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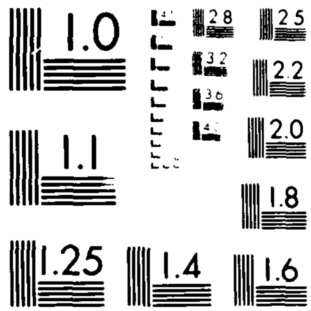

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CHROMOSPHERIC HEATING BY ELECTRON AND PROTON BOMBARDMENT IN THE SOLAR FLARE OF JUNE 7, 1980 (RESEARCH NOTE)

by

A. Gordon Emslie

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CHROMOSPHERIC HEATING BY ELECTRON AND PROTON BOMBARDMENT IN THE SOLAR FLARE OF JUNE 7, 1980

(RESEARCH NOTE)

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Abstract. Using observations of both hard X-rays and γ-rays in the large solar flare on June 7, 1980, we infer the amount of chromospheric heating due to bombardment both by non-thermal electrons and by protons, respectively. If a thick-target model for the X-ray bremsstrahlung is adopted, then proton heating is shown to be important only in the lower chromosphere; however, if the hard X-rays are substantially thermal in origin, then proton heating may play an important or indeed dominant role in determining the structure of the entire flaring chromosphere.

1. Introduction

Observations of solar flares in hard X-rays and γ-rays provide information on the populations of energetic electrons and protons, respectively, in the flare. In the case of electrons, the observed hard X-ray emission is simply proportional to the rate of injection of energetic electrons (except for very rapid events--Emslie, 1982), and one can, from pulse height bremsstrahlung spectra, deduce the form of the injected energetic electron energy distribution at each instant throughout the flare. The determination of the instantaneous injected proton spectrum is not so straightforward, since γ-ray emission takes the form of line

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emission superimposed on a continuum, and since some γ-ray emissions (such as the deuterium formation 2.223 MeV line: Ramaty, 1982) are delayed phenomena. Nevertheless, it is still possible to obtain an estimate for the time-integrated flux, or fluence, of both electrons and protons from observation.

Once the form of the fluence energy spectrum is known, it is a relatively straightforward matter to compute the variation of deposited energy with depth throughout the atmosphere, caused by the collisional degradation of the energetic particles (Emslie, 1978). It is therefore possible, and of course of interest, to compare the heating rates due to both electron and proton bombardment in events where both hard X-ray and γ-ray observations are available. Our conclusions will necessarily depend on interaction models adopted for the hard X-ray and γ-ray emission processes, since this affects the emitted photon/injected particle ratio. Ramaty (1982), on the basis of a comparison of interplanetary proton spectra and γ-ray fluxes in a number of events, has shown that γ-rays are almost certainly formed by a thick process involving non-thermal proton streams. On the other hand, there are at present two viable possibilities for the hard X-ray emission process--either thick target (Brown, 1971) or thermal (Brown et al., 1979; Smith and Lilliequist, 1979; Smith and Auer, 1980). Both models appear to be consistent with hard X-ray intensities and spectra (Brown, 1974; Elcan, 1978), and with available polarization measurements (Emslie and Brown, 1980). However, a thermal interpretation of the hard X-ray burst implies fewer electrons precipitating into the lower atmosphere (Emslie and Vlahos, 1980; Smith and Brown, 1980), and so a lower chromospheric heating contribution from electrons. In this article we therefore compare electron and proton collisional heating rates under both interpretations of the hard X-ray emission. We apply our results to the event of June 7, 1980, for which good observations in both hard X-rays and γ-rays were obtained.

