THE YOHKOH CONTEXT FOR HIGH-ENERGY PARTICLES IN SOLAR FLARES

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ABSTRACT

Yohkoh, a satellite dedicated to high-energy observations of solar flares, began observations in September, 1991. It carries (i) a soft X-ray telescope with arcsecond resolution and excellent temporal sampling; (ii) a hard X-ray imager making the first images above 30 keV; (iii) a sensitive Bragg crystal spectrometer for soft X-ray emission lines, and (iv) a set of proportional and scintillation counters. The flare observations confirm the central role of impulsive-phase electron acceleration in causing "evaporation" and white-light flare emission. SXT has found impulsive soft X-ray time profiles at the footpoints. It also shows compact bright structures apparently at the tops of flaring loops during the gradual phase. Large flares may show cusp-shaped structures that strongly resemble the usual picture of coronal magnetic reconnection, but otherwise do not match the details of the classical flare scenario. The data taken as a whole suggest that large-scale magnetic reconnection in the solar corona does not drive flare energy release, but rather is driven by the flare; the reconnection may have an important role in flare triggering.

INTRODUCTION: YOHKOH

Our physical interpretation of solar high-energy observations of the Sun, thus far mainly non-imaging at hard X-ray and γ-ray energies, depends intimately upon our knowledge of the ambient conditions at the sources of the hard radiations. The corona represents a difficult observational problem at optical wavelengths because of the proximity of the bright photosphere, in spite of the invention of the coronagraph many decades ago. Soft X-radiation represents the natural product of the most prominent coronal plasma, which has temperatures on the order of (1-5) $\times$ 10^6 K. Until the present time, our knowledge of coronal structure and conditions based upon soft ($\sim$1 keV) X-ray observations has been limited to *Skylab* (ca. 1973-1974), plus limited sounding-rocket observations mainly using grazing-incidence telescopes with obsolete technology.

The *Yohkoh* satellite, launched at the end of August 1991 and almost fully functional at the time of writing of this paper (April 1993), has filled this observational gap by use of a modern soft X-ray telescope (SXT) with "superpolish" mirror technology and a CCD readout[1]. The CCD has 1024 $\times$ 1024 square pixels 2.46 arc s across. These advantages let SXT observe with large image dynamic range (because of the low-scattering optics and the CCD linearity) and with high time resolution. In addition to the SXT observations, *Yohkoh* carries a novel hard X-ray imager sensitive to flare radiations in the 15-100 keV range, plus spectrometers and photometers. The results are quite remarkable[2] and are beginning to inform us about many aspects of coronal physics, especially the physics of solar flares, the main target of *Yohkoh*. Initial results from *Yohkoh* have been published in a special issue of the *Publications* of the Astronomical Society of Japan.

Figure 1 demonstrates the sensitivity of the SXT observations by showing soft X-ray emission to be detectable some 20 arc min (1.1 $\times$ 10^{10} cm) above the solar limb in a set of medium-length exposures made on 8 May 1992. These clear low-scattering views of the direct X-ray emission of the hot corona may rank with Lyot's introduction of the coronagraph as a tool for general coronal investigation.

