HARD X-RAY IMAGING AND THE RELATIVE CONTRIBUTION OF THERMAL AND NONTHERMAL EMISSION IN FLARES

Gordon D. Holman

NAS/NRC Resident Research Associate
Laboratory for Astronomy and Solar Physics, Code 682,
NASA Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.

The question of whether the impulsive 25 to 100 keV X-ray emission from solar flares is thermal or nonthermal has been a long-standing controversy. Both thermal and nonthermal (beam) models have been developed and applied to the hard X-ray data. It now seems likely that both thermal and nonthermal emission have been observed at hard X-ray energies. The Hinotori classification scheme (Tsuneta, 1984), for example, is an attempt to associate the thermal/nonthermal characteristics of flare hard X-ray emission with other flare properties. From a theoretical point of view, it is difficult to generate energetic, nonthermal electrons without dumping an equal or greater amount of energy into plasma heating. On the other hand, any impulsive heating process will invariably generate at least some nonthermal particles. Hence, strictly speaking, although thermal or nonthermal emission may dominate the hard X-ray emission in a given energy range for a given flare, there is no such thing as a purely thermal or nonthermal flare mechanism.

For a hard X-ray instrument covering a wide range of photon energies, such as the HXRBS on SMM, it would not be surprising to find both thermal and nonthermal processes contributing to the X-ray emission from a given flare. Hence, instead of simply applying a specific thermal or beam model to the hard X-ray data, it would be more instructive to use combined flare data to try to determine the relative importance of these emissions for a given flare. Combined hard X-ray and microwave images and spectral data are particularly valuable for this. Since the energy released in flares is understood to derive from magnetic field energy, it is most likely that the impulsive phase heating and particle acceleration occur in the current channels associated with these magnetic fields. Electron heating and acceleration in these current channels have recently been studied by Holman (1985a,b). The use of hard X-ray imaging to determine the thermal/nonthermal character of the emission is discussed in light of these results in the following paragraphs.

Simple considerations of the induction magnetic field associated with a current of accelerated electrons have shown that the flux of electrons required for a 25 to 100 keV nonthermal hard X-ray burst cannot be generated by direct electric field acceleration in a single current channel (Hoyng, 1977; Spicer, 1983; Holman, 1985a,b). If this emission is to be nonthermal, a large number of oppositely directed current sheets is required. The relationship between the electron flux needed for the nonthermal X-ray burst, N, and the minimum number of current sheets required for the burst, s, is

$$N = 10^{30}\, s w_9 B_2 \text{ electrons s}^{-1}$$

(see Holman, 1985b), where w_9 is the width of the sheets in units of 10^9 cm and B_2 is the magnetic field strength in units of 100 Gauss. Since a typical hard X-ray burst requires 10^{35} electrons s^{-1} for B = 300 G and w = 3 x 10^9 cm, a minimum of 10^4 current sheets is required. The thickness of each sheet is generally less than 1 km. Imaged hard X rays can be used to better determine N and estimate an upper limit for w.

Although a large number of current sheets makes the generation of the nonthermal X-ray emission possible, the heating of the thermal plasma in the acceleration region is also increased. Hard X-ray imaging in different energy bands can be used to determine the relative importance of the thermal and nonthermal emissions at different photon energies, and how the emission is distributed within the flaring region. Simultaneous second-of-arc resolution soft X-ray images would also be useful for determining how thermal energy (both from direct Joule heating in the acceleration region and the evaporation of chromospheric material by the nonthermal beam) is distributed within the flaring region. Hard X-ray images and spectra will also be valuable for determining if the transition from impulsive to gradual emission observed in many flares represents a transition from nonthermal to thermal emission, as is widely believed.

An interesting test for multiple current sheets with an X-ray imager would be to search for small-scale spatial structure in the emission region. Although the individual sheets would not be resolvable, spatial variations in the X-ray emission due to variations in the physical properties of the individual sheets may be detectable. This may be detectable in the thick-target, nonthermal emission region if the accelerated electrons from the individual sheets remain well separated, but is more likely to be detected in the thermal emission from the acceleration region.

A large number of current sheets is not required when the 25 to 100 keV X-ray emission is thermal. Holman (1985b) has shown that a thermal hard X-ray burst can be generated by a single current sheet within a flaring region. The energetic electrons required for a nonthermal microwave burst can also be accelerated within the single current sheet. Although the 25 to 100 keV X rays from the single sheet cannot be nonthermal, a transition to nonthermal emission is expected at energies above 100 keV. Hence, X-ray imaging (and spectra) in the 100 to 500 keV range is particularly valuable for testing for bursts generated within a single sheet. Simultaneous microwave images and spectra are, of course, also valuable for comparison with the X-ray data.

An interesting result of the single current sheet analysis was that a thermal hard X-ray burst can be generated without requiring anomalous resistivity in the sheet if the density in the X-ray emitting region is 10^{11} cm^{-3} or greater. Since the emission measure and estimated source volume obtained from hard X-ray imaging data can be used to estimate the density in the source region, the observations can yield information about the resistivity in the current sheet. The resistivity in the sheet must be anomalous if the average density in the X-ray emitting volume is less than 10^{11} cm^{-3}.

It is shown in the previously cited paper (Holman, 1985b) how a comparison of hard X-ray and microwave rise times (or, more specifically, the Joule heating and electron acceleration time scales) can be used to obtain more detailed information about the flaring region (see Shevgaonkar and Kundu, 1985, for a recent application). In particular, the electric field strength and resistivity in the current sheet can be deduced from such a comparison. The maximum energy to which electrons are accelerated in turn depends upon the electric field strength and the length of the current sheet. This maximum energy can be estimated from the hard X-ray or gamma-ray continuum data for a given flare. For complex, multiple-spike bursts, hard X-ray and microwave imaging will help in properly identifying the Joule heating and acceleration timescales.

An additional important task for X-ray imaging (both hard and soft) is to determine how thermal energy, once deposited, is transported within the flaring region. The observed properties of the thermal X-ray emission will be quite different if the thermal energy is readily transported to large volumes rather than primarily confined to the energy deposition region. High spatial and temporal resolution X-ray observations will provide a tracer for the transport of this energy during a flare.

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