THERMAL PLASMAS IN THE SOLAR CORONA: the *Yohkoh* Soft X–Ray Observations

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Abstract

The *Yohkoh* observatory carries two instruments whose main emphasis is the observation of soft X–radiation, principally emitted by thermal radiation processes. The other two *Yohkoh* instruments also observe some of these thermal sources. The combination of instruments makes *Yohkoh* unprecedented in its ability to observe the remarkable array of hot plasmas in the solar corona, and this has resulted in many new discoveries as well as in the sharpening of our knowledge of known (but often unexplained) phenomena. The scope of this review consists of the *Yohkoh* observations of thermal plasmas, and it emphasizes the new discoveries. The SXT data show many phenomena whose geometry and dynamics strongly suggest magnetic reconnection.

1. Introduction

Soft X–rays (~1 keV, or ~10Å) give us our most direct views of hot plasmas in the solar corona. Observations of solar soft X–radiation have now entered their fifth decade, but new techniques of observation and new facilities have resulted in a continual expansion of discovery and understanding. Past observational work in this area has seen many spacecraft (OSO, OGO, *Solrad*, *Prognoz*, *Interkosmos*, *Skylab*, GOES, P78–1, SMM, *Hinotori*, CGRO, among others) and of course many sounding rockets with advanced and novel instrumentation.

The *Yohkoh* satellite has continued this tradition in a spectacular manner with two dedicated instruments: the soft X–ray telescope (SXT; see Tsuneta *et al.*, 1991 for a description of the instrumentation) and the Bragg crystal spectrometer (BCS; see Culhane *et al.*, 1991). Acton *et al.* (1992) give an early description of the observations, with many examples of the coronal structures observed. The instruments on board *Yohkoh* combine to provide unprecedented sensitivity and data flow. Because of *Yohkoh*'s primary scientific objective, to understand solar flares, the launch took place near the peak of the current activity cycle. *Yohkoh* arrived too late in orbit to observe the great flares of June 1991, but it has produced spectacular results as summarized below. At the same time the SXT in particular has observed many things outside the domain of flares, or associated only indirectly with flares. With an active lifetime now exceeding two years, we expect that *Yohkoh* data will allow us to study the solar–cycle dependence of many coronal X–ray phenomena (*e.g.*, Hara, 1994).

Radio astronomers discovered and have long studied the dynamic corona (*e.g.* Kundu, 1964). Although we can also clear see the outer corona in eclipses or in white– light coronagraph data, only the radio observations gave us a direct view of the high–temperature and non–thermal plasmas that make it so interesting. The radio observations suffer from a lack of angular resolution and also often from the complexity of the radiative transfer. Because of this, the *Yohkoh* soft X–ray observations represent a breakthrough. We can now directly see some of the emitting plasmas in relatively simple optically thin thermal radiation. The comparison of *Yohkoh* data and ground–based radio data proving extremely powerful (*e.g.*, Hanaoka *et al.*, 1994), both for flare problems and for non–flare problems.

2. Comments on the Instrumentation

SXT follows the tradition of the grazing–incidence telescopes of *Skylab*, *Einstein*, and various sounding rockets, but with many important innovations. The mirror has a short length along the optical axis, resulting in a large field of view at high angular resolution. The mirror polishing used new technology that resulted in greatly reduced scattering, again a benefit for observations over a wide field of view. SXT reads its image with a 1024 $\times$ 1024–pixel CCD detector, a great improvement in linearity and data throughput with respect to film. Finally, the instrument design incorporates a 5–cm lens mounted coaxially and viewed by the same CCD detector through a set of glass filters, opaque to X–rays but transparent to visible light. By this technique SXT could record sunspot images and obtain precise coalignment with any ground–based observations also capable of making sunspot images. The available telemetry bandwidth of about 20 kbps (average) limits the number of images obtainable.