2. Observations

At approximately 0312 UT on June 7, 1980, an intense solar flare (X-ray class M7) was observed near the west limb of the solar disk (coordinates N12° W74°) in active region 2495. The event is characterized by a series of sharp spikes, observed in hard X-rays, γ-rays, and microwaves, and presents many fascinating problems of interpretation (Bai et al., 1982; Kane et al., 1982; Kiplinger et al., 1982). As mentioned in Section 1, determination of the instantaneous injected fluxes of both electrons and protons is not possible. However, under an assumed interaction model, the particle number spectra may be obtained for both sets of particles, and this is sufficient to compare the specific energy deposited (erg per cm of vertical distance per unit ambient density) by electrons and protons. In Table I we present the parameters of the particle number spectra dN/dE for the June 7, 1980 event, under the assumption of thick-target models for both hard X-ray and γ-ray production, where the functional form

$$\frac{dN(E)}{dE} = (\delta-1)\,\frac{N(E_1)}{E_1}\left(\frac{E}{E_1}\right)^{-\delta}; \; E \geq E^*, \tag{1}$$

has been assumed. Here $N(E_1)$ is the total number of particles injected with energies greater than E_1 (arbitrary, except for the condition $E_1 > E^*$; here we take $E_1 = 20$ keV for electrons and 10 MeV for protons), δ is a constant spectral index, and E^* is a lower cutoff energy to the particle number spectrum. Note that the spectral form (1) is principally for mathematical convenience (see Section 3), and should not be taken as accurately corresponding to the actual particle spectra. Also note that the time and area integrations performed in arriving at the values in Table I of course obscure many of the interesting features of the June 7 event (e.g. the multiple spike character, also possibly related to a multiple-loop character for the event [Emslie, 1981a]); however, this will not affect the order-of-magniturde conclusions presented here.

3. Variation of Deposited Energy with Depth

The transport and collisional degradation of energetic charged particles through the solar atmosphere during flares has been studied by a number of authors, and energy deposition rates as a function of depth evaluated (see, e.g., Najita and Orrall, 1970; Brown, 1972, 1973; Orrall and Zirker, 1976; Emslie, 1978, 1980; Hudson and Dwivedi, 1982). While it is generally accepted that energetic electrons may be responsible for depositing a substantial amount of energy in the chromosphere during the flare flash phase, the role of protons in heating the lower atmosphere is still somewhat controversial. Most of the discussion regarding proton heating has concentrated on the lower chromosphere/temperature minimum/upper photosphere regions of the atmosphere, due to the greater penetrating power of deka-MeV protons compared with deka-keV electrons (Machado _et al._, 1978; Brown _et al._, 1981; Hudson and Dwivedi, 1982), but few authors have considered the role of proton heating in the upper chromosphere (see Lin and Hudson, 1976). In this section we shall follow the analysis of Emslie (1978) in order to assess the relative roles of proton and electron heating at various levels of the atmosphere in the June 7, 1980 event.

The energy deposition (erg $cm^{-3}s^{-1}$) due to the passage of a beam of charged particles through a relatively cold background target is given by Equation (36) of Emslie (1978); using the spectrum (1) and integrating this rate over the area of the flare and over the duration of the event gives the total energy deposited per cm of height throughout the event:

$$I_B = \tfrac{1}{2} K\, n\, \gamma(\delta-1)\, B\left(\frac{\delta}{2}, \frac{2}{4+\beta}\right) \frac{N_1}{E_1} \left[\frac{\left(2+\frac{\beta}{2}\right) \gamma K N}{\mu_o\, E_1^{\,2}}\right]^{-\delta/2}, \tag{2}$$

where $K = 2\pi e^4$ (e = electronic charge [e.s.u.]), n (cm^{-3}) is the ambient density, μ_o is the cosine of the injected pitch angle (to the downward pointing magnetic field) of the beam, $N(cm^{-2})$ is the overlying proton column density at the point in question, B is the beta function and the parameters β and γ are defined as follows (Emslie, 1981b):

$$\beta_e = \frac{2\, x\, \Lambda + (1-x)\, \Lambda''}{\Lambda' + x\, (\Lambda-\Lambda')}, \quad \beta_p = 0$$

$$\gamma_e = \left[x\, \Lambda + (1-x)\, \Lambda'\right], \quad \gamma_p = \frac{m_p}{m_e} \left[x\, \Lambda + (1-x)\, \Lambda'\right]. \tag{3}$$

In these expressions subscripts e and p refer to electron and proton bombardment respectively, x is the fractional ionization level of the target, m_e and m_p are the electron and proton masses, and Λ, Λ' and Λ'' are Coulomb logarithms, defined in Emslie (1978). (Note that the expressions (3) correct an error in Emslie [1978], see Emslie [1981b].)

