Solar Physics with Radio Observations, Proceedings of Nobeyama Symposium 1998, NRO Report 479

Solar Max 2000: Scientific Objectives and Coordinated Observations

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Abstract

The solar maximum 2000 will be an unprecedented opportunity for solar physicists to conduct detailed studies of various solar active phenomena with a lineup of advanced, space-borne, and ground-based observing instruments. Of particular importance is a combination of hard X- and gamma-ray imaging made with the High Energy Solar Spectroscopic Imager (HESSI) and radio imaging made with, e.g., the dual-frequency Nobeyama Radioheliograph, with which we anticipate being able to understand magnetic energy release and particle acceleration mechanisms more deeply than so far achieved. The lineup of the observing instruments in the coming Max 2000 and their scientific objectives are discussed from a viewpoint of coordination of observations.

Key words: Sun: magnetic activity — Sun: flares — Sun: X-ray emission — Sun: radio emission

1. Introduction

Since the launch of *Yohkoh* (Ogawara et al. 1991) in 1991, our understanding of the solar corona and of active phenomena taking place there have been revolutionarily improved. Continuous observations with the Soft X-ray Telescope (SXT; Tsuneta et al. 1991) have revealed that the solar corona is an entity that changes its structure much more dynamically in various space- and time-scales than had been thought before. They have also revealed that most of the structural changes involve magnetic reconnection as an essential process. The occurrence of magnetic reconnection is best evidenced by the cusp-shaped arcade of loops frequently seen in the gradual phase of long-duration flare events (LDEs) as well as in arcade formation events associated with prominence eruption (Tsuneta et al. 1992a,b). Such a cusp-shaped structure itself could not be formed without a current sheet above it. Moreover it is confirmed that temperatures increase towards the outer edge of the continuously growing cusp-shaped structure, which suggests that magnetic reconnection is in progress in the current sheet above the cusp-shaped arcade, releasing magnetic energy there.

Hard X-ray imaging of impulsive flares with the Hard X-ray Telescope (HXT; Kosugi et al. 1991) on board *Yohkoh*, in conjunction with soft X-ray imaging with SXT, has further confirmed this reconnection picture. Hard X-rays above ~ 30 keV are mainly emitted from a pair of footpoints of a flaring soft X-ray loop. The two sources vary their intensity almost synchronously within a fraction of a second. These facts can be interpreted as thick-target Bremsstrahlung emission from down-streaming electrons energized near the loop apex (Sakao 1994). A third hard X-ray source, located above the corresponding soft X-ray loop apex, has been found in a number of flares occurring near the limb, which is named the above-the-looptop source (Masuda 1994; Masuda et al. 1994; see also Kosugi 1996). This may originate in either the energy release site, i.e., the reconnection point, or the site where the fast shock is formed due to a collision of super-Alfvenic reconnection outflow against previously reconnected magnetic fields now seen as soft X-ray loop. In either case, it is suggested that the impulsive flare involves a much wider volume than that seen as bright, soft X-ray loop. In fact, Shibata et al. (1995) found that a dynamical process, faintly seen in soft X-rays as plasmoid ejection and/or jet, takes place in the surroundings and plays a key role in impulsive flares. Independently the electron time-of-flight analysis by Aschwanden et al. (1996a,b,c) presented supportive evidence for electrons being accelerated outside the bright, soft X-ray loop. All of these new observations are consistent with the standard 2-D picture of magnetic reconnection, i.e., the Carmichel/Sturrock/Hirayama/Kopp and Pneuman (CSHKP) model for eruptive flares (see, e.g., Svestka and Cliver 1992). Note, however, that actual 3-D magnetic field configuration for magnetic reconnection is still only vaguely known. Also note that quantitative analysis of solar flare observations in the context of magnetic reconnection theory has been barely made successfully; for a primitive trial toward this goal, see, e.g., Tsuneta et al. (1997).

