EVIDENCE FOR BOTH ELECTRON ACCELERATION AND DIRECT HEATING IN SOLAR FLARES

B. R. Dennis [1], G. D. Holman [1], H. S. Hudson [2], T. Kosugi [3], K. T. Strong [4], and D. M. Zarro [5]

[1] *Solar Physics Branch, Code 682, Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.*
[2] *Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, U.S.A.*
[3] *National Astronomical Observatory of Japan, Mitaka, Tokyo 181, Japan*
[4] *Lockheed Palo Alto Research Lab., Dept. 91-30 Bldg. 252, 3251 Hanover Street, Palo Alto, CA 94304, U.S.A.*
[5] *Applied Research Corp., Solar Data Analysis Center, Code 682, NASA Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.*

Abstract

It is well known that in many impulsive solar flares, the time profile of the total soft X-ray flux closely matches the time integral of the hard X-ray profile, the so-called Neupert Effect. We have selected several flares detected by the X-ray telescopes on Yohkoh that clearly show this effect and examined the time profiles for different spatial locations throughout the flaring region. We find that footpoint locations show coincident impulsive bursts in both soft and hard X-ray emissions whereas loop-top locations show more gradually varying soft X-ray emission with weaker hard X-ray emission. We interpret these observations in terms of an electric field model in which both Joule heating and electron runaway acceleration take place, with the ratio of the two dependent on how strong the field is compared to the local Dreicer field. The pre-impulsive phase emissions and the early gradually-varying soft X-ray emission can be attributed to the direct heating by the electric field in the coronal part of the loop and the impulsive footpoint emission can be attributed to both enhanced Joule heating and electron precipitation.

1. Introduction

We propose a basic flare scenario in which all aspects and phases of a typical impulsive flare result from the generation of an electric field in the corona parallel to the magnetic field.

We do not address the origin of this electric field in this paper although we surmise that it is driven by fluid motions in the convection zone. The electric field both heats the ambient plasma by Coulomb collisions and accelerates runaway electrons to high energies. As the strengths of the electric field and the Dreicer field vary in space and time during the different stages of the flare, so the different thermal and nonthermal flare manifestations are produced. In this paper, we show how the observations of an impulsive flare can be interpreted on the basis of this simple scenario.

2. Observations

The basic phases of an impulsive flare are illustrated in Figure 1, where SXT images are shown at different times throughout an X1 flare that occurred at 15:28 UT on 26 January, 1992. This flare shows distinct impulsive footpoint emission simultaneous in both hard and soft X-rays peaking at 15:28:30 UT (Hudson et al. 1993) providing further evidence for nonthermal electron precipitation and chromospheric evaporation. However, even before the first hard X-rays were detected with HXT at ~15:26 UT, the soft X-ray images in Figure 1 taken as early as 15:25 UT showed already bright loops with temperatures of $\sim 11 \times 10^6$ K and densities of $\sim 5 \times 10^{10}$ cm^{-3} indicating that significant preheating must have taken place. Further, after the last hard X-rays were detected at ~15:30 UT, the soft X-ray emission continued to rise and the loops became more uniformly bright with the brightest areas near the loop tops. This behavior is typical for impulsive flares except that the bright area near the top of the loops appeared less concentrated in this flare than is the case for other flares (Feldman et al. 1993). Nevertheless, in this and in similar impulsive flares, there is strong evidence for continued heating, even after the last hard X-rays are detected.

3. Interpretation

Holman (1985) and Tsuneta (1985) have considered the acceleration of electrons out of a thermal plasma and the simultaneous Joule heating by multiple oppositely-directed electric fields parallel to the magnetic field. The response of the plasma to an imposed electric field (E) is to set up an electric current with a current density $J = -env_d = \sigma E$ where n is the number density of thermal electrons, e is the electron charge, v_d is the mean drift velocity of the current-carrying electrons, and σ is the conductivity of the plasma. Those electrons with a velocity greater than the critical velocity, v_c, will be freely accelerated out of the thermal distribution to an energy dependent on the field strength and the time they spend in the field. This critical velocity is given by the relation $v_c = (E_D/E)^{1/2} v_e = (v_e/v_d)^{1/2} v_e$ where $E_D = 2.33 \times 10^{-8}\, n_9\, T_7^{-1}\, (ln\,\Lambda/23.2)$ statvolts cm^{-1} is the Dreicer field, i.e., the field at which the critical velocity equals the thermal velocity $v_e = (kT/m)^{1/2}$.