The BCS instrument also incorporates significant improvements. Its "bent crystal" format, also used on SMM, avoids confusion caused by time variability. The *Yohkoh* instrument has small wavelength ranges for each channel, restricted just to the spectral region of interest for the solar emission lines. This results in greater effective area and hence sensitivity. It has a queue memory that gives flexibility in data acquisition. Finally, BCS incorporates a channel devoted to wavelengths around the sulfur resonance line at 5.04Å. The sulfur lines form at low enough temperatures to make ordinary non– flaring active regions detectable, and also contribute new understanding to the flare spectra.

The operation of the *Yohkoh* spacecraft itself deserves a comment. The simplicity of the telescopes (both SXT and the hard X–ray telescope HXT view the whole Sun) and the availability of telemetry support from the NASA Deep Space Network has allowed *Yohkoh* to catch most of the flare events occurring during orbit day. At the same time a relatively high setting for the flare–mode trigger threshold has allowed the steady accumulation of the "SXT movie", which usually contains about 70 whole–Sun images per day. This whole–Sun movie, plus a parallel continuous sequence of frequent small images (normally restricted to the brightest active region) enables *Yohkoh* to observe both non–flare and small flare phenomena quite efficiently.

The status of the instruments at the time of writing (late 1993) remains satisfactory. BCS has no problems, while SXT has minor problems that will not impede future data collection. These include the loss of an aperture filter in late 1992, which ended the SXT white–light observations (but not before they had accomplished their work for coalignment), and the gradual decay of the CCD in terms of general dark current and hot pixels. The loss of the aperture filter increased the level of stray light in the X–ray images, but most of this can be corrected. These problems will not limit the useful lifetime of *Yohkoh*. At least some of the CCD degradation has resulted from soft X–ray damage, so perhaps it is a blessing in disguise that the telemetry bandwidth does not permit continuous operation of the CCD.

3. Interesting Results and Discoveries: Non–Flare

The wealth of phenomena observed by SXT includes (in roughly increasing order of spatial scale): unresolved brightenings, small flare–like events, small jets, compact loops in active regions, flares, bilateral jets, large jets, individual twisted loops, large active–region loops, loops interconnecting active regions (including trans–equatorial loops), X–ray counterparts of CMEs, filament channels and eruptions, huge coronal restructurings, the general corona, and of course coronal holes. This list is probably neither exclusive nor complete, but its length gives an idea about the wealth of physically distinct coronal regimes now observable. In the following I summarize interesting results and discoveries, divided somewhat arbitrarily into non–flare and flare categories. Shibata (1994) gives a contemporaneous brief review of the SXT observations with different perspectives. For a pre–*Yohkoh* review of the physics of solar and stellar flares, see for example Haisch *et al.* (1991).

The Outer Corona. SXT observes X–ray emission to great heights, often exceeding one $R_\odot$ above the photosphere (Figure 3a). The morphology includes a quasi–spherical component (avoiding coronal holes) and large–scale loop configurations, often seen over the polar crown region defined by the boundaries of the polar coronal hole. These outer coronal images lack the nearly linear streamer morphology commonly seen further out in white–light coronagraph images. Nevertheless, cusped coronal structures (helmet streamers) do frequently occur.

Expanding Active Region Loops. The SXT movie made it possible to recognize a frequent slow eruption of active–region loops (Uchida *et al.*, 1992). The velocities involved — 10–100 km s^{-1} — place these expanding loops outside the domain usually associated with CMEs. Their existence calls into question the dominant theoretical view of active–region loops as magnetostatic structures, and suggests interesting possibilities for the solar wind.

Filament Activations. The structures associated with Hα filaments, and their spectacular time evolution, occur frequently in the SXT images (Khan *et al.*, 1994; McAllister *et al.*, 1992). The basic phenomenology seems similar both in the active–region latitudes (but outside active regions) and in the polar–crown filament zone. Large polar structures often develop on a vast scale (Tsuneta *et al.*, 1992b), in a manner that strongly suggests the streamer blow–out phenomenon known from coronagraph observations (*e.g.* Kahler, 1992).