Equation (2) is valid only if we are considering values of $N > \left[E^{*2}/(2 + \frac{\beta}{2})\, \gamma K\right]$, where E^* is the cutoff energy in the injected particle spectrum (see Equation (1)). For values of N less than this, the beta function in Equation (2) should be replaced by an incomplete beta function (see Equation (8) below), which results in a reduced heating rate I_B. In view of the uncertainty in the value of E^*, we (formally) take E^* as zero for both electrons and protons; for $N \simeq 10^{20}$ cm^{-2} (see discussion in Section 4), Equation (2) then yields correct values for I_B if $E_e^* \lesssim 30$ keV and $E_p^* \lesssim 2$ MeV, which seem to be reasonable conditions to satisfy (e.g. Kane et al, 1980; Ramaty, 1982).

Since we are here interested principally in the ratio of energies deposited by proton and electron bombardment, we can take the target to be fully ionized; setting $x = 1$ in equations (3) and substituting in Equation (2) results in the required energy deposition amounts:

$$I_{B,e} = \pi e^4 \, n \, \Lambda \, (\delta_e - 1) \, B\left(\frac{\delta_e}{2}, \frac{1}{3}\right) \frac{N_{1,e}}{E_{1,e}} \left(\frac{6\pi e^4 \, \Lambda \, N}{E_{1,e}^{\,2}}\right)^{-\delta_e/2}$$

$$I_{B,p} = \pi e^4 \left(\frac{m_p}{m_e}\right) n \, \Lambda \, (\delta_p - 1) \, B\left(\frac{\delta_p}{2}, \frac{1}{2}\right) \frac{N_{1,p}}{E_{1,p}} \left(\frac{4\pi e^4 \, \left(m_p/m_e\right) N}{E_{1,p}^{\,2}}\right)^{-\delta_p/2}, \quad (4)$$

where we have set $\mu_o = 1$ (vertical injection). If we now set $E_{1,e} =$ 20 keV, $E_{1,p} = 10$ MeV, and use the values of N_1 and δ from Table I, we arrive at the energy deposition amount versus column depth curves of

FIGURE 1 Figure 1, to be discussed in the next Section.

4. Discussion

From Figure 1 it is immediately apparent that electron heating predominates down to $N \simeq 2.5 \times 10^{22}$ cm^{-2} in the June 7, 1980 event, at least in a thick target interpretation for the hard X-ray burst. The level of the flaring chromosphere lies around $N \simeq 10^{20} - 10^{21}$ cm^{-2} (Machado and Linsky, 1975; Machado et al., 1980); thus we see that in such an interpretation, proton heating is unimportant in the upper chromospheric energy balance. We note in passing that the June 7, 1980 event has a remarkably high γ-ray to hard X-ray flux ratio (A. L. Kiplinger, private communication), so that in other events proton heating will be of even lesser importance.

However, in a thermal interpretation of the hard X-ray emission, the situation could change substantially. As remarked in Section 1, such an interpretation involves a fewer number of precipitating electrons (in agreement with other observational determinations of this precipitating flux -- Brown *et al.*, 1978; Emslie *et al.*, 1978; Donnelly and Kane, 1978), thus reducing the value of $I_{B,e}$, while $I_{B,p}$ remains unaltered. Vlahos and Papadopoulos (1979), Emslie and Vlahos (1980) and Smith and Brown (1980) have considered the precipitation of high energy electrons from a principally thermal source at a temperature of several x 10^8 K, with somewhat varied conclusions regarding the role of such precipitating electrons in the flare process. Emslie and Vlahos (1980) consider a model in which the beam is instantaneously repopulated by direct electron field acceleration and Dreicer runaway in the source; the injected precipitating flux is

$$F(E_o) = \left(\frac{2}{\pi}\right)^{\frac{1}{2}} \left(\frac{n}{m_e v_e}\right) e^{-E^*/kT} \left(\frac{E_o}{E^*}\right)^{-\delta} \text{ electrons cm}^{-2}\text{s}^{-1},\ E_o \geq E^*, \qquad (5)$$

where n and T are the source density (cm^{-3}) and temperature (K) respectively, m_e is the electron mass, k is Boltzmann's constant, $v_e = (kT/m_e)^{\frac{1}{2}}$ is the electron thermal velocity and E^* is the minimum energy necessary for escape ≈ 5kT (Brown *et al.*, 1979; Smith and Brown, 1980). Multiplying $F(E_o)$ by $A\tau$, where A is the injection area and τ the duration of the event gives N^*, the number of injected electrons above energy E^*.