Holman (1985) and Holman, Kundu, and Kane (1989) have shown that the ratio of the Joule heating rate (Q in ergs s^{-1}) to the number of electrons that runaway per second ($\dot{N}$ in electrons s^{-1}) is given by the following relation:

$$Q/\dot{N} = 3.92 \times 10^{-9}\, T_7\, (E_D/E)^{-19/8} \exp\{(2\mathrm{E_D/E})^{1/2} + \mathrm{E_D/4E} + \mathrm{C}\} \qquad (1)$$

where T_7 is the temperature in units of 10^7 K and C is a relativistic factor that is negligible if v_c is small compared to the velocity of light. Note that as the critical velocity is decreased by decreasing the ratio E_D/E, the number of electrons that run away is a very steep exponential function of the critical velocity since the Maxwellian thermal velocity distribution is exponential on the tail. Thus, a small change in either E or E_D can result in a very large change in the number of electrons that run away.

In our flare scenario, with the initial measured values of n and T, we assume that E is less than $\sim 1\%$ of E_D, i. e., $E < 10^{-8}$ statvolts cm^{-1}. Then almost all of the energy released from the magnetic field will go to Joule heating in the loop and few electrons will run away. This early heating produces the observed soft X-ray emission and other manifestations of the preflare phase. The heated plasma in the loop will produce the unshifted soft X-ray emission lines while both direct heating by the currents in the low corona and chromosphere and conduction to the foot points will produce chromospheric evaporation.

As the flare progresses, the temperature in the loop increases as a result of the the direct Joule heating and the density increases through chromospheric evaporation. Thus, it is not clear if the Dreicer field will tend to increase or decrease during this early stage. Nevertheless, if E_D/E in the loop decreases, either because of the decreasing value of E_D resulting from the increasing temperature in the loop or because E itself increases, then significant numbers of runaway electrons can be produced. Since the relation between heating and acceleration is such a strong function of E_D/E, the turn on and turn off of the runaway electron flux can be very rapid, explaining the subsecond to second time scales characteristic of the impulsive phase. The Joule heating rate itself will, however, be relatively unaffected by the fraction of the energy going to accelerate runaway electrons and should vary more slowly since it depends only linearly on the electric field. The runaway electrons will propagate down to the footpoints producing thick-target hard X-ray emission and additional chromospheric evaporation. The evaporated plasma increases the density in the loop, thus increasing the Dreicer field and reducing the number of runaway electrons even if the applied field stays constant. The Joule heating in the loop will, however, continue as long as the electric field remains present.

4. Conclusions

This simple electric field model can explain many of the observational characteristics of flares. The progress of the flare is decided primarily by the relation between the electric field and the Dreicer field in the current sheets. This relation changes with time as the temperature and density change in the current sheets and as the electric field changes, presumably as the result of the dynamics of the energy release process itself. A quantitative scenario for a specific flare is presented by Zarro et al. (1994) using the basic thermal/nonthermal model of Holman and Benka (1992) and the soft and hard X-ray emissions measured with instrumentation on Yohkoh and the Compton Gamma Ray Observatory. Microwave observations can also help to establish the different parameters of the model as a function of time throughout the flare (Benka and Holman 1992).

References

1. Benka, S. G. and Holman, G. D., 1992, *Ap. J.* **391**, 854.
2. Benka, S. G. and Holman, G. D., 1994, *Ap. J.*, submitted.
3. Feldman, U., Hiei, E., Phillips, K.J.H., Brown, C. M., and Lang, J., 1994, *Ap. J.*, in press.
4. Holman, G.D., 1985, *Ap. J.* **293**, 584.
5. Holman, G.D., Kundu, M.R., and Kane, S.R., 1989, *Ap. J.* **345**, 1050.
6. Holman, G.D. and Benka, S.G., 1992, *Ap. J. Letters* **400**, L79.
7. Hudson, H. S., Strong, K.T., Dennis, B.R., Zarro, D.M., Inda, M., Kosugi, T., and Sakao, T., 1993, *Ap. J.*, in press.
8. Tsuneta, S., 1985, *Ap. J.* **290**, 353.
9. Zarro, D. M., Mariska, J., and Dennis, B. R., 1994, these proceedings and *Ap. J. Letters*, to be submitted.

