THE HEATING OF THE THERMAL PLASMA WITH ENERGETIC ELECTRONS IN SMALL SOLAR FLARES

Hua-An Lin and Robert P. Lin

Space Sciences Laboratory, University of California, Berkeley

The energetic electrons deduced from hard X-rays in the thick target model may be responsible for heating of soft X-ray plasma in solar flares. Datlowe (1975) has shown from OSO-7 studies that if a cutoff of 10 keV is assumed, the total electron energy is comparable to the thermal plasma energy. However, (1) the soft X-ray emission often appears to begin before the hard X-ray burst, (2) in about one-third of flares there is no detectable hard X-ray emission, and (3) for most events the energy content (assuming constant density) of soft X-ray plasma continues to rise after the end of the hard X-ray burst. To understand these problems we have analyzed the temporal relationship between soft X-rays and hard X-rays for 20 small events observed by ISEE-3 during 1980. One example is shown in Figure 1. The start of soft X-ray and hard X-ray bursts is defined as the time when the counting rates of the 4.8 to 5.8 keV and 25.8 to 43.2 keV channels, respectively, exceed the background by one standard deviation.

Problem (1) mentioned above may be due to the low sensitivity and high background of the solar hard X-ray detector. We find that Δt_{SH}, the difference in start times between the soft X-ray and hard X-ray burst, and $\Delta F_H/\Delta t_{HM}$, the rate of increase of the hard X-ray flux, are anti-correlated with a linear correlation coefficient of 0.70 (Figure 2). This result suggests that the hard X-ray burst may start simultaneously with the soft X rays, and the faster F_H grows, the shorter the time till F_H exceeds the hard X-ray detector background. In some flares the peak flux of hard X rays may not exceed the detector background rate, leading to an apparent absence of hard X-ray emission.

The thermal energy ϵ is proportional to $\epsilon \cdot n_e$ = 3KT·EM for n_e = constant and to $\epsilon \cdot V^{-1/2}$ = $3KT \cdot EM^{1/2}$ for V = constant. Figure 1 shows that t_N, the time of maximum thermal energy for n_e = constant, is later than t_V, the time for V = constant. We have obtained Δt_N, Δt_V and τ_H (Figure 1) from each event. Figure 3 shows that the thermal energy reached maximum before the end of hard X rays for about 30% of the analyzed events for n_e = constant, and for about 65% for V = constant. On average, the Δt_N is larger by 20 to 30 s than Δt_V. Thus, the temporal agreement [problem (3)] may be greatly improved if the volume rather than the density of the thermal plasma region is assumed constant in the flare process. In fact, the observations show that the volume of soft X-ray region varies relatively little compared with the density for compact flares (Moore et al., 1980).

Energetic electrons may provide energy to the soft X-ray plasma region in two ways: (1) chromospheric evaporation by the energy deposition of the higher energy electrons, which mainly increases the emission measure of the thermal plasma; and (2) energy deposition of lower energy electrons directly into the thermal plasma region, which mainly increases the temperature. The increase of the thermal energy for V = constant can be split into two components $\Delta\epsilon(\sqrt{EM})$ and $\Delta\epsilon(T)$, due to the increase in emission measure and in temperature, respectively. Since $\epsilon = 3KV^{1/2} \cdot T \cdot \sqrt{EM}$, we obtain $\Delta\epsilon \approx 3KV^{1/2} \cdot \overline{T} \cdot \Delta\sqrt{EM} + 3KV^{1/2} \cdot \overline{\sqrt{EM}} \cdot \Delta T$, where the first term is $\Delta\epsilon(\sqrt{EM})$ and the second $\Delta\epsilon(T)$, and $\overline{T}$ and $\overline{\sqrt{EM}}$ are average values. We compute the ratio $\Delta\epsilon(\sqrt{EM})/\Delta\epsilon(T)$ during the phase of increasing temperature when the energy loss of thermal plasma by heat conduction and radiation may be ignored. This ratio and γ_{MIN}, the lower hard

X-ray spectral index, are anti-correlated (Figure 4). The correlation coefficient between $\ln(\Delta\epsilon(\sqrt{EM})/\Delta\epsilon(T))$ and γ_{MIN} is 0.62. This result indicates that as the proportion of higher energy electrons increases, the fraction of the thermal energy contributed by the emission measure correspondingly rises, and vice versa.

From an analysis of 20 small events, we conclude that if the volume rather than the density of the thermal plasma region is assumed constant in the flare process, energetic electrons could heat the soft X-ray plasma.

Acknowledgments. We would like to thank Dr. S. R. Kane for useful discussions. This research was supported by NASA grant NAG5-376.

REFERENCES

Datlowe, D. W., 1975, in *Solar Gamma-, X-, and EUV Radiation* (ed. by S. R. Kane), IAU Symposium No. 68, p. 191.

Moore, R., McKenzie, D. L., and 14 co-authors, 1980, in *Solar Flares* (ed. by Peter A. Sturrock), Colorado University Press, Boulder, p. 341.

