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A HYBRID THERMAL/NONTHERMAL MODEL FOR THE ENERGETIC EMISSIONS FROM SOLAR FLARES

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ABSTRACT

We present an alternative interpretation of the high-resolution solar flare spectra obtained in 1981 by Lin et al. In our interpretation electron heating and acceleration are simultaneous and physically linked, rather than heating being a secondary effect of particle acceleration. We show that the observed properties of solar flare X-ray emission can in general be explained through the Joule heating and electric field acceleration of runaway electrons in current channels. We have fitted a hybrid thermal/nonthermal electron distribution, consisting of hot isothermal electrons with a nonthermal tail of runaway electrons, to representative spectra obtained by Lin et al. The hybrid model relaxes the electron number and energy flux requirements for the hard X-ray emission over those of a purely nonthermal model. The low-energy "cutoff" to the nonthermal part of the X-ray spectrum is determined by the critical velocity in the electron distribution above which runaway acceleration occurs. We relate the fit parameters to the physical properties (such as the electric field strength in the current channels) of the acceleration region.

Subject headings: acceleration of particles — plasmas — Sun: flares — Sun: X-rays

Ever since the first observation of hard (>20 keV) X-rays from solar flares (Peterson & Winckler 1958), there has been considerable controversy over the origin of this emission. Peterson & Winckler (1958, 1959) interpreted their results as thick-target bremsstrahlung from a nonthermal beam of MeV electrons. Chubb, Friedmann, & Kreplin (1960), on the other hand, interpreted their observations as bremsstrahlung from hot, thermal plasma. These authors (Chubb, Kreplin, & Friedmann 1966) later argued that both their observations and those of Peterson & Winckler were consistent with thermal bremsstrahlung from 10^8 K plasma. On the other hand, Anderson & Winckler (1962) argued that correlations with radio emission and the spectral shape and evolution of the flare emission observed by them favored the nonthermal interpretation.

Observations of γ-ray continuum and spectral lines (Chupp et al. 1973) have made it clear that both electrons and protons are accelerated to suprathermal energies in solar flares. Despite the acquisition of many moderate-resolution flare spectra, however, the origin of the bulk of the hard X-ray emission is still undetermined (see Kundu, Woodgate, & Schmahl 1989). Only a single hard X-ray burst (Lin et al. 1981) has been observed with high enough spectral resolution to unambiguously distinguish between the exponential spectral shape characteristic of emission from an isothermal plasma and the power-law spectrum characteristic of nonthermal emission.

Most flare models involve electric currents. These currents and their associated electric fields are either aligned with the magnetic field or are in reconnection regions where a component of the magnetic field reverses direction. In the presence of these electric fields, part of the thermal electron distribution will not be collisionally confined to the bulk current, but will run away and be freely accelerated by the electric field. This electric field acceleration of runaway electrons provides the most direct means of producing and accelerating energetic electrons in flares.

Electron runaway occurs in a current-carrying plasma because the collisional drag on a particle decreases with increasing velocity (Dreicer 1960; Knoepfel & Spong 1979). For electrons with velocities above a critical velocity v_c, the force exerted by the electric field exceeds the collisional drag and the electrons are accelerated out of the thermal bulk. Electrons with velocities below v_c remain thermalized and the electric field drives Joule heating of the plasma. Hence electron heating and acceleration naturally occur together in the acceleration region. Comparing heating and acceleration in flares provides information about the physical conditions in the acceleration region (Holman 1985). The properties and evolution of hot flare plasma can be determined from observations of its thermal bremsstrahlung emission at soft X-ray wavelengths. The hottest plasma may also be observed at the lowest hard X-ray energies, or at microwave frequencies through its thermal gyrosynchrotron radiation.

One of the most important constraints on the direct electric field acceleration of electrons in flares is the flux (and, therefore, current) of electrons required for a nonthermal hard X-ray burst (Hoyng 1977; Spicer 1983; Holman 1985). Taking the hard X-ray emission observed above photon energies of 25 keV to arise entirely from thick-target nonthermal bremsstrahlung, the electron flux required to generate this emission is typically 10^{35} electrons s^{-1} or higher (a current of 10^{16} amps). Taking a maximum possible current channel width of 10^5 km (the radius of the Sun is 7×10^5 km), the induction magnetic field associated with the runaway electrons alone is, from Ampere's law, 10^6 G. Since the maximum magnetic field

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strengths observed on the Sun are on the order of 10^3 G, the *total* electron flux in a single current channel is limited to 10^{32} electrons s^{-1} (10^{13} amps). Hence, if the accelerated electrons remain in the current sheets, $\sim 10^4$ or more oppositely directed current channels (i.e., current/return current pairs) are required. It is feasible to accelerate the electrons in a single current channel if they escape the channel on a short scale length so that the total current does not become too large. However, acceleration to the required energies requires a resistivity in the channel that is much greater than the classical Coulomb resistivity (Holman, Kundu, & Kane 1989).