During the past seven and half years since *Yohkoh* was launched, several instruments for studying the solar corona have been newly built or drastically upgraded both on the ground and in space. The Nobeyama Radioheliograph started its routine observation at a single frequency of 17 GHz in 1992 (Nakajima et al. 1994; see also Nishio et al. 1994 and Hanaoka et al. 1994) was upgraded into a dual frequency system in 1995 (Takano et al. 1996). The Nancay Radioheliograph was upgraded into a complete 2-D imaging instrument (Kerdraon and Delouis 1996). The SOHO spacecraft started its full operation in 1996 with state-of-the-art instruments (e.g., Domingo, Fleck & Poland 1995), followed by the TRACE satellite in 1998 (Tarbell et al. 1994). All of these instruments, including both SXT and HXT on board *Yohkoh*, are expected fully operational during the coming solar maximum, Max 2000. In addition the High Energy Solar Spectroscopic Imager (HESSI) will come soon (Hurford et al. 1999). In the following, we first briefly see what instrumentation we have for Max 2000 in Section 2. Then we discuss what problems will be challenged with what combination of instruments in Section 3. Final remarks, based upon discussions made during the Symposium at Kiyosato, will be given in Section 4 for realizing better coordination of observations and data analyses.

2. Solar Observation Networks during Max 2000

Let us briefly summarize the key instrumentation we will have in the year 2000 for the study of the solar corona. Emphasis is put on high-energy phenomena detectable with radio instruments.

In short radio wavelengths, the Nobeyama Radioheliograph operating at 17 and 34 GHz most continuously provides full Sun images eight hours daily with moderate spatial resolution, while the OVRO solar array has an advantage in spectral imaging of an active region below ~ 10 GHz (Gary and Hurford 1999). On the contrary, VLA and BIMA provide radio imaging with the highest spatial resolution and in the highest frequency range, respectively, either of which is of crucial importance in deeply understanding the site and mechanism of electron acceleration. These latter two instruments are not dedicated for solar observations alone so that we need to obtain telescope time on a competition basis via the peer review process.

In the decimeter, meter, and decameter wavelengths, the Nancay Radioheliograph (Kerdraon and Delois 1996) is a solar-dedicated instrument capable of providing full Sun images. It is supplemented by digital radiospectrographs such as PHOENIX-2 at Bern (Messmer et al. 1999) in the European time zone. Another important telescope will be the Giant Meterwave Radio Telescope (GMRT) in India, the current status of which is not well known to the author unfortunately. There is no doubt, however, that GMRT is potentially a unique telescope operating in the decameter wavelengths so that it may play a vital role in the study of birth and early development of coronal mass ejections in combination with SOHO LASCO white-light coronagraphs (Brueckner et al. 1995).

In space, the *Yohkoh* SXT and HXT will be operated and provide, respectively, soft X-ray imaging that is most sensitive to the hot corona, say above 3 MK, and hard X-ray imaging of solar flares. At the same time, SOHO EIT (Delaboudiniere et al. 1995) and CDS (Harrison et al. 1995), as well as TRACE hopefully, will be operated and provide arcsec-level spatial resolution imaging in the EUV range that covers throughout the chromosphere and the corona with temperatures below a few MK. Also SOHO MDI (Scherrer et al. 1995) provides magnetograms with moderate spatial resolution. And HESSI will start its hard X- to gamma-ray imaging hopefully by summer 2000. The Compton Gamma Ray Observatory will also continue its operation.

Magnetographs on the ground will continue to play an important role. In particular, vector magnetic field measurement, under rapid upgrading at several observatories over the world, will play a central role in unambiguously deriving coronal magnetic field and electric current distributions.

3. Problems to Challenge

With the lineup of these powerful instruments discussed above at hand, we solar physicists will soon have an unprecedented opportunity to conduct detailed studies of solar active phenomena during the coming maximum, Max 2000. Below we discuss some of the key problems to challenge shortly.

(1) Coronal Loops and the Cause of Their Dynamics

The solar corona, seen in soft X-ray and EUV lines, consists of numerous loops (best seen in high resolution TRACE observations) and there is a consensus in solar physics that these loops trace magnetic field lines. In fact, the majority of quasi-static loops tend to rather smoothly connect northern and southern photospheric magnetic polarities, which resembles a potential field configuration. Some other quasi-static loops, however, are S-shaped or sigmoidal, indicating electric currents flowing. Even in the latter case the fields need be approximately force-free, i.e., the currents flow only along the magnetic field lines, since the corona is in a so-called low-β plasma condition, i.e., the gas pressure is overwhelmingly dominated by the magnetic pressure. Once the currents flow, then the magnetic field lines inevitably become helical, which has not yet been observed in tiny scales of individual coronal loops. Hence, though there is no doubt that the apparent loop structure well represents the magnetic field structure in general, a simple question such as which is magnetically more intense, loops or inter-loop gaps, has not yet been answered.