The complicated geometry of filament activations is apparent in the SXT images, but it would be fair to say that no individual event can easily be understood three–dimensionally from these data. A full synthesis of many events is not yet available. The movie representations give the clear impression that the evolution is not two–dimensional, but it is not clear how the cusps and the "spine" features along the arcades (Kano, 1994; see also Figure 3b for an example) relate to the eruption.

X–ray "CME"s. SXT observes many material ejections, identified in an initial survey of the routine movie data (Klimchuk *et al.*, 1994). This particular sample is biased away from flare associations because of the data sampling pattern for the movie, which avoids flare times by design. The survey found a mean projected speed of 48 km s^{-1}, faster than the active–region expansions studied by Uchida *et al.* (1992).

Yohkoh would observe more rapid transients with improved image cadence, as found for example in the flare–mode data (see below). Some of these ejections (if not all) correspond to coronal mass ejections (CMEs) as observed by coronagraphs. These ejections occur both in active regions (*e.g.* Watanabe *et al.*, 1992) and at polar latitudes (*e.g.* Hiei *et al.*, 1993; see Figure 3b).

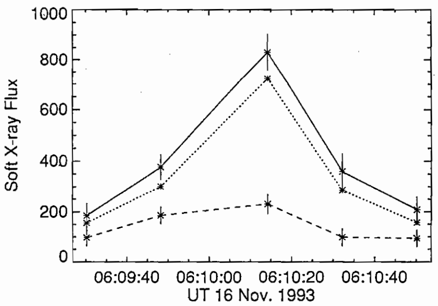

Fig. 1. An unresolved microflare. The plot shows light curves of two individual adjacent pixels, plus a third reference pixel about 6,000 km distant, in the thin Al filter of SXT. The total radiated energy was on the order of 10^{23} ergs.

4. Interesting Results and Discoveries: Flares

X–ray Jets. The SXT movie revealed the existence of many soft X–ray jets, of several kinds (Shibata *et al.*, 1992; Strong *et al.*; 1992; Shibata *et al.*, 1994). This new discovery probably has some relationship with the small–scale non–thermal phenomena observed in the UV (Brueckner and Bartoe, 1983), but the lack of simultaneous observations makes this identification difficult. The soft X–ray jets often are tightly collimated and their temporal developments strongly suggest reconnection geometries. Figure 3d shows one of the more striking cases.

Microflares. *Yohkoh* detects many "active–region transient brightenings" (Shimizu *et al.*, 1994), many of them unresolved with SXT sampling and resolution. The SXT observations extend the range of total energies for these events to well below 10^{24} ergs, spanning the "microflare" range and extending below the "nanoflare" range (Parker, 1988), and they show no tendency for a preferred scale. No physical properties of these events appear to distinguish them from ordinary flares. Watanabe Te. *et al.* (1994) have shown that microflares, as observed with the BCS sulfur channel, have flare–like temperatures. These numerous events therefore provides a wonderful tool for statistical research on flares, because they are so common.

SXT observes events below its temporal and spatial resolution, *i.e.* brightenings that extend over one or two pixels and last for one or two frames. The energy of a marginal event of this type can be as low as 10^{22} ergs, comparable to the energy of a terrestrial aurora. Figure 1 shows an large example.

Inpulsive Footpoints. Time–resolved soft X–ray images of flares commonly show impulsive footpoint brightenings in this band (Hudson *et al.*, 1994a). These sources appear to represent the evaporating material as it flows upwards into the flare loops from the chromosphere, as implied by much other evidence. Often SXT can follow the upwards flow of the evaporating plasma. The emission line profiles observed by BCS often show blue shifts sychronized with the impulsive flare emissions (*e.g.* Mariska *et al.*, 1993), with timing that is consistent with the evaporation scenario (Bentley *et al.*, 1994).