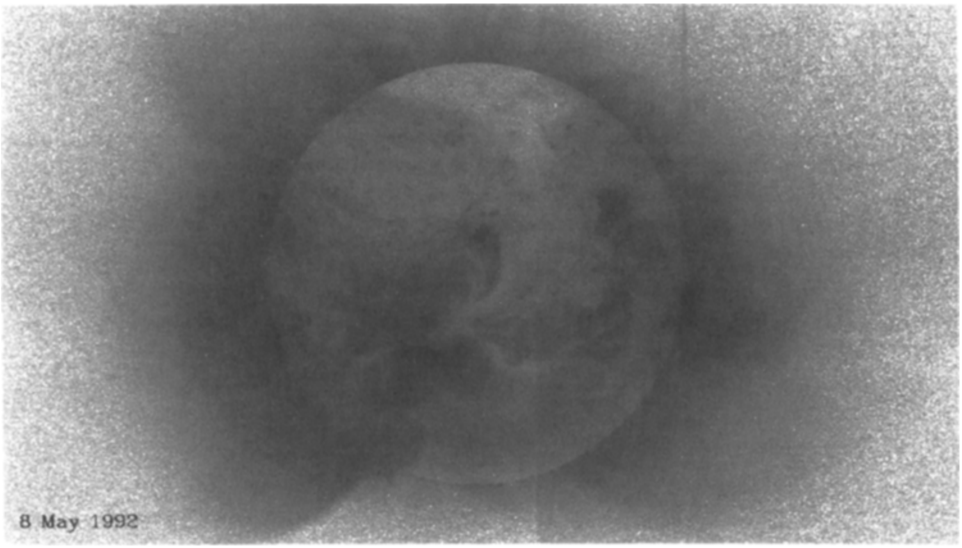

Fig. 1. Composite image of the soft X-ray corona obtained 8 May 1992. This and other images shown later are data from the Soft X-ray Telescope (SXT) on board *Yohkoh*. This telescope uses grazing-incidence "superpolish" optics, broad-band spectral filters sensitive in the 1–3 keV range, and a 1024 x 1024-pixel CCD readout. At the time of the Waterville workshop, it had returned almost 10^6 images of the corona, the quiet Sun, and flares. The images presented here are negatives.

This paper reviews the early results from *Yohkoh*, first in the area of "quiet" coronal structure, and then for flares specifically. As implied in the title, the major objective here is to present these results in a manner that will help to place non-imaging observations, for example from *Compton/GRO*, in the context of the solar phenomena that give rise to the hard radiations.

CORONAL STRUCTURES

Quasi-Static Structures

The large-scale structures visible in Figure 1 include the well-known active regions and coronal holes, plus a not-very-well-investigated "general corona" apparently consisting of plasma trapped in closed magnetic fields. Here "closed" means re-entrant into the photosphere relatively near to the exit point. The general corona has a more amorphous appearance than the active-region corona, which consists of discrete bright loops. Finally, the "outer" corona, extending in Figure 1 to distances greater than 10^{11} cm above the solar surface, appears to fall off in brightness with a power-law dependence upon radial distance. This presumably represents the region in which the solar wind is formed on open field lines that extend outwards into the heliosphere. None of these large-scale structures have been analyzed thoroughly yet in the *Yohkoh* data, largely because their low intensity and diffuse character make it necessary to have exact knowledge of telescope properties such as point-response function, vignetting, spectral calibration, and scattering. Information in these areas is now quite comprehensive, and quantitative results are in progress.

The loops seen mainly at lower altitudes and in active regions represent regions of high gas pressure, which can vary by perhaps as many as four decades across the loop boundaries. The magnetic pressure presumably does not vary as rapidly with position because of the observed persistence of the structures, which must thus have a nearly magnetostatic or force-free character. What causes a particular loop (or perhaps more appropriately, 'channel') to have strong energy input and a resulting high pressure represents an important sub-question to the general problem of coronal heating. The *Yohkoh* data, in comparison with ground-based vector magnetograph data, show that the relationship between X-ray brightness and the distribution of vertical electric currents in an active region is not simple[3].

The compact active-region bright loops appear to arise in sunspot penumbrae, rather than in the stronger fields of the umbrae themselves[4]. Although analysis is at a preliminary level, it appears that the main heating of these loops is continuous, rather than episodic[5], consistent with the finding that "microflares" cannot support coronal heating without having a physical nature different from that of ordinary flares[6].