The *Yohkoh* SXT has observed even smooth, semi-circular coronal loops above an active region gradually and intermittently expanding (Uchida et al. 1992). Sometimes the expansion seems to be associated with kink-shaped magnetic fields and followed by onset of some flaring activity (Acton et al. 1992). What makes coronal loops expand? It is widely believed that either flux emergence from below the photosphere or convective motion of magnetic elements at the photosphere triggers this expansion. However, we have not yet understood the conditions of coronal loop expansion.

These basic questions may be answered by a detailed comparison between the high-resolution TRACE images, supplemented by *Yohkoh* SXT and SOHO EIT images, and high-resolution vector magnetograms taken on the ground.

(2) Energy Release via Magnetic Reconnection

The solar flare, and solar eruptive phenomenon in general, may be fully understood when we become acquainted with the necessary and sufficient conditions for the following three steps: a) energy buildup, b) sudden destabilization, and c) total disruption, of the coronal magnetic field above an active region. Since the coronal magnetic field may gradually change its structure adaptively to evolution of the photospheric magnetic field, buildup of a certain amount of energy would not occur without a specific condition satisfied. In other words, we do need to distinguish two cases of coronal magnetic filed restructuring, one is associated with significant energy release (the flare itself) and the other with energy accumulation (the flare buildup). Destabilization of the coronal field may be attributable to sudden increasing jump of resistivity (anomalous resistivity) due to gradually increasing current density crossing over a certain threshold. However, this remains just as a hypothetical view with no direct observational evidence.

A breakthrough toward this goal may be obtained when we successfully determine pre- and post-flare magnetic field configurations in the corona. By combining soft and hard X-ray images taken by *Yohkoh* with microwave images taken with the Nobeyama Radioheliograph, Hanaoka (1996, 1997) and Nishio et al. (1997) have shown that a flaring region contains a more complex magnetic field structure than had been expected from the CSHKP model. They have stressed the loop-loop interaction process as essential for the flare energy release. Though the relation between the 2-D CSHKP model and the 3-D loop-loop interaction concept has not yet been so clear, it is evident that a simple loop-with-a-cusp structure extracted from *Yohkoh* observations alone is oversimplification. In order to further investigate this point, soft and hard X-ray images at higher spatial resolution than those from *Yohkoh* need be compared in detail with microwave images at arcsec-level spatial resolution, hopefully supplemented by vector magnetograms. It has also to be emphasized that the observations presented by Hanaoka and by Nishio et al. have not directly provided information on the pre-flare magnetic field configuration. Since the pre-flare magnetic field configuration may be seen only as faint loops, we need higher-quality images both in spatial resolution and in dynamic range, which will be hopefully provided by TRACE.

(3) Particle Acceleration in Flares

This problem is one of the most complicated. First, it is not rare that energetic particles, mainly protons, are detected by near-Earth spacecraft or as ground-level proton events even without chromospheric flares reported. These particles may be due to interplanetary shocks. Similarly most of interplanetary type III radio bursts, for which electrons with energies of several keV to a few tens of keV are responsible, are associated with meter-wave or decameter-wave type I storms but not with any chromospheric flares. Hence particle acceleration does not necessarily require a chromospheric flare process; both ions and electrons are readily accelerated high in the outer corona or in interplanetary space. In fact particle acceleration in shock fronts has been confirmed by *in situ* observations at the Earth's bow shock. Second, a flare may generate a coronal fast-mode shock, detected as meterwave type II burst, which is powerful enough to accelerate both ions and electrons. In this case the particle acceleration may not be directly related to the primary energy release in solar flares. Here just for simplicity, let us limit our scope into particle acceleration in the flare impulsive phase, which is widely believed to represent the primary energy release.

Even so limited, particle acceleration is among the most mysterious. Electrons are accelerated to several tens of keV in less than a second. The total energy carried by these electrons, estimated from hard X-ray Bremsstrahlung emission, occupies a large fraction of the total energy released in a flare, say more than a few tens of percents. How is the magnetic energy converted into particle energy so efficiently? In addition, in some intense flares, ions are similarly efficiently energized to a few hundred MeV/nucleon or above one GeV/nucleon in a few seconds. How are ions accelerated to such high energies so quickly? To make things more puzzling, the total energy carried by ions is estimated to be as large as that by electrons.