Interestingly, these footpoint sources are relatively cool (McTiernan *et al.*, 1993; Hudson *et al.*, 1994a), and they therefore do not explain the "superhot" component identified by Lin *et al.* (1984).

Loop–top Kernels. Another striking characteristic of flare loops as observed by SXT is the appearance of kernels or condensations near the loop tops (Acton, *et al.*, 1992; Feldman *et al.*, 1994). That loop tops often have compact hot sources was known from the *Skylab* era (Widing and Cheng, 1974; Cheng and Widing, 1975), but these could be explained by simple conductive–radiative loop equilibrium (*e.g.* Rosner *et al.*, 1978) within the limits of the data of that time. *Yohkoh* may have found *anomalous* brightenings, consistent with the possibility of overpressure high–density regions. Potential explanations for the loop–top kernels start with simple geometry; projections of curved flux tubes in the optically–thin corona tend to

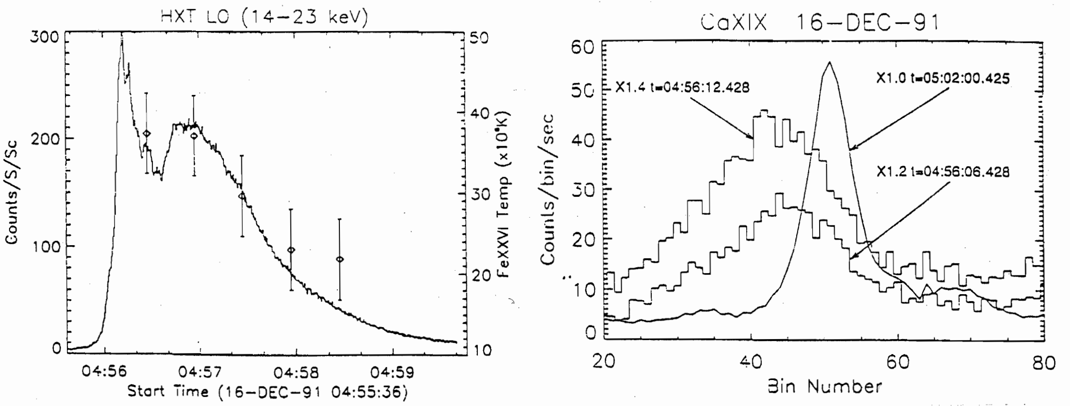

Fig. 2. The extreme blue–shift/"superhot" event of 16 Dec. 1991 as observed by BCS (Culhane *et al.*, 1994; Inda–Koide *et al.*, 1994).

have loop–top enhancements. A curved and twisted flux tube (*i.e.*, one carrying a parallel current) could even have the appearance of a cusp. On beyond this the plasma physics of stable overpressure regions at loop tops remains unclear at the time of writing, but the list of theoretical possibilities includes plasma pinch or kink behavior, or phenomena associated with magnetic reconnection in neutral sheets. Seely (these Proceedings) discusses the data further.

Superhot Sources. The "superhot" phenomenon, identified by Lin *et al.* (1984) and incorporated into the *Hinotori* classification as "Type A" (Tanaka, 1987), consists of a nearly isothermal plasma at a temperature elevated above the normal flare range of up to $\sim 2 \times 10^7$ K. The FeXXV and FeXXVI channels of BCS, as well as the low–energy channels of HXT, allow *Yohkoh* to study such flares. The "Pike's Peak" event of 16 Dec. 1991 (Figure 2), alas not observed by SXT, represents an early beautiful example (Culhane and Phillips, 1994; Inda–Koide *et al.*, 1994). There is now a considerable list of *Yohkoh*/BCS events with FeXXVI emission (Pike *et al.*, 1994). Work in progress suggests that the superhot sources may behave differently from the standard footpoint evaporation scenario (Kosugi *et al.*, 1994).