Dynamic Structures

The SXT data show a great deal of variability in the solar corona, seemingly on all spatial or temporal scales. The types of variability range from jets and other transient ejecta, which can occur on small spatial scales, to huge developments in large volumes of the polar coronal regions[7]. This variability is best appreciated from a movie representation of the SXT data, which are hard to represent in a simple manuscript. The SXT movie consists of composite images assembled from multiple exposure times to increase the dynamic range, typically several frames per 96-minute orbit of *Yohkoh*. The sampling restriction acts like a "slow-pass filter", but nevertheless many events resembling slow coronal mass ejections have been observed.

Figure 2 shows a remarkable jet event of 7 Dec. 1991, in which a blob of plasma rose out of a compact active region, moved along a high-lying magnetic loop (about 8×10^{10} cm)[8]. at a velocity of some 1000 km/sec through the corona, and then re-entered the photosphere and apparently causing a secondary soft X-ray brightening. Such remote brightenings have previously been inferred from Hα and meter-wave observations, but with soft X-ray observations we can trace out the entire structure in which the motions occur. The X-ray plasmas appear to be well-collimated in jets of this type, unlike the geometry that might be expected from field line diverging in a potential-field configuration from photospheric sources alone[9]. A movie representation may give the appearance of whip-like motions of some of the jet trajectories[10], and there are many interesting unanswered questions regarding the physics of phenomena of these types — in the event shown, for example, why is the subsidiary brightening at the N end of the long trajectory so energetic and so confined?

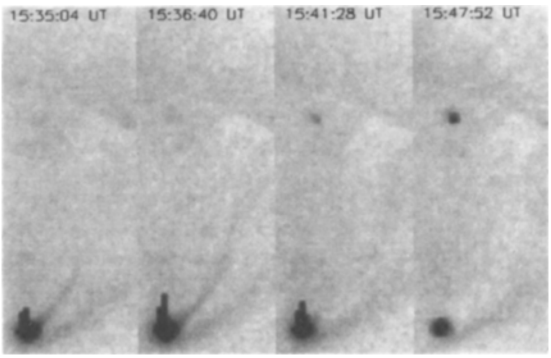

Fig. 2. Sequence of soft X-ray images showing the eruption of a jet from a flare-like brightening[8]. The ejected plasma followed a well-collimated trajectory, at a speed of approximately 1000 km/s, and produced a secondary brightening at the impact point near the N pole.

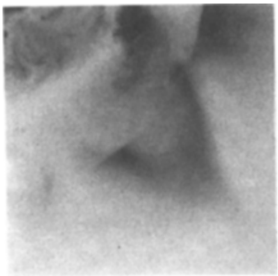

Fig. 3. X-ray helmet streamer formed after the eruption of a filament and a coronal mass ejection seen in white light[11].

On larger scales, SXT shows well-developed helmet-streamer structures, both in active regions (see the discussion of the 21 Feb. 1992 flare below) and in the aftermath of filament eruptions outside active regions[11], as shown in Figure 3. Finally, on the largest size scales observable with the SXT field of view of about 42 arc min (some 2×10^6 km), huge diffuse brightenings occur, often in the vicinity of the polar coronal holes[7]. In all of these dynamical effects, there is a general tendency to make interpretations in terms of magnetic reconnection, especially in view of the extremely suggestive helmet-streamer geometry.

The active-region loops in general appear to ignore magnetostatic constraints on intermediate time scales, and limb observations show[12] a general tendency for expansion at velocities of tens of km/sec. We conjecture that these active-region expanding loops may lead to solar wind formation outside the context of the classical Parker mechanism, *i.e.* in which the flow is perpendicular to the field lines; such a mechanism, if established, could help to explain the slow-speed streams of the solar wind.

FLARES

The *Yohkoh* results on flares are probably of greatest interest to the high-energy community. During a flare, *Yohkoh* switches to a high-time-resolution observing mode, with an SXT image cycle time through several filters typically on the order of 10–12 sec. The use of multiple filters allows the data to be used diagnostically, *i.e.* to characterize the temperature distribution in the soft X-ray sources. At the same time the flare mode enables observations by the *Yohkoh* hard X-ray imager, HXT, which observes in four energy bands (~15–100 keV) with an array of 64 individual scintillation counters each viewing the Sun through a different image-modulating grid collimator.