So far no consensus has been achieved on the particle acceleration mechanism. To the author's knowledge, basic questions, such as whether particles are accelerated in parallel or perpendicular to the magnetic field or whether ions are accelerated to the same direction as electrons, are still open issues. We anticipate that HESSI, the first imager capable of gamma-ray line imaging in addition to hard X-ray imaging, will provide us with some definitive observational answers to these simple but crucial questions. Also in combination with soft X-ray and EUV images that reflect magnetic field structure of a flaring region, we anticipate that HESSI be capable of pinpointing the magnetic field configuration that is essential for particle acceleration.

(4) Coronal Mass Ejections (CMEs) *versus* Flares

The majority of (chromospheric) flares occur in a single active region near sunspots, while CMEs may occur outside active regions, with some occurring at high latitudes near the poles, and hence a CME usually occupies a much larger volume than a flare. However, no clear-cut classification of eruptive solar events into the two categories seems possible. On one hand, flares are frequently associated with activation or eruption of active region filaments, which is one of the signatures that are intimately related to CMEs. On the other hand, careful examination reveals that CMEs without flares are frequently associated with faint brightenings of chromospheric patches. Hence, these two may be regarded as two representative aspects of an identical process, i.e., disruption of coronal magnetic structure, though diversely different in spatial and temporal scales as well as in energy density released.

A CME typically consists of three ascending components: a frontal loop, void (or cavity), and a dense core (or erupting filament). This three-component structure cannot be interpreted in terms of piston-driven shock; even the frontal loop expansion speed is not necessarily super-Alfvenic. Then, what drives the CME to ascend? The driving force is magnetic in origin, since the kinetic energy conveyed by a CME frequently dominates the thermal energy. However, we have not yet known observationally what magnetic field instability gives rise to a CME to launch.

High solar activity such as expected in Max 2000 may not be suitable for understanding the CME's driving mechanism because of complexity of a single event or possible superposition of multiple events. On the other hand, we may have a better possibility of detecting the most energetic CME events. The relation of CME to flare may be clarified by comparing radio and X-ray images with SOHO LASCO observations.

(5) Coronal Heating and the Solar Wind

How is the solar corona heated to millions K? How is the solar wind accelerated to faster than several hundred km/s? These are very basic problems remaining unsolved. Though solar maximum conditions may not be suitable for challenging these problems, let me briefly touch them.

Recently, and especially since *Yohkoh* revealed the presence of numerous tiny energy release events named active region transient brightenings (Shimizu et al. 1992), a hypothesis that microflares or nanoflares heat the corona has received wide attention. An important piece of evidence for this hypothesis has been obtained from SOHO EIT observations that the number distribution of network flares or tiny, heating events increases toward less energetic events with a power-law slope steeper than the critical one with the index of -2 (Krucker and Benz 1998). Such a study need be made throughout the whole electromagnetic wavelengths with the most modern high-sensitivity and high-resolution instruments to clarify the energy flow and the dissipation mechanism.

It is more than a mystery that high-speed solar wind originates from coronal hole regions, which apparently contradicts the fact that coronal holes are regions to which less energy is supplied. Thus direct transfer of momentum to solar wind is required. However, no knowledge has been obtained on where and how the momentum flows and is transferred to solar wind.

4. Toward Max 2000: Schemes for Coordinated Observations

As discussed in the previous sections, we have at hand many new, powerful instruments for advancing our knowledge on the solar corona. Some of the basic problems are also specified, each of which is better challenged with a good coordination of observations covering wider electromagnetic wavelengths as far as possible. Based upon such a common understanding, several key issues for better coordination were discussed in the Symposium, which are briefly summarized below.

(1) Organization of campaign-type observations. Though some of the instruments are solar-dedicated, have wide fields of view covering the whole Sun, and hence are operated on a routine basis, even such instruments are benefited by well organized campaigns to select the intervals of concentrated observation. For other instruments that have narrower fields of view, worldwide campaigns help to select observing targets and modes. Of crucial importance is the fact that campaigns would help solar physicists to apply to telescope times of non-solar-dedicated radio instruments such as VLA and BIMA. Hence it is urgently needed to start organizing such worldwide campaigns.

(2) Exchange of observation information. This is the most rapidly developing area in our collaboration. The Internet and Web system has now become popular so that we can exchange observation logs almost in real time. It is recommended that not only the observing logs but also as large a fraction of raw observation materials as possible be made accessible from outside for joint data analyses.