Cusps in Flares. The dramatic observation of the "candle flame" flare of 21 Feb. 1992 (Figure 3b; Tsuneta *et al.*, 1992a), and many other examples, establishes the presence of the neutral–sheet geometry in association with some flares. In the 21 Feb. event, the early development shows a rapidly–rising structure just at the onset of the soft (GOES) and hard (BATSE) X–ray bursts. This timing supports the finding that CME's accelerate prior to the main energy release time (Harrison, 1986; *cf.* Kahler, 1992). In this case the rapid outward motion of the compact feature, at ~ 300 km s^{-1}, appeared to coincide with a broad expansion visible in the movie representation of the data. These SXT observations strongly support the idea of ongoing magnetic reconnection in a neutral–sheet configuration (see Priest *et al.*, 1991, for a recent discussion).

5. Discussion

In addition to showing us almost totally new things, such as the X–ray jets, the *Yohkoh* observations have confirmed some of our most cherished preconceptions regarding previously observed phenomena. The neutral–sheet configuration for large flares as originally proposed by Carmichael (1964) and subsequently embellished by many authors is one of the most important. Equally the Neupert effect (Neupert, 1968), the general scenario of chromospheric evaporation to explain flare loop brightness, has also received abundant confirmation.

On the other hand, some of the conventional wisdom has *not* received strong confirmation under this new scrutiny. Microflares or nanoflares do not appear to explain coronal heating, at least within the range of flare energies observable by SXT. This results from the continuity of the distribution function of total flare energy over the many decades of the range now observable. Hudson (1991) suggested that this implies different physics for microscopic non–thermal events, if they are to explain coronal heating (Parker, 1988). Likewise loop–loop interactions have not found strong support (but see Akioka *et al.*, 1993; Cheng, 1993, Hanaoka, 1994). Although flares and microflares often consist of multiple loops, it has been virtually impossible to prove that they have physically interacted. This may be the result of the extremely difficult task of obtaining convincing evidence with the *Yohkoh* observational limitations.

I think there are many puzzling aspects of large–scale magnetic reconnection as an explanation for solar flares — there are many flares with no observable eruptive behavior (*e.g.* de la Beaujardière *et al.*, 1993). The required inward flows of reconnecting magnetized plasma are not detectable, except when inferrred indirectly from the geometry of an eruptive flare (Martens, 1994). Most flares do not have the right geometry (no cusp configuration) and when a soft X–ray cusp does develop, it often appears to be passive and to be present outside the time of major flare energy release. Reconnection jets, or phenomena easily associated with them, are usually not detectable. With these uncertainties, I believe that it is still not clear whether the reconnection signatures *Yohkoh* sees in some flares are the direct *cause* of the energy release in the flare, or whether they are *driven* by the flare energy release. There seems to be an echo here of the long–lasting controversy in magnetospheric physics regarding the fundamental question of whether a substorm is "driven" or "unloading" (*e.g.* Akasofu, 1988).

On smaller scales, the same dichotomy appears. The soft X–ray jets strongly suggest macroscopic reconnection. Loop flares (the commonest kind) do not. Does this help to justify the argument that the *Skylab* division of flares into long–duration and compact events (Pallavicini *et al.*, 1977) requires different physics of energy release in the two categories? If the magnetic reconnection seen in events of the long–duration type drives the energy release in those flares, they may be the "unloading" events, and the compact flares would be driven by stresses intrinsic to the flaring flux tubes (*e.g.*, models such as those of Alfvèn and Carlqvist, 1967, Spicer, 1977, or Uchida and Shibata, 1988).

6. Conclusions

These beautiful observations have brought us to a new level of empirical knowledge, and over the next few years we can expect that explanations of some of the presently mysterious aspects of the observations will begin to emerge. Nevertheless, even though solar soft X–ray astronomy is in many ways a mature field, it is far from clear that this will result in an adequate theoretical understanding of some of the phenomena of broad interest (*e.g.*, jet collimation; see Klimchuk *et al.* , 1992, for a discussion of the tendency for X–ray loop structures to have constant cross–sections). Soft X–ray observations at higher angular resolution, and with much better temporal coverage, would go a long way towards helping our quantitative understanding of the physics. In addition to this, though, these results suggest new kinds of observations for future development:

Stereoscopic observations. For much of the interpretation of the SXT and BCS observations, one is limited by the lack of knowledge of the true three–dimensional geometry. For the study of loop–loop interactions, for example, this poses an almost insurmountable barrier because of foreground/background confusion in these optically–thin radiations. The direct way around this problem is to make simultaneous observations from multiple perspectives, an idea most recently proposed as "tomography" by Davila (1994; cf. Grigoryev, 1993).

