flux tubes may play an important role in heating the upper atmosphere and triggering dynamical phenomena in the corona.

Important objectives of Solar-B magnetic field measurements for understanding the processes by which magnetic flux evolves are:

1. To explore the nature of newly emerging magnetic flux.
2. To explore the dynamical and physical properties of magnetic flux in association with convective motions.
3. To determine the magnetic flux evolution of individual active regions, and
4. To explore the fate of quiet region magnetic flux.

In the objectives stated above, the precision of magnetic field measurement is essential. The Solar-B optical telescope will provide the first opportunity to measure vector magnetic fields with sufficient precision and temporal continuity to address these fundamental objectives.
3.2. COUPLING OF CORONAL DYNAMICS WITH PHOTOSPHERIC MAGNETIC FIELDS

Yohkoh observations show that the hot corona consists of dynamical phenomena, such as flares, microflares, jets, and coronal restructuring. It is clear that observing photospheric magnetic field changes is the key to understanding flares and dynamical phenomena. It is well known that phenomena such as δ-sunspot configurations and newly emerging flux are associated with these events.

Due to limitation of the seeing condition, however, we have not clearly identified the photospheric magnetic activities responsible for coronal disruptions. The Solar-B optical telescope will provide continuous sequences of images of the magnetic field at the photosphere with high spatial, temporal, and spectral resolution. Joint observations involving the optical and X-ray telescopes will be used to identify the key changes in the vector magnetic fields that are responsible for flares and coronal activities.

The following example tells us the importance of high spatial and temporal resolution observations with high precision in understanding physical processes of coronal dynamics. Visible light high-resolution observations were made at La Palma (Swedish Solar Observatory) simultaneously with Yohkoh soft X-ray observations. Figure 10 shows a microflare (transient brightening) which had a close connection with the emergence of new small magnetic elements. The small-scale emergence of a magnetic flux pair took place ~ 10 minutes prior to the onset of the brightening. The bulk of the positive-polarity magnetic flux moved outward with the speed of 2.8 km/s, while the bulk of the negative-polarity flux moved in the opposite direction. The flux magnitude of the emerging flux elements is in order of $10^{17} \sim 10^{18}$ Mx, meaning that this emerging activity is small. This study (Shimizu 1996) found that such a small-scale emerging flux was associated with the onset of brightenings for 8 events of 16 microflares examined. Many of the 8 events accompanied the emergence of a small-scale flux element 5 ~ 30 minutes prior to the onset of the brightening. On the other hand, the study showed no evolutorial changes in photospheric magnetic field for the rest of the examined microflares (8 events). Most of these microflares were observed in relatively strong magnetic field regions, such as plage regions and satellite sunspots. The reason why no evolutorial changes were observed for the microflares occurring in strong magnetic field regions may be the lack of spatial resolution and accuracy in the measurement of polarization; in observations from the ground, seeing introduces false, rapidly fluctuating noise in the measurement of polarization, making it difficult to identify the small-scale emerging flux in strong magnetic field regions.

Establishing the coupling between the corona and photosphere is essential in understanding coronal dynamics and heating as a system. Important objectives of Solar-B for the coupling are:

1. To explore the processes responsible for the energy build-up in the corona,
2. To identify the topology of magnetic fields responsible for energy release (magnetic reconnection) in the corona, and
3. To identify key changes in vector magnetic fields responsible for triggering flares and coronal activities.

3.3. CORONAL HEATING

The mechanisms that heat the solar corona to high temperatures ($> 10^5$ K) remain controversial. Solar-B can be expected to give observational hints to answer why the corona is so hot. The corona is inhomogeneous, meaning that magnetic fields play a major role of the heating. High temperature coronal plasma is much observed in magnetic bundles connecting magnetic polarities within active regions. It is widely accepted that the energy to heat the corona to high temperatures originates in the convection below the photosphere. This energy propagates into the upper atmosphere through magnetic field lines and then dissipates in the corona.

Alfvén waves and electric currents have been mainly considered as mechanisms to transport the energy into the corona. Alfvén waves generated by twisting and bending of the magnetic field propagates along magnetic flux tubes into the corona. Current sheets (tangential discontinuities) arise as a consequence of intermixing of the footpoints of the magnetic field due to convective motions in the photosphere. Joule heating and magnetic reconnection (Parker’s nanoflares) have been proposed as mechanisms for the dissipation of currents.

The main questions on coronal heating are as follows:

1. Are Alfvén waves and/or currents generated by convective motions sufficient to heat the corona?
2. Can Alfvén waves and/or currents propagate into the corona?
3. Can Alfvén waves and/or currents be efficiently dissipated in the corona?

