CURRENT STATUS OF THE DISSIPATIVE THERMAL MODEL FOR SOLAR HARD X-RAY BURSTS

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Up until about five years ago all models for hard X-ray bursts consisted of streaming nonthermal electrons interacting with an ambient plasma (Brown 1975). Even in its most efficient form of thick-target emission in which electrons are stopped in the ambient plasma, this type of model is very inefficient because the electrons lose about 10^5 times more energy in Coulomb collisions with the ambient plasma than in X-rays resulting from bremsstrahlung. As a result, according to the latest estimates, at least 20% of the dissipated flare energy must go into accelerated electrons at the peak of the impulsive phase (Duijveman et al. 1982). Stimulated by observations of hard X-rays with thermal spectra (Crannel et al. 1978; Elcan 1978), analysis of a thermal model in which all the electrons in a given volume are heated to a temperature $T_e \simeq 10^8$K was begun (Brown et al. 1979; Smith and Lilliequist 1979; Vlahos and Papadopoulos 1979). It was recognized from the beginning that some electrons in the tail of the distribution would escape through the conduction fronts formed and mimic nonthermal streaming electrons. This thermal model with loss of electrons or dissipation became known as the dissipative thermal model (Emslie and Vlahos 1980). If the escaping electrons are not replenished, they will cease to make a contribution after a fraction of a second and the source will become a pure thermal source. It will be shown below that collisional replenishment (Smith and Brown 1980) is too slow.

The Solar Maximum Mission (SMM) and HINOTORI results with spatially resolved X-rays up to 30 keV and millisecond time resolution to ∿ 500 keV have done much to resolve the nonthermal versus thermal controversy for hard X-ray models. These observations show the following pattern. In some flares two or more footpoints separated by tens of thousands of kilometers brighten simultaneously to within the time resolution of 1.5s. In some flares this phase is absent although for compact flares it is difficult to tell. This phase which we shall call the nonthermal phase lasts ∿ 40s and can only be explained by thick-target interactions of streaming electrons with the chromosphere. After this phase a single source appears between the original footpoints which lasts for ∿ 10 minutes and has a temperature $T_h \sim 4 \times 10^7$K. The energy

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dissipated during this phase which we shall call the thermal phase is $\sim$ 10 times that of the nonthermal phase. Neither phase is purely nonthermal or purely thermal. In the nonthermal phase the region between the footpoints emits X-rays with about one-third the flux of the footpoints. During the thermal phase μ-waves and hard X-rays indicating electron energies of several hundred keV continue to be emitted. Thus the names of the phases simply refer to the dominant energy loss mechanism. Since most of the energy is dissipated during the thermal phase and a dissipative thermal model with additional acceleration can explain the nonthermal phase, it appears that this model is the best candidate for explaining hard X-ray bursts.

It has been shown (Duijveman 1983) that the mean free path, λ, for electrons in the thermal phase is of order the temperature scale height. Under these conditions classical heat conduction is no longer appropriate and saturated heat conduction, the conduction of freely flowing electrons, applies (Smith and Lilliequist 1979). There is at present no observational evidence that T_e becomes sufficiently large for conduction anomolously limited by the ion-acoustic instability to apply. Although the spectra in this case agree with observations for the nonthermal phase (Smith and Auer 1980; Smith and Harmony 1982), the predicted spatial distributions clearly do not. The 1980, July 14, 08:24 UT flare consists of two spikes which show no footpoints in the 16-30 keV X-rays. There is no time delay between the 30 and 100 keV emission for the first spike and a 1.4s delay of the 100 keV emission relative to the 30 keV emission for the second spike (Orwig, private communication).

As a basis on which some results for dissipative thermal models can be discussed, we summarize the following results. When a current is flowing in a loop with a primary toroidal magnetic field, the current produces a poloidal field which can be dissipated by tearing mode instabilities (Spicer 1977). In the case of the collisional tearing mode, about 47% of the energy released will go into ion motion (Arion 1983) which is perpendicular to the primary toroidal field of the loop. When this drift velocity, v_D, is in the range of 2-3 v_i, where v_i is the ion thermal velocity, the kinetic cross-field streaming instability can create an electron beam at $\sim 6\ v_e$, where v_e is the electron thermal velocity (Tanaka and Papadopoulos 1983). This beam travels along the toroidal field and $\sim$ 50% of the ion energy goes into the electrons. For $v_D > 3\ v_i$, all of the electrons are heated out to $\sim 6\ v_e$ with $\sim$ 50% of the ion energy going to electrons. This instability will only work if $\Omega_e/\omega_{pe} \gtrsim 1$, where Ω_e and ω_{pe} are the electron gyro- and plasma frequencies, respectively.

We show that collisional replenishment of the tail of a Maxwellian distribution is too slow to explain the number of electrons required for the nonthermal phase. The tail of a Maxwellian is populated like an advancing wave in velocity space on a time scale $\tau = 2\lambda(v_b)/v_b$, where v_b is the velocity required for an electron to escape through the conduction front ($\sim 2\ v_e$). During the nonthermal phase, $T_e \simeq 10^8$K, $2v_e = 10^{10}$cm s^{-1} and the density $n_e \simeq 10^{10}$ cm^{-3}. These lead to τ = 1.2s which is much longer than the escape time of electrons $\lesssim 0.1$s for a thermal source of scale $\sim 10^9$ cm. Thus continuous acceleration is required.