High–resolution photospheric observations. We generally believe that solar activity is driven by sub–photospheric processes, even if there is short–term energy storage in the corona. Details of the nether regions are "visible" only dimly via helioseismology and other indirect means. In the photosphere we see or infer the existence of fine structures, down to the limit of the photon mean free path and (presumably) sometimes even finer. A complete knowledge of this boundary layer for the coronal activity would clearly help wonderfully in understanding this activity. The knowledge attainable in principle includes the distribution of electric currents that thread between the solar interior and the corona; these can be measured using vector magnetographs at visible or infrared wavelengths.

XUV imaging spectroscopy. SXT has a limitation in the form of rapidly diminishing response at long wavelengths. The XUV wavelength range contains strong lines from every intermediate temperature regime, and imaging these lines would give us a complete inventory of the contents of the corona. With this, we might resolve the mystery of the non–observation of reconnection flows and reconnection jets. At the same time the existing technology allows for effectively monochromatic imaging, for example with an "overlappograph" or a stigmatic slit spectrograph. The additional advantage Doppler measurements would help considerably in resolving the three–dimensional geometry of the sources.

Acknowledgements

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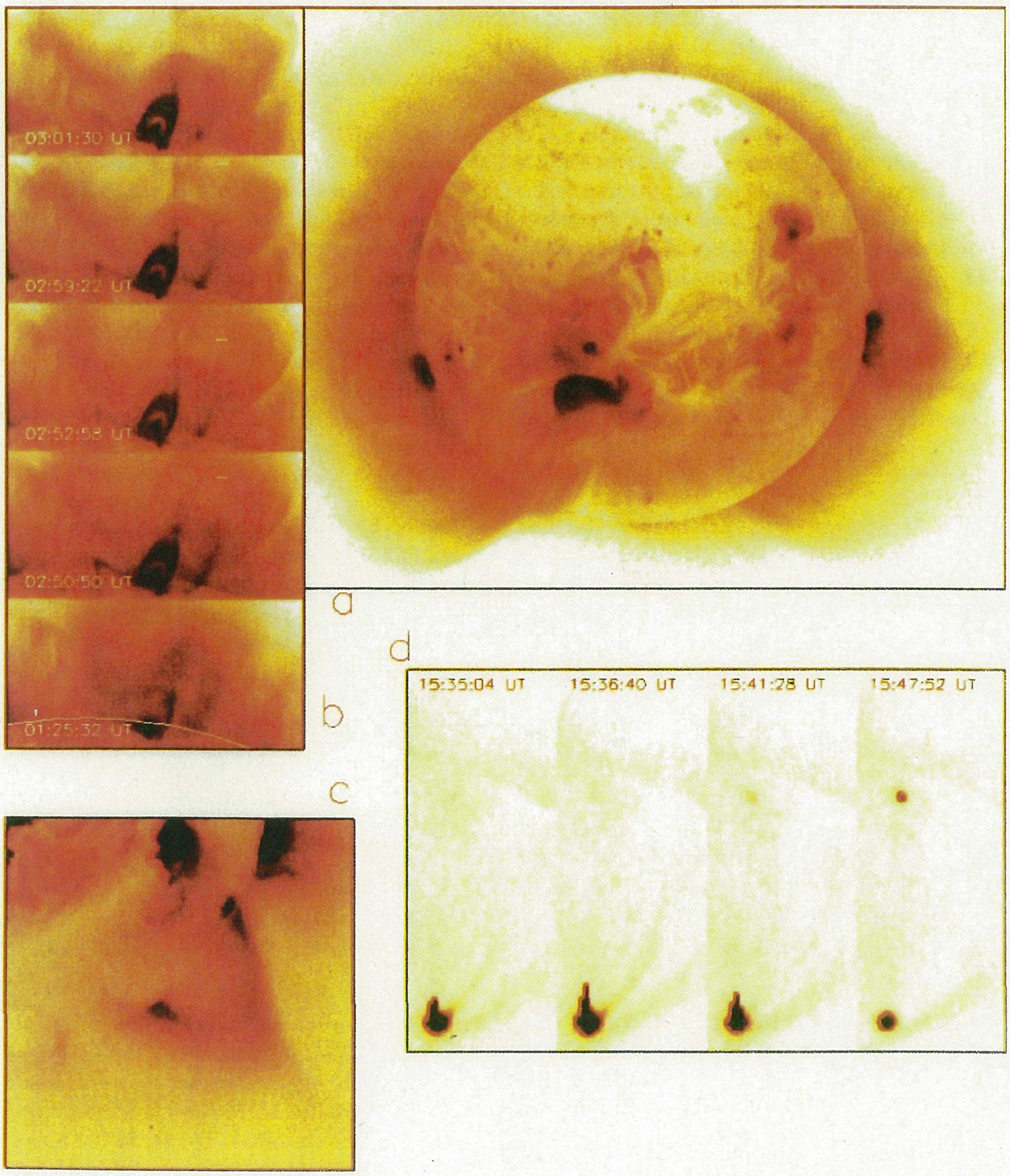
Caption for Color Plate