In general the *Yohkoh* results confirm earlier results on flare morphology, with the important new dimensions of high time resolution in soft X-radiation. In hard X-radiation, the HXT instrument[13] provides great sensitivity, approximately equal to that of the HXRBS non-imaging instrument on *Solar Maximum Mission* . Its response at high energies definitely extends to the non-thermal bremsstrahlung domain, and it has better angular resolution than instruments on *Solar Maximum Mission* and *Hinotori*. The best-studied of the *Yohkoh* flares to date is doubtless the 3B/X1.5 event of 15 Nov. 1991[14–18], partly because of the excellent ground-based observations from Mees Observatory. This event exhibited most of the interesting features of a major flare, with the exception of a long-duration post-flare loop system. The papers cited will give a comprehensive view of the *Yohkoh* capabilities for flare observation in general.

The following sections discuss different aspects of the flare observations.

The 'Thick Target' Paradigm

The most significant finding thus far from the *Yohkoh* flare observations has been a rather complete confirmation of the 'thick target' paradigm for the energetic parts of flare development[19,20]. In this model, internal stresses in coronal magnetic-field structures relax, accelerating 10—100 keV electrons. These electrons fly to the chromospheric footpoints of the field lines, energizing the plasma there and causing evaporation. This results in high gas pressure in the corona and the observed soft X-radiation.

Several key new *Yohkoh* observations support this general picture:

- The non-thermal hard X-ray sources closely match the footpoints of magnetic loops defined by the soft X-rays[14];
- SXT commonly observes *impulsive* soft X-radiation from the footpoints of flaring loops, closely synchronized with non-thermal bremsstrahlung[21];
- White-light continuum, from the lower solar atmosphere, matches the impulsive phase quite well[22,16];
- The Neupert relationship between hard and soft X-rays[23] holds generally, even for "slow" LDE events[24].

These findings all support the ideas of chromospheric evaporation that were developed during the analysis of data from the *Solar Maximum Mission* and *Hinotori* satellites. These ideas were first clearly described by Neupert[23] and the main photometric signature has been termed the "Neupert Effect"[25]. Spectroscopically, the coincidence of blue-shifted X-ray emission lines with the impulsive phase established the upflow of chromospheric material into coronal trapping regions[26].

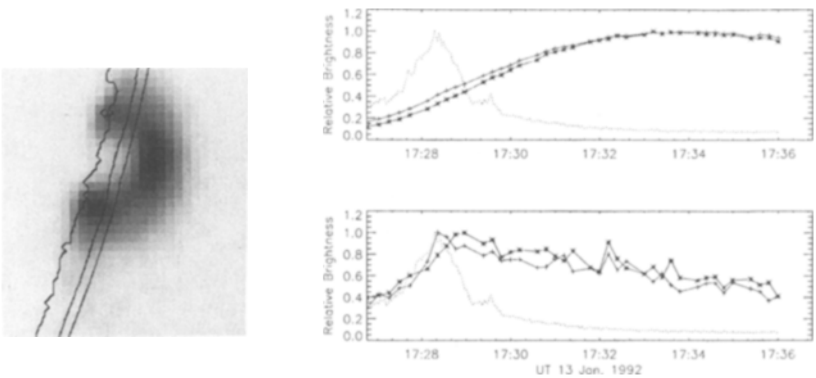

Fig. 4. (Left) Limb flare of 13 January 1992, early in its development, showing bright footpoint regions. Image dimension is 1.2×10^4 km. (Right) Light curves of soft and hard X-rays. The upper panel shows the SXT light curves from the whole flare and from the loop top, overlaid on hard X-ray photometric data from HXT (22.7-32.7 keV). The lower panel shows light curves from the footpoints, overlaid on the same HXT data. The comparison shows that the energization of the loop system begins with the footpoints.