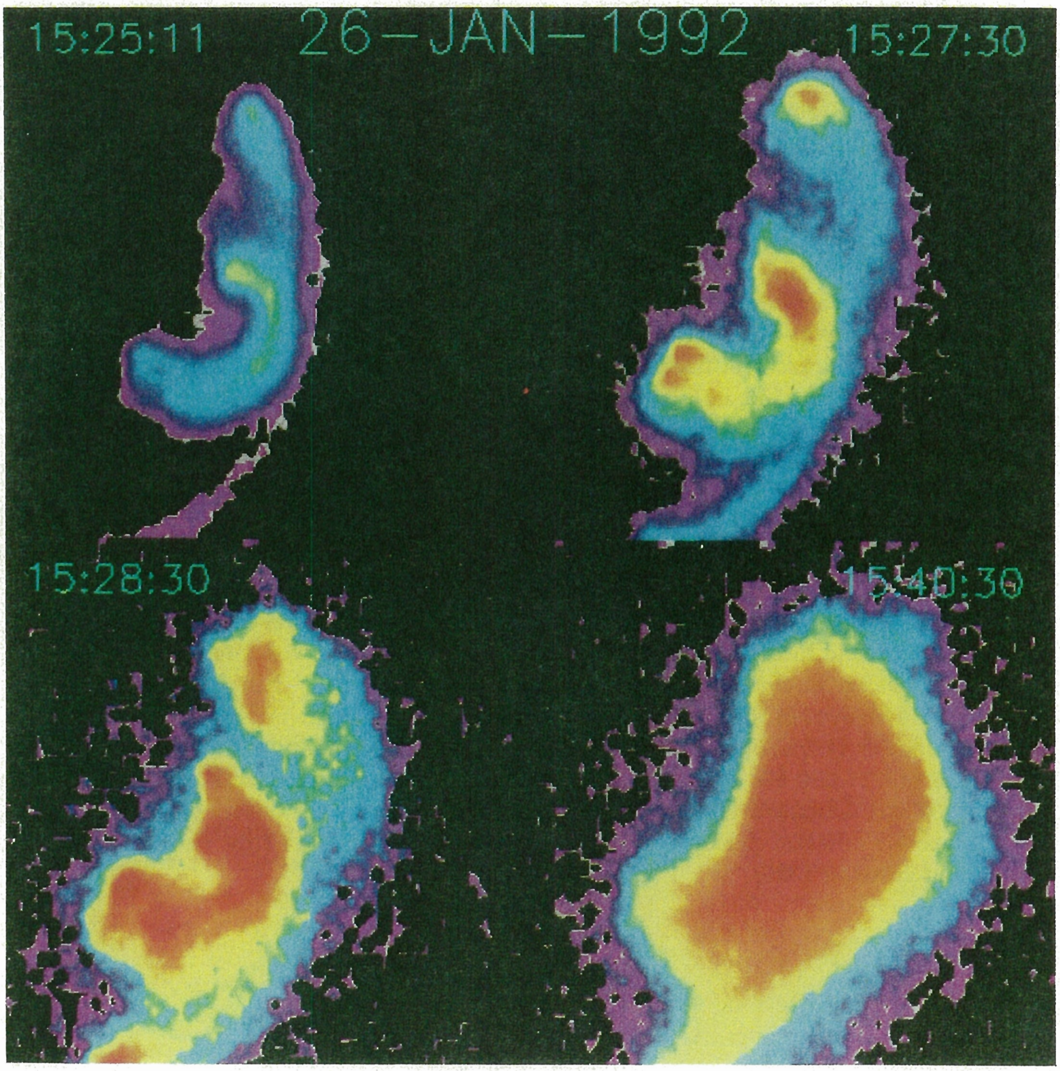

Fig. 1. SXT images through the beryllium filter at four different times during the X1 impulsive flare on 26 January, 1992. Upper left: prior to the first detectable hard x-ray emission; upper right: during the rise of the impulsive hard X-ray emission; lower left: at the peak of the impulsive hard X-ray emission; lower right: late in the flare after the end of the hard X-ray emission and after the peak in soft X-rays.