In addition to the high electron flux, the nonthermal hypothesis for the hard X-ray emission generally also implies that most of the energy released in the flare goes initially into accelerated electrons. These requirements are relaxed if part of the hard X-ray emission is from thermal electrons. Unfortunately, most X-ray observations have been unable to distinguish these possibilities. High spectral resolution observations of one flare have clearly demonstrated the presence of emission from hot thermal plasma at hard X-ray energies below 40 keV (Lin et al. 1981). This thermal component, which first appeared around the time of the peak hard X-ray emission, may have resulted from the secondary heating of plasma by the nonthermal electrons. In this case the high electron flux and total energy are still required. Alternatively, however, the hot plasma may have resulted from the Joule heating of plasma in and around current channels in which runaway electrons are also accelerated. In this case the tail of nonthermal electrons needs only to extend down to electron energies $\sim$40 keV and most of the released energy could go into heating rather than particle acceleration.

Using an electron distribution consisting of an isothermal component and a nonthermal tail of runaways, we have fitted representative spectra from the flare observed by Lin et al. (1981). The results are shown in Figure 1. The top frame in the figure shows the best fit to a spectrum from early in the flare, before the presence of a thermal component is apparent. The bottom frame shows the best fit to a spectrum from later in the flare, when the thermal component is clearly present. The spectral fit is characterized by five free parameters: the temperature (T) and emission measure (EM) of the thermal plasma; the energy ($\mathscr{E}_{\rm crit}$) of an electron with critical velocity v_c; the maximum energy cutoff ($\mathscr{E}_{\rm cut}$) attained by a particle with initial energy $\mathscr{E}_{\rm crit}$; and the area of the thick-target interaction region (A). The derived values for these parameters are given in the figure caption. Also given in the figure caption are the ratio of the electric field strength to the Dreicer field strength (ϵ), where the Dreicer field is the electric field strength for which all of the thermal electrons are in the runaway regime, and the electric field strength (E) and density (n) in the current channel when the length of the channel (L) is taken to be 30,000 km. The density ($\sim 10^{11}$ cm^{-3}) is obtained on the assumption that the resistivity in the channels is classical. The distribution function used here for the runaway electrons is described in Benka (1991) and Benka & Holman (1992b). It varies as $\mathscr{E}^{-1/2}$ between $\mathscr{E}_{\rm crit}$ and $\mathscr{E}_{\rm cut}$, and falls off exponentially above $\mathscr{E}_{\rm cut}$.

The parameters derived from the spectral fits demonstrate that the X-ray emission can be produced with a sub-Dreicer electric field and classical resistivity with a reasonable density in the flaring region. This is generally true for typical flare parameters (Holman 1985; Holman, Kundu, & Kane 1989). The total potential drop ($V = EL$) derived from these spectral fits is only $\sim$30 kV. The small area of the interaction region is consistent with the thickness of the current channels which, from Ampere's law, is $\sim$1 m. The temperature and emission measure derived for the thermal component in the later spectrum are consistent with those obtained by Lin et al. (1981). Our best fit to the earlier spectrum, however, provides an interesting alternative to the nonthermal interpretation of Lin et al. and Lin & Schwartz (1987). We find that hot plasma is present here as well, but with a higher temperature (10^8 K) and a lower emission measure. This would occur if early in the flare the heating is confined to a volume in the immediate vicinity of the current channels, while later in the flare the heat is distributed to a larger volume.

The traditional nonthermal interpretation of the Lin et al. spectra, after removing the 35×10^6 K thermal component and assuming that the nonthermal component extends down to the lowest observed energy channel (13 keV), requires a flux in accelerated particles of 10^{35}–10^{36} electrons s^{-1}. Our hybrid thermal/nonthermal interpretation, on the other hand, requires 10^{33}–10^{34} electrons s^{-1}, about two orders of magnitude smaller. Likewise, the energy flux in accelerated electrons is $\sim$30 times smaller than that required by the nonthermal interpretation. In the hybrid thermal/nonthermal model, most of the released energy goes directly into heating the thermal plasma rather than accelerating particles. This will always be the case as long as the electric field strength is much less than the Dreicer field ($\epsilon \ll 1$).

We have also applied the hybrid model to flare microwave emission (Benka 1991; Benka & Holman 1992a). High-resolution spectra from the Owens Valley Radio Observatory have shown numerous departures from expectations based upon simple thermal or nonthermal models (Stäli, Gary & Hurford 1989, 1990). On the order of 80% of the flare microwave spectra show more than one spectral peak, many bursts have a spectral index on the low-frequency side of the spectral peak which is steeper than the expected maximum of 3, and the peak frequency stays relatively constant throughout a given event. We have found that the hybrid thermal/nonthermal model provides natural explanations for these features.