Fig. 3a. Image of the extended X–ray corona observed by SXT through the thin Al filter, showing many of the features discussed in the text. This composite image, from multiple exposures on 1992 May 8, was assembled by L. Acton and J. Lemen; the brightness scale has been compressed in dynamic range, but there has been no other image enhancement. This image shows substantial X–ray brightness to be detectable more than one solar radius above the photosphere in a 15–sec exposure. North to the top, west to the right.

b. Early images from the flare of 1992 Feb. 21 (*cf.* Tsuneta *et al.*, 1992), showing many dynamical features at the very beginning of the GOES flux increase. Among these features one can see a hollow structure (marked with lines) that is rising directly above the cusp, which had already formed before the flare began and persisted for many hours during this "slow LDE" event (Hudson *et al.*, 1994a). The lines give a scale reference of 20,000 km. The hollow structure appeared to accelerate between the images at 02:52:58 and 02:59:22 UT, and the movie view of these images gives the impression of a fan–shaped expansion centered on the rising structure, which we suspect is the location of a filament that had prior to the time of the major energy release. The velocity of this feature as it left the field of view was $\sim$300 km s^{-1}. East to the top, north to the right.

c. Soft X–ray helmet streamer at the SW limb associated with a coronal mass ejection observed in white light (Hiei *et al.*, 1993), 1992 Jan. 4. Over the few days prior to the event, the southern polar crown filament zone was observed to increase in size gradually, leading up to an eruption. This event appears to have similar physical properties to those of LDE flares seen in active regions (*e.g.*, Figure 3b), and to filament eruption events seen at lowe latitudes in the quiet Sun. North to the top, west to the right.

d. Spectacular jet from 1991 Dec. 7 (Strong *et al.*, 1992). This remarkable event consists of a collimated stream of plasma emanating from a compact active region; the plasma flows along an arc at a speed of about 1,000 km s^{-1} and causes a second event at its terminus. SXT observes many other jets of several types, including cases in which the ejection appears to depart from the Sun on open field lines. North to the top, west to the right.


03:01:30 UT
02:59:22 UT
02:52:58 UT
02:50:50 UT
01:25:32 UT
a
b
c
d
15:35:04 UT
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15:47:52 UT