Figure 4 shows the existence of impulsive soft X–ray emission at the footpoints of flaring loops. This phenomenon occurs commonly, and the soft X–ray footpoint emission appears to have a relatively cool thermal spectrum, consistent with the expectation for particle–driven evaporation. This finding essentially completes the observational picture of chromospheric evaporation, in the sense that SXT directly images the dense chromospheric plasma in the process of its upflow. The remarkable appearance of compact bright points at the tops of loops[27] remains unexplained in this picture, however, and this remains one of the interesting puzzles of the SXT flare observations.

The energetic importance of non–thermal electrons has been clearly recognized for powerful impulsive flares[28], as confirmed by the observations of impulsive soft X–ray footpoints just discussed. How about more gradual events? Among the most–cited results from the *Skylab* observations[29] has been the idea of post–impulsive–phase energy release, found specifically in large two–ribbon flares[30]. Is this also mediated by particle acceleration? What role is played by the filament eruption and coronal mass ejection, in flares they are associated with?

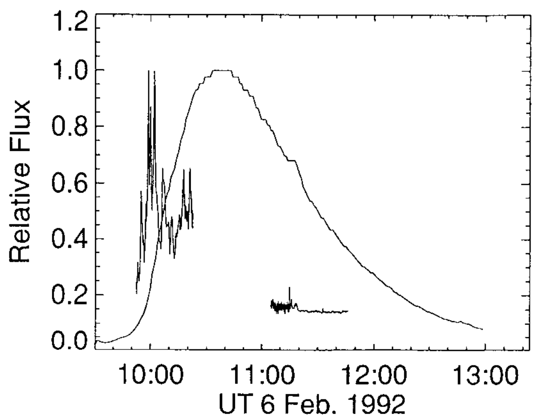

Fig. 5. Light curves of a "slow LDE" flare (6 February 1992), comparing the GOES soft X–ray flux (linear scale) with the hard X–ray photometric data from HXT. The hard X–ray burst lasted for more than 30 minutes, at a low flux level as expected from the Neupert effect. During the orbital gap in the *Yohkoh* data the large–area BATSE detector on board *Compton/GRO* continued to observe hard X–radiation[24] during the remainder of the rise phase of the event.

The comprehensive and sensitive observations of soft X–rays from *Yohkoh*, and of hard X–rays from the BATSE instrument on *Compton/GRO*, now make it possible to look more deeply for non–thermal effects in gradual events[24]. This has been done for a sample of "slow LDE events", one of which is shown in Figure 5. These events were chosen to have slow rise times, long durations, and no apparent impulsive–phase effects, in an effort to isolate as strongly as possible any intrinsically thermal energy release. As Figure 5 shows, non–thermal hard X–radiation does occur in these slow and apparently thermal events. We found that all of the slow LDE events selected had powerful acceleration of non–thermal electrons, just as in the more impulsive events. The fluxes are lower because of the longer time scales involved, consistent with the integral relationship of the Neupert effect. As Figure 5 shows, the hard X–ray emission coincides closely in time with the rise phase of the event in soft X–radation, as expected.

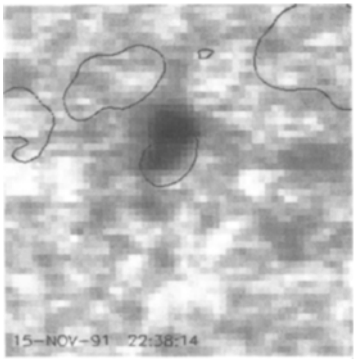

Fig. 6. White-light flare of 15 November 1991, as observed by the aspect camera of the *Yohkoh* SXT experiment[16]. Image dimension is 1.2×10^4 km. This negative image represents the difference between an image at the peak of the hard X-ray emission and a pre-flare image. The sunspots thus do not appear in the gray scale, but they have been drawn back in with the contours. All major flares observed to date with *Yohkoh* have been shown white-light continuum emission.