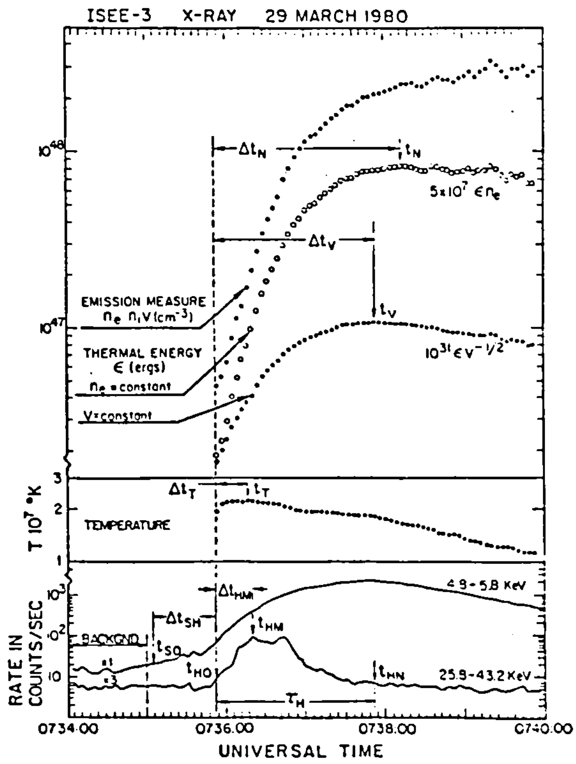

Figure 1. The temporal evolution of the solar flare of 29 March 1980 and the definitions of various times.

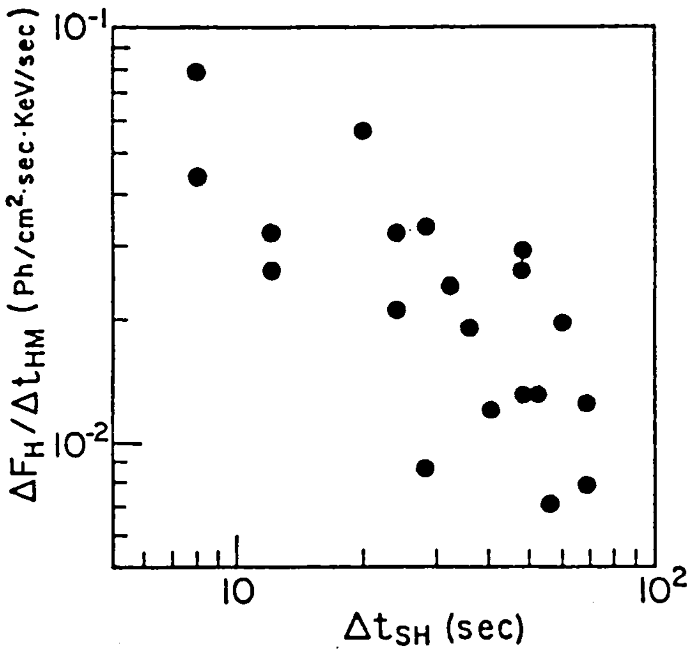

Figure 2. Rate of increase of hard X-ray flux versus the difference in start times between soft and hard X-ray bursts.

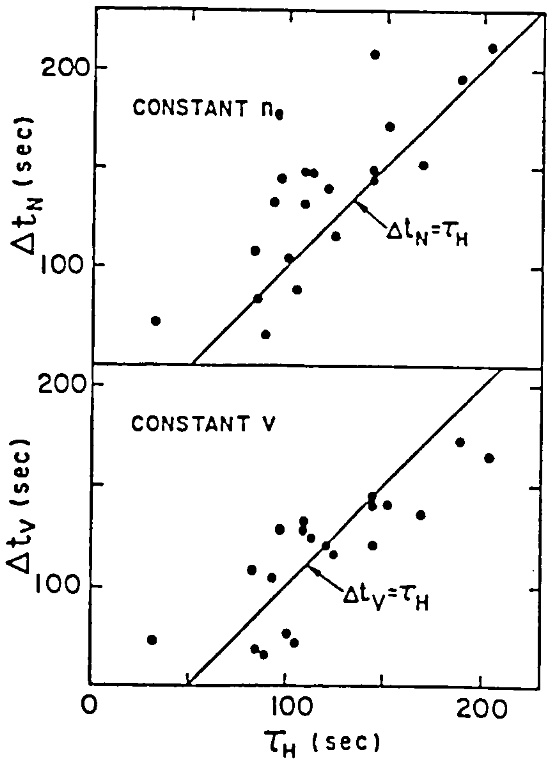

Figure 3. The relationship between the time when the thermal energy reached maximum and the duration of hard X-rays. Top panel: for constant density; bottom panel: for constant volume.

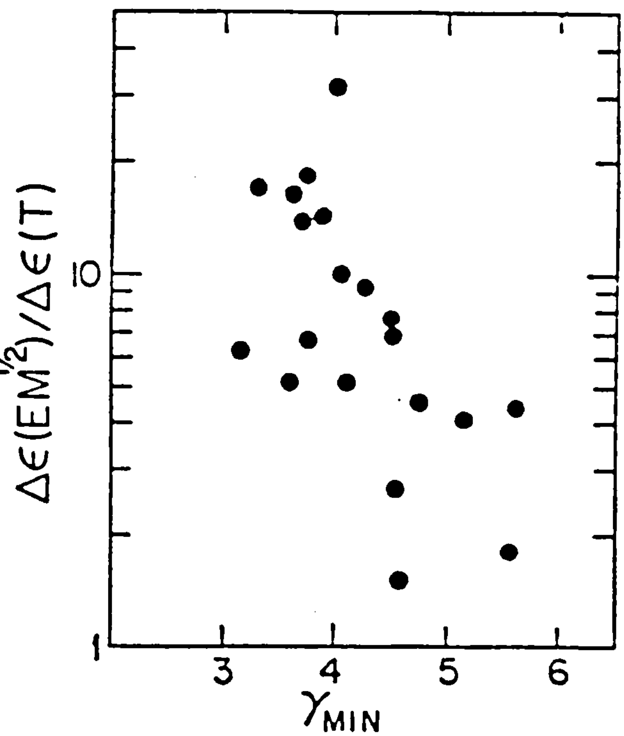

Figure 4. The ratio of the increase in thermal energy caused by increasing emission measure and by increasing temperature, versus the lowest hard X-ray spectral index.