We now consider the following source parameters (L = source length)

$$\begin{aligned} n &\simeq 10^{11}\ \text{cm}^{-3} \\ T &\simeq 3 \times 10^{8}\ \text{K} \\ L &\simeq 10^{8}\ \text{cm} \\ A &\simeq 10^{15}\ \text{cm}^{2} \\ \tau &\simeq 60\ \text{s} \\ \delta &\simeq 4 \end{aligned} \qquad (6)$$

appropriate to the June 7 event (with emission measure $n^2 V \simeq 10^{45}$ cm^{-3}). Substituting these values in eq. (5) gives $E^* = 130$ keV and N_{130} keV $= 3.6 \times 10^{35}$; eq. (4) then gives an expression for the energy deposited as a function of depth N (Emslie, 1978; Emslie and Vlahos, 1980):

$$\frac{I_{B,e}}{n} = \begin{cases} 8 \times 10^{49}\ N^{-2}\ \alpha(N) & ;\ N \leq 1.7 \times 10^{21}\ \mathrm{cm}^{-2} \\ 1.8 \times 10^{50}\ N^{-2} & ;\ N \geq 1.7 \times 10^{21}\ \mathrm{cm}^{-2}, \end{cases} \tag{7}$$

where

$$\alpha(N) = \int_0^{\frac{3KN}{E^{*2}}} x\ (1-x)^{-2/3}\ dx = \frac{9}{4}\left[1-(1+\tfrac{y}{3})(1-y)^{1/3}\right], \tag{8}$$

where $y = 3KN/E^{*2}$. Note that the energy deposited has a maximum at $y = 1$ ($N = E^{*2}/3K$), since no electrons of energy $< E^*$ escape from the source. For small N, $\alpha \simeq \frac{1}{2}(3KN/E^{*2})^2$, giving $I_{B,e}/n \simeq 1.4 \times 10^7$ ergs, independent of N. The full behavior of $I_{B,e}/n$ with N from eq. (7) is shown in Figure 1. We see that below $N \simeq 10^{21}$ cm^{-2} the value of $I_{B,e}$ (N) is not substantially different from its value in the thick target case. Physically this is because the flux of high energy electrons is similar in both models. However, at lower N values, corresponding to low energy electrons, $I_{B,e}$ in the thermal model is much smaller than in the non-thermal case, because the collisional damping rate of high energy electrons is low, and there are no low energy electrons precipitated (as these would be in the thick target model). Thus for $N \lesssim 5 \times 10^{20}$ cm^{-2} proton heating can in fact dominate over electon heating. This value of N is entirely consistent with the position of the upper chromosphere in flares, especially in the impulsive phase (Machado et al., 1980; Emslie et al., 1981), and so we conclude that, in a thermal interpretation of the hard X-ray burst, proton heating may be important in the chromospheric energy balance, at least in events with relatively high γ-ray/hard X-ray flux ratios, such as the June 7, 1980 event. Further clarification of this issue must await a better understanding of the tail repopulation mechanism in hybrid thermal/non-thermal models (see discussion in Smith and Brown, 1980), and an anambiguous determination of the thermal or non-thermal character of the hard X-ray emission in flares.

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*Visitor at Stanford University June 14 to July 7, 1982.

Table I

Thick Target Injected Number Spectra

Electrons*		Protons†	
$N_{20\ keV}$	δ_e	$N_{10\ MeV}$	δ_p
7×10^{37}	3.9	8.5×10^{32}	2.2

*A. L. Kiplinger, private communication.

†Ramaty, 1982, Table 3 and Figure 1.