In summary, the hybrid thermal/nonthermal model relaxes the particle flux and total energy requirements for accelerated electrons in a solar flare. It is consistent with theoretical expectations that most of the energy released into the flare plasma will go directly into heating rather than accelerated particles (see Smith 1980). The model also provides natural explanations for the low-energy cutoff in the nonthermal electron distribution and for several previously unexplained features of flare microwave spectra. Interpreting the results in terms of simultaneous Joule heating and direct electric field acceleration of runaway electrons, the coupling between the two components is apparent and the model provides physical information about the acceleration region. This interpretation is consistent with most global models for the energy release mechanism in flares. It requires either multiple current channels, consisting primarily of current/return current pairs so that most of the current is neutralized, or a single current channel with anomalous resistivity in the channel and rapid escape of the accelerated electrons out of the channel. We note the similarity of the need for multiple current channels to current ideas about coronal heating (e.g., Parker 1988) and to the results of in situ observations of the currents associated with Earth's aurora (Hoffman, Sugiura, & Maynard 1985). We are currently investigating the possibility of rapidly escaping runaways (Benka & Holman 1992b).

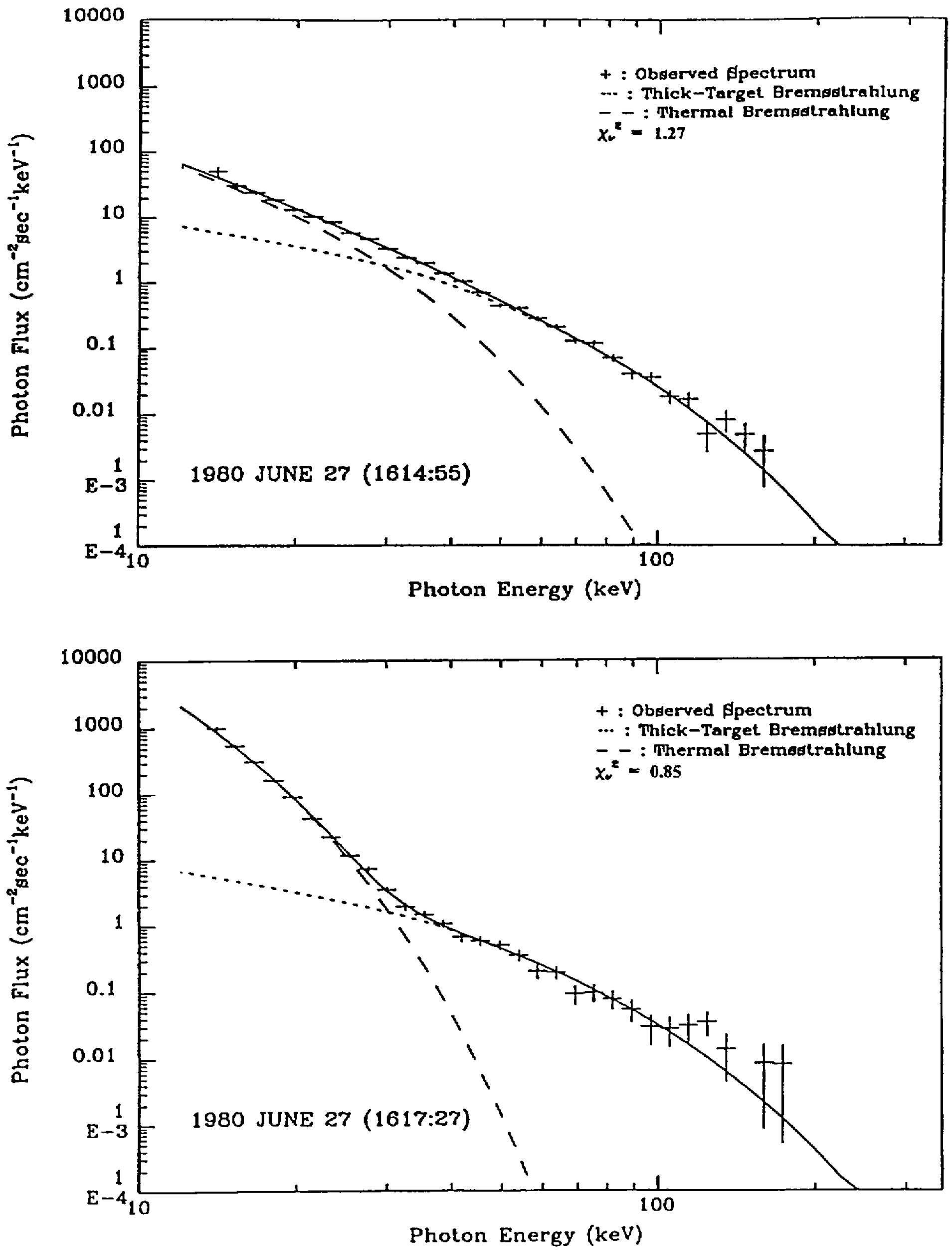

FIG. 1.—X-ray spectra computed from the hybrid thermal/nonthermal electron distribution function fitted (minimum χ^2) to representative spectral data from the 1980 June 27 flare. The thermal bremsstrahlung and thick-target bremsstrahlung components of the computed spectrum are also shown. *Top:* Early in the flare, before the emission peak. The best-fit parameters are (see text for definitions) $T = 1.0 \times 10^8$ K, EM $= 6.8 \times 10^{45}$ cm^{-3}, $\mathscr{E}_{crit} = 38$ keV, $\mathscr{E}_{cut} = 61$ keV, and $A = 9.1 \times 10^{13}$ cm^2; related (derived) parameters are $\epsilon = 0.13$ and, assuming $L = 3 \times 10^9$ cm, $E = 7.7 \times 10^{-6}$ V cm^{-1} and $n = 9.8 \times 10^{10}$ cm^{-3}. *Bottom:* Later in the flare, after the emission peak. The best-fit parameters are $T = 3.6 \times 10^7$ K, EM $= 2.7 \times 10^{48}$ cm^{-3}, $\mathscr{E}_{crit} = 31$ keV, $\mathscr{E}_{cut} = 61$ keV, and $A = 3.5 \times 10^{15}$ cm^2; related (derived) parameters are $\epsilon = 0.054$ and, assuming $L = 3 \times 10^9$ cm, $E = 9.9 \times 10^{-6}$ V cm^{-1} and $n = 1.1 \times 10^{11}$ cm^{-3}.

Future theoretical work of particular interest to this research would be a better determination of the runaway electron distribution function and runaway rate. Existing calculations and numerical simulations have generally been done for a spatially infinite, homogeneous current. Recent numerical computations have shown that the distribution function and runaway rate can be significantly different from these results in a finite-length current channel (MacNeice & Ljepojevic 1992). This is particularly important for determining the shape of