Great advances in answering these questions can be made with a coordinated set of instruments on Solar-B.
Table 4. Advances Expected from Solar-B.

<table>
<thead>
<tr>
<th>Topics</th>
<th>Expected Advances</th>
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<tbody>
<tr>
<td>Coronal heating</td>
<td>Processes of current / Alfven wave generation</td>
</tr>
<tr>
<td></td>
<td>Processes of Alfven wave propagation</td>
</tr>
<tr>
<td></td>
<td>Processes of current / Alfven wave dissipation</td>
</tr>
<tr>
<td>Thin flux tubes</td>
<td>Direct detection of thin flux tubes</td>
</tr>
<tr>
<td></td>
<td>Formation and diffusion of flux tubes</td>
</tr>
<tr>
<td></td>
<td>Group motions of flux tubes</td>
</tr>
<tr>
<td>Magneto-convection</td>
<td>Interaction between convection and magnetic field</td>
</tr>
<tr>
<td></td>
<td>Details of granules, meso-granules, and super-granules</td>
</tr>
<tr>
<td>Active regions</td>
<td>Precise magnetic field structures</td>
</tr>
<tr>
<td></td>
<td>Precise current system</td>
</tr>
<tr>
<td></td>
<td>Processes of flux emergence and disappearance</td>
</tr>
<tr>
<td>Coronal Dynamics (flares)</td>
<td>Coupling with photospheric magnetic field</td>
</tr>
<tr>
<td></td>
<td>Magnetic field changes responsible for coronal dynamics</td>
</tr>
<tr>
<td></td>
<td>Plasma motions in dynamics</td>
</tr>
<tr>
<td></td>
<td>Plasma motions (outflows and inflows)</td>
</tr>
<tr>
<td>Magnetic reconnection</td>
<td>Magnetic field structures associated with reconnection</td>
</tr>
<tr>
<td></td>
<td>Drivers to trigger reconnection</td>
</tr>
<tr>
<td>Solar wind</td>
<td>Dynamics of EUV jets and associated magnetic field</td>
</tr>
<tr>
<td>Dynamo</td>
<td>Magnetic field structures in active regions</td>
</tr>
</tbody>
</table>

3.4. PHYSICS OF MAGNETIC RECONNECTION

Yohkoh has illustrated that magnetic reconnection plays a major role of the release of energy in solar flares. In long duration flares, cusp-shaped soft X-ray structure was observed with highest temperatures in the periphery. Such a cusp structure had been predicted by the theory of magnetic reconnection. In impulsive flares, a hard X-ray source is found above a flaring loop, which could possibly be explained as a consequence of magnetic reconnection with rapid outflow impinging on denser material in the underlying loop.

Understanding the process of magnetic reconnection in detail is also an important objective for Solar-B. Since Solar-B will fly near the end of solar maximum, large flares will not occur frequently during the mission. Yet, smaller flares and microflares still occur throughout the solar cycle. Magnetic reconnection may play a major role of the release of energy even in smaller flares and microflares. Yohkoh showed that the frequency distribution continues from flare range over microflare range, suggesting that microflares share the same physics.

The velocities expected to be associated with the processes of magnetic reconnection range from a few tens to more than 1000 km/s; the velocity of plasma inflow into a reconnection site is expected to be a few tens km/s, and the high-speed jets ejected outwards from reconnection site move at the Alfvén speed in the corona. Slow and fast mode shocks may be produced by the reconnection jet. By measuring mass motions over a range of temperatures characteristic of the pre-flare and flaring states, the X-ray telescope and the imaging spectrometer will be able to identify the role of magnetic reconnection in flares.

4. SUMMARY

Advances we are expecting with Solar-B are summarized in Table 4. These advances can be achieved only with a coordinated set of optical and X-ray instruments with high resolution.

ACKNOWLEDGMENTS

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Yohkoh/SXT - La Palma Observations

Active-Region Transient Brightening
21-June-92 9:48 UT  AR 7201

La Palma

Yohkoh/SXT

(a) Time Profile of Soft X-Ray Intensity

(b) Time-Space Slice through Small-Scale Magnetic Emergence

Figure 10. An example of the connection between the photosphere and the corona. Visible light observations were made at La Palma (Swedish Solar Observatory) simultaneously with Yohkoh X-ray observations. Time-space slice map (right) shows the evolutionary change of the longitudinal magnetic field at the spatial section indicated by arrows in the magnetogram image.