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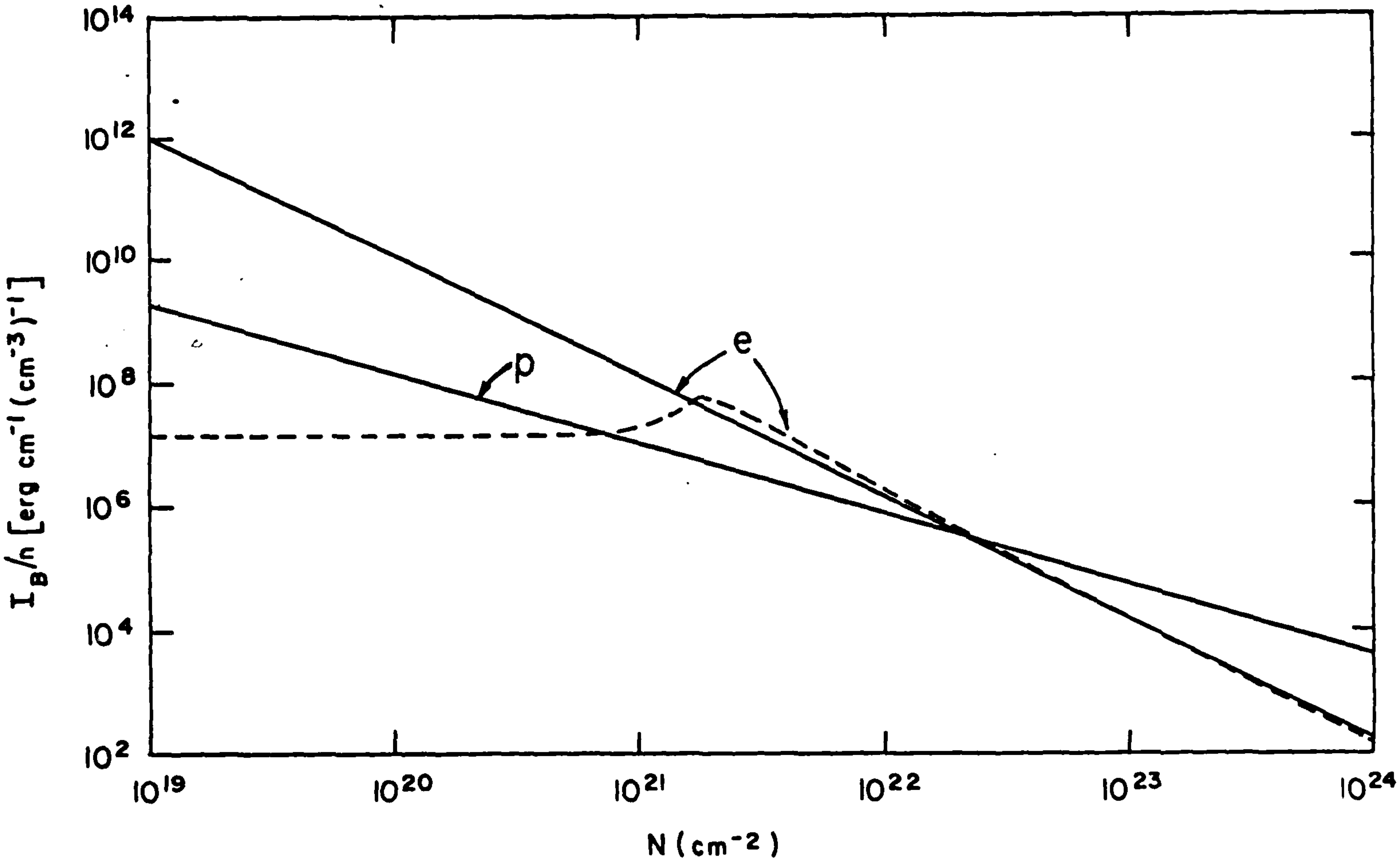
FIGURE CAPTION

Figure 1: Energy deposited per unit ambient particle number density n by electrons (e) and protons (p) in the June 7, 1980 event. The solid lines refer to a thick-target model, and the dashed line to a thermal/ thick-target "hybrid" model of Emslie and Vlahos (1980); see Section 4.



10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
I_B/n [erg cm^{-1} (cm^{-3})$^{-1}$]
e
p
10^{19}
10^{20}
10^{21}
10^{22}
10^{23}
10^{24}
N (cm^{-2})

FIGURE 1

DAT

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