the distribution function above $\mathscr{E}_{cut}$. A comparison of the computed emission from the runaway tail with high-resolution hard X-ray and γ-ray spectra can be used to determine if another acceleration mechanism (a stochastic mechanism, for example) is required at the higher electron energies. More studies of the distribution function in a finite-length current channel are needed for this to be done with confidence. Computations that account for the finite width of the current channel and include the magnetic field are also needed (particularly in a sheet geometry). These calculations would also provide a better starting point for studying instabilities in the current channels. (Moghaddam-Taaheri & Goertz 1990 have done a recent study of the stability of and microwave emission from runaway electrons confined within a spatially infinite current channel.)

Observationally, the most immediate need is for more high-resolution X-ray spectra. The Lin et al. (1981) spectra, obtained for a single flare, are still the only available high-resolution flare spectra. Also desirable are simultaneous high-resolution microwave spectra, so that the properties of the plasma and accelerated electrons deduced for each can be compared for the same flare. Such observations are possible now, but depend upon the availability and success of balloon flights for the X-ray observations. The hard X-ray observations are limited to energies above ~ 20 keV, so that plasma with a temperature below $\sim 20 \times 10^6$ K is not detectable. Thanks to *Yohkoh*, the Japanese satellite dedicated to solar observations, and the *Gamma-Ray Observatory* (*GRO*), lower resolution hard X-ray and γ-ray spectra are now being obtained. *GRO* is obtaining moderate-resolution spectra above 15 keV, allowing thermal components to be distinguished in some flares. *Yohkoh* is obtaining rudimentary imaging of hard X-ray bursts in four energy bands between 15 and 100 keV, in addition to low-resolution spectra. (Microwave imaging is available with the VLA and the Owens Valley Radio Observatory.) These low-to-moderate resolution spectra are valuable, but there is greater ambiguity in their interpretation.

A NASA program that is in the developmental stages and is well suited to this line of research is the High-Energy Solar Physics Mission (HESP). The primary HESP instrument, to be flown on an Earth-orbiting satellite at the time of the next solar maximum, is designed to obtain high-resolution X-ray spectra from 2 keV up to γ-ray energies of 20 MeV. Obtaining high-quality spectra from a single instrument over this wide range of photon energies will remove most of the uncertainty which has plagued previous attempts to determine the distribution of electrons that are impulsively heated and accelerated during a flare. The instrument is also designed to obtain, using pairs of grids and a Fourier transform technique, imaging of the emission as a function of photon energy. This high-resolution imaging spectrometer will provide valuable new information about the spatial relationship between the thermal and non-thermal hard X-ray and γ-ray emissions.

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