Finally, with respect to the thick-target paradigm, the SXT contributions to the observation of white-light flares are most important. The data come from the aspect sensor of SXT, a simple telescope with two-inch aperture normally viewing through a 30Å bandpass centered at 4308Å. We find all major flares observed by *Yohkoh* to be accompanied by emission in this passband. The emissions have a strong correlation with the impulsive phase and in particular with the hard X-ray burst. This is consistent with the thick-target paradigm[31] and implies that particle acceleration to the highest energies occurs during the epoch of major energy release in a flare, because high-energy particles have sufficient range to be able to penetrate to the height of formation of the continuum radiation.

Coronal Magnetic Structures and Reconnection

The SXT soft X-ray images give us our first systematic look, with reasonably high resolution, at the coronal structures of solar flares. Because the highly-ionized material of the hot coronal plasmas is tied to the magnetic field lines, these data promise a major step forward in our understanding of the role of magnetic reconnection in the generation of solar activity. In this section we discuss large flares with an eye towards understanding their geometrical properties. Each appears to consist of an arcade of large coronal loops, as expected from the *Skylab* data, and we see them in all orientations according to their locations on the disk. Often a single bright loop will dominate the appearance of the arcade in soft X-rays. The soft X-ray perspective on the dynamical development of these flare structures contains much of *Yohkoh*'s contribution to understanding macroscopic reconnection processes in solar flares.

The flare structure of the remarkable *Yohkoh* limb flare of 21 February 1992 is a good starting point for discussion of events of this type. This flare[32], seen in Figure 7, displays a helmet–streamer configuration that closely resembles flare models involving coronal neutral sheet formation[33] that we will refer to below as the "classical" picture of flare development, in which initially closed field lines open prior to the flare, and the flare energy release then originates in the reconnection of the open field lines. Cusped structures such as that seen in this flare commonly occur in the SXT images, although not always identifiably with a flare (see also Figure 3).

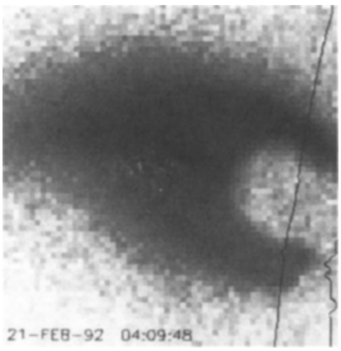

Fig. 7. Limb flare of 21 February 1992 as observed by the *Yohkoh* soft X-ray telescope[33]. This event, discussed in detail below, also was a "slow LDE" and exhibited long–enduring particle acceleration throughout the rise phase[24].

The geometry of this flare strikingly suggests magnetic reconnection in a coronal neutral sheet as a source of flare energy, but the other half of the classical picture is not obvious in the SXT data: there is no apparent tendency for the opening of magnetic field lines prior to the reconnection thought to drive the flare. In fact this active region provides a good example of the general expansion of active–region coronal flux tubes noted in the SXT data[12], with a relatively clear example at about 01:40 UT (some two hours before the flare) at speeds of about 30 km/sec. This opening could of course occur on relatively long time scales, involving magnetic structures with low gas pressure, and thereby escape easy detection by SXT. In the 21 February event, however, there is clearly no restructuring of the corona during the flare brightening itself, since the pre–flare configuration was well observed and had essentially the same geometry. Essentially the previously existing structure brightened in place, expanding gradually as is the pattern for Hα loop prominence systems. In particular, there is no evidence for inflow of the type required to drive energy release by reconnection in the classical model. The projected geometry of the event gives the clear appearance of closed field lines above the flaring loop, rather than open ones. These findings disagree substantially with the expectations from the classical model.