(3) Data exchange. Some participants strongly argued for the so-called open-data policy that allows any outsiders to freely access any data. Others opposed this policy, claiming that each observatory (and observers there) should be privileged to access its own data in comparison with from outside. This latter view is not for excluding access to data by outside users, however. It is, instead, based upon a sincere desire that data be used in a collaborative way between inside and outside users, rather than in simple outflow of the data. Although the two policies apparently differ from each other, there was a consensus that all the data need be shared on a give-and-take (or exchange) basis for the benefit of either side. It was agreed that individual observatories would make their best efforts to accommodate this basic principle in various ways.

(4) Data exchange media and analysis tools. Though not fully discussed in the Symposium, this is one of the most important for practically developing our worldwide collaboration. We need to continue our discussion for establishing better ways.

References

Acton, L. W. et al.: 1992, S*Science* **258**, 618.
Aschwanden, M. J. et al.: 1996a, *ApJ* **464**, 965.
Aschwanden, M. J. et al.: 1996b, *ApJ* **468**, 398.
Aschwanden, M. J. et al.: 1996c, *ApJ* **470**, 1198.
Brueckner, G. E. et al.: 1995, *Solar Phys.* **162**, 357.
Delaboudiniere, J.-P. et al.: 1995, *Solar Phys.* **162**, 291.
Domingo, V., Fleck, B. & Poland, A. I.: 1995, *Solar Phys.* **162**, 1.
Gary, D. E. and Hurford, G. J.: 1999, in these Proceedings.
Hanaoka, Y. et al.: 1994, in S. Enome and T. Hirayama (eds.), *Proc. Kofu Symp.* (NRO/NAO; Nobeyama, Japan), pp.35-43.
Hanaoka, Y.: 1996, *Solar Phys.* **165**, 275.
Hanaoka, Y.: 1997, *Solar Phys.* **173**, 319.
Harrison, R. A. et al.: 1995, *Solar Phys.* **162**, 189.
Hurford, G. J. and the HESSI Team: 1999, in these Proceedings.
Kerdraon, A. and Delois, J.-M.: 1996, in G. Trottet (ed.), *Coronal Physics from Radio and Space Observations* (Springer-Berlag; Berlin), pp.192-201.
Kosugi, T. et al.: 1991, *Solar Phys.* **136**, 17.
Kosugi, T.: 1996, in R. Ramaty et al. (eds.), *High Energy Solar Physics* (AIP Conf. Proc. **374**), pp.267-274.
Krucker, S. and Benz, A. O.: 1998, *ApJ. Lett.* **501**, L213.
Masuda, S.: 1994, PhD thesis, University of Tokyo (available upon request from author).
Masuda, S. et al.: 1994, *Nature* **371**, 495.
Messmer, P. Benz, A. O., & Monstein, C.: 1999, *Solar Phys.* (in press).
Nakajima, H. et al.: 1994, *Proc. IEEE* **82**, 705.
Nishio, M. et al.: 1994, in S. Enome and T. Hirayama (eds.), *Proc. Kofu Symp.* (NRO/NAO; Nobeyama, Japan), pp.19-33.
Nishio, M. et al.: 1997, *ApJ* **489**, 976.
Ogawara, Y. et al.: 1991, *Solar Phys.* **136**, 1.
Sakao, T.: 1994, PhD thesis, University of Tokyo (available upon request from author).
Scherrer, P. H. et al.: 1995, *Solar Phys.* **162**, 129.
Shibata, K. et al.: 1995, *ApJ. Lett.* **451**, L83.
Shimizu, T. et al.: 1992, *PASJ* **44**, L147.
Svestka, Z. and Cliver, E. W.: 1992, in Z. Svestka et al. (eds.), *Eruptive Solar Flares* (Springer-Verlag; Berlin), pp.1-11.
Takano, T. el al.: 1996, in G. Trottet (ed.), *Coronal Physics from Radio and Space Observations* (Springer-Berlag; Berlin), pp.183-191.

Tarbell, T. D. et al.: 1994, in *Proc. 3-rd SOHO Workshop* (ESA SP-373).
Tsuneta, S. et al.: 1991, *Solar Phys.* **136**, 37.
Tsuneta, S. et al.: 1992a, *PASJ* **44**, L63.
Tsuneta, S. et al.: 1992b, *PASJ* **44**, L211.
Tsuneta, S. et al.: 1997, *ApJ* **478**, 787.
Uchida, Y. et al.: 1992, *PASJ* **44**, L155.