Using a flux corrected transport code with implicit correction for heat conduction and radiation, we have followed a single velocity two-temperature fluid along a 47,000 km loop heated near its top. Both classical and saturated heat conduction are included and the maximum T_e was 8×10^7 K. The X-ray yields at 30 and 100 keV for the case where the heating is cut off at 8s are shown in Figure 1. Note the $\sim$ 1.5s time delay between the peaks of the 30 and 100 keV emissions.

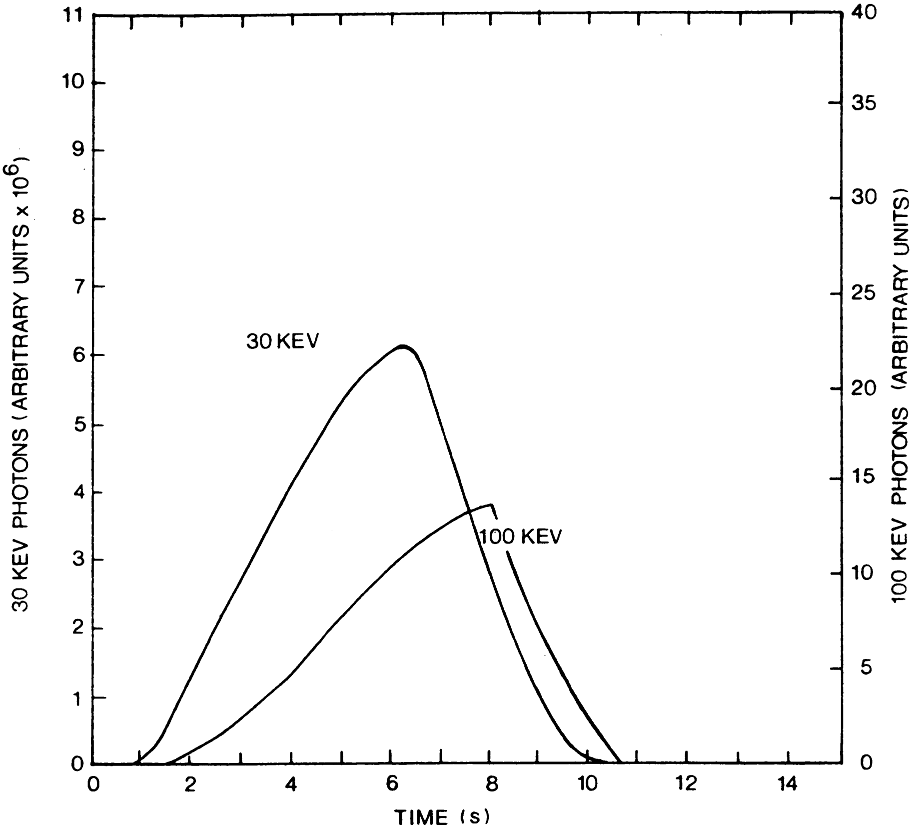

Figure 1. The 30 and 100 keV emission versus time with an energy input of 2.8×10^2 erg cm^{-3} s^{-1}.

A possible scenario for the dissipative thermal model is the following. During the nonthermal phase the loop density is comparatively low and $\Omega_e/\omega_{pe} \gtrsim 1$. Tearing mode instabilities give rise to ion flow at the Alfven speed v_A of the poloidal field across the primary toroidal field. For plausible field values $\sim$ 140G with $n = 10^{10}$ cm^{-3}, $v_A = 3 \times 10^8$ cm s^{-1} which is about $3v_i$ for an ion temperature T_i of 10^8K. This instability gives rise to electrons streaming along the primary toroidal field at ∿ 6 v_e which leads to ∿ 160 keV electrons for $T_e = 10^8$K. The maximum efficiency for conversion of flare energy into streaming electrons is ∿ 23%. These electrons cause plasma to be boiled off the chromosphere which flows back up the loop causing $\Omega_e/\omega_{pe} < 1$ and effective acceleration ceases. The hydrodynamics must still be followed in this stage to determine when effective acceleration stops. During the thermal phase tearing mode instabilities continue to occur in the loop, mostly in regions where $\Omega_e/\omega_{pe} < 1$, resulting in heating with a small amount of acceleration. In the nonthermal phase the efficiency is almost the same as in a nonthermal streaming model. In the thermal phase it is almost the same as in a thermal model.

The nonthermal phase would give rise to footpoints for sufficiently large loops and no time delays between 30 and 100 keV emissions. This is in agreement with observations as long as efficiencies < 23% are required. The thermal phase would give rise to time delays ∿ 1.5s between 30 and 100 keV emissions and a single source. Some continuing acceleration in regions where $\Omega_e/\omega_{pe} \gtrsim 1$ or via another mechanism is required to explain the μ-wave and harder hard X-ray observations.

Thus the dissipative thermal model with additional acceleration is the most likely candidate for the whole hard X-ray burst. In both phases, but especially in the thermal phase, the plasma beta approaches unity and two-dimensional modelling of the hydrodynamics is required. Following the accelerated electrons only without taking into account the response of the bulk of the plasma is inadequate. A useful approach might be a multifluid one using ∿ 15 fluids with the possibility of transfer between fluids in one- and two-dimensions. Thus, while this model contains much promise, many details remain to be worked out.

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