There is a speculative way in which we can rationalize the clear evidence for large–scale reconnection in a coronal neutral sheet, with the equally clear disagreements between the *Yohkoh* data and with the standard model of solar flares. This would be to hypothesize that the flare energy release actually takes place predominantly in closed magnetic field structures. The perturbations associated with the flare energy release then drive macroscopic reconnection, rather than the other way around. The key test of this hypothesis lies in analyzing the energetic relationships of the different components of solar flares, thereby tracking the energy released to its immediate origins and also revealing the mechanisms of its transport. This kind of quantitative analysis is still in a preliminary state in the *Yohkoh* data base, but much progress can be anticipated.

Finally, I would like to point out the attractiveness of using high-energy particles to study the connectivity of flaring plasma structures. The common occurrence of foot-point brightenings and the other paraphernalia of the thick-target paradigm for solar flare development clearly indicate that high-energy particles are usually present at the time of flare energy release. At exactly this time the plasma is undergoing some convulsion, whose details we really don't understand yet. The geometry of the field is central to our understanding, and an extension of the concept of *conjugacy* from magnetospheric physics to solar physics will be helpful. Essentially the high-energy particles can serve as a natural tool for discerning the connectivity of the magnetic field, via the matching of the footpoints of a given field line by use of simultaneity or correlation between the variations at the two locations. This tool is actually physically more correct than any technique based upon the extrapolation of photospheric field observations, or even from more direct coronal magnetic field measurements if they were possible. The gyroradii of the particles are far smaller than the angular resolutions of the magnetographs, for example. To make good use of observations of conjugacy, we need detailed modeling of the relevant observations of the type pioneered by Newkirk[34]. Such observations and calculations probably should start with slowly-developing large events, such as these "slow LDE" events, because of limitations of angular resolution.

CONCLUSIONS

The high-energy particles responsible for solar high-energy (hard X-ray and γ-ray emissions, as well as for non-thermal radio emissions, reside in the solar corona. Here they are accelerated, propagate, and radiate. With the *Yohkoh* data we now have soft X-ray observations that can show the coronal structures of the corona clearly, even on the disk. It is a natural prediction that we will be able to put these data together in a manner in such a manner as to be able to learn a great deal about acceleration, propagation, and radiation of high-energy particles. At present, unfortunately, little of this comparative work has been done in detail. In the future we expect a rich harvest of understanding from comparisons of SXT data with microwave and longer-wavelength radio data in particular. We are also waiting for the recurrence epoch of the historically great flares of August 1972 or April 1984 — these times translate to 1994 and 1995, respectively, in terms of a mean solar cycle duration. At this epoch we might hope to obtain simultaneous *Yohkoh* and *Compton/GRO* observations of γ-ray flares of similar significance.

The *Yohkoh* data by themselves, however, are already making important contributions to our understanding of flares and other dynamic structures in the corona, as are the *Compton/GRO* data. The most striking of these contributions, described in the preceding sections, confirms the relationship of high-energy particles and flare energetics that is implied in the Neupert effect and the general thick-target picture of flare evolution[19,20]. At the same time the soft X-ray observations from SXT clearly show helmet-streamer structures presumably associated with neutral sheets and magnetic reconnection. I have argued above that these structures probably do not supply the main energy of a flare, because of their passivity, but are instead driven by the flare. The difficult point in this argument is the well-known fact that coronal mass ejections are often associated with flares and may have large energy content[35], whereas they at least begin early in the flare process (as do filament eruptions, when they occur), well before the main energy release of the impulsive phase. The outstanding problem of *Yohkoh* flare research, therefore, seems to be to reconcile these different discoveries into a single self-consistent picture of what we normally think of as distinct problems: flare energy storage, triggering, energy release, and particle acceleration. On the observational side, the outstanding problem in interpreting the SXT images is the three-dimensionality of the source, and the corresponding difficulty of inferring the true geometry of the complicated optically-thin phenomena that we observe. As mentioned above, the concept of foot-point conjugacy introduced earlier may be helpful in clarifying the geometry and the physics dictated by it.

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