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THE GENERATION OF RAPID SOLAR FLARE HARD X-RAY AND MICROWAVE FLUCTUATIONS IN CURRENT SHEETS

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Abstract. The generation of rapid fluctuations, or spikes, in hard X-ray and microwave bursts via the disruption of electron heating and acceleration in current sheets is studied. It is found that 20 msec hard X-ray fluctuations can be thermally generated in a current sheet if the resistivity in the sheet is highly anomalous, the plasma density in the emitting region is relatively high ($\sim 10^{11}$ cm^{-3}), and the the volume of the emitting region is greater than that of the current sheet. A specific mechanism for producing the fluctuations, involving heating in the presence of ion acoustic turbulence and a constant driving electric field, and interruption of the heating by a strong two-stream instability, is discussed. Variations upon this mechanism are also discussed. This mechanism also modulates electron acceleration, as required for the microwave spike emission. If the hard X-ray emission at energies less than ~ 100 keV is nonthermal bremsstrahlung, the coherent modulation of electron acceleration in a large number ($>10^4$) of current sheets is required.

1. Introduction

Fluctuations in the impulsive hard X-ray emission from solar flares with rise and fall times as short as 20 msec have been reported (Kiplinger et al. 1983). Spikes in the microwave emission from solar and stellar flares with time scales as short as 1 msec are also observed (Slottje 1978, 1980; Kaufmann et al. 1980, 1985; Zhao and Jin 1982; Gary et al. 1982; Lang et al. 1983). The high brightness temperature and polarization of the microwave spikes clearly indicate that this emission is nonthermal, while the hard X-ray emission may be either thermal or nonthermal. Mechanisms that might be responsible for these rapid fluctuations are (1) an instability in the heating/acceleration region, (2) rapid compression and expansion of the emitting and/or heating/acceleration region, or (3) an instability in the "beam" of streaming, accelerated particles when the emission is nonthermal.

Flares are generally understood to be associated with the formation and instability of current sheets. This paper therefore addresses mechanisms of the first type for producing the observed fluctuations or spikes; specifically, unstable electron heating and acceleration in current sheets. In a previous study of electron heating and acceleration in current sheets (Holman 1985; hereafter, H85) it was found that impulsive phase solar flare hard X-ray and microwave emission can be generated in a single current sheet if the bulk of the X-ray emission is thermal, while a large number of oppositely directed sheets ($>10^4$) is required if the bulk of the hard X-ray emission is nonthermal (see also Spicer 1983, Hoyng 1977). Hence, the following section is concerned with the generation of thermal hard X-ray fluctuations in a single current sheet. The general physical conditions required for the fluctuations to be produced are determined, and a specific mechanism for generating the fluctuations is discussed. In Section 3 the generation of microwave and nonthermal hard X-ray spikes is discussed.

2. Thermal Hard X-ray Fluctuations

The results of Kiplinger et al. (1983) indicate that the X-ray flux can increase by a factor of two on a time scale of 20 msec. For one such fluctuation they deduce a peak temperature and emission measure of 2.4×10^8 K and 6×10^{44} cm^{-3}. Since the bremsstrahlung emissivity is proportional to $T^{1/2}\exp(-E_{min}/kT)$, where E_{min} is the minimum observed photon energy (29 keV), if the emission measure remains constant the temperature must increase by a factor of 1.4 in 20 msec, and the initial electron temperature, T_0, is 1.7×10^8 K. These values will be used in the following paragraphs.

The characteristic time required to heat the plasma within a current sheet, $\tau_J \equiv nkT/JE$, where J is the current density and E the electric field strength, can be written as (see H85, Eqns. 4 and 20)

$$\tau_J = (v_e/v_d)^2 \nu_e^{-1}, \tag{1}$$

where v_e is the electron thermal speed, v_d is the drift speed of the current-carrying electrons, and ν_e is the thermal collision frequency. The precise relationship between this time scale and the actual rise time, t_r, depends upon which quantities vary or remain constant while the heating is occurring. When the electric field E and the total current I are both held constant, and $\nu_e \propto T^{-3/2}$, this relationship is (H85, Eqn. 24)

$$t_r = (3/2)[(T/T_0)-1]\tau_J. \tag{2}$$

Writing, in general, $t_r = \alpha\tau_J$, $T/T_0 = 1.4$ gives $\alpha = 0.6$. Since $T/T_0 \sim 1$, other conditions give comparable values for α. Holding E and the volume of the current sheet constant gives a smaller value (0.3), while holding J and I constant gives a slightly

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larger value (0.8) for α.

In addition to obtaining the 20 msec rise time, the emission measure, EM = n^2V_J, must also be correct. The current sheet volume can be written as $V_J = wL\delta r$, where w, L, and δr are the width, length, and thickness of the sheet. All three dimensions are constrained to be less than ct_r, where c is the speed of light, and δr is further constrained by the requirement that the induction magnetic field associated with the current sheet not be unacceptably large. Taking w and L to be $\leq ct_r$, using Eqn. 8 from H85 for δr, and combining this with $t_r = \alpha\tau_J$ and Eqn. 1 for τ_J gives the following expression for ν_e:

$$\nu_e \geq 1.89 \times 10^{11}\ \alpha(EM_{44})^2 T_8 (B_2)^{-2}(n_{11})^{-2}(t_{r(-2)})^{-5}\ \ s^{-1}, \quad (3)$$

where all parameters are in cgs units and the numerical subscripts indicate the exponent of the value assumed for each parameter ($n_{11} = n/10^{11}$). With B = 300 gauss and n = 10^{11} cm^{-3}, a collision frequency of 3×10^{10} s^{-1} is obtained. This is well above the classical collision frequency. A plasma density of 10^{12} cm^{-3} brings this down to a value that is comparable to the highest anomalous collision frequency expected from the ion acoustic instability, but the corresponding value of v_d is, from Eqn. 1, $3 \times 10^{-4} v_e$, much too small to drive such an instability. Electron acceleration in such a sheet would also be negligible. The reason for the low value of v_d (and the correspondingly large value of ν_e) is the need for the thickness of the sheet, δr, to be large enough for the required emission measure to be obtained. Therefore, in the following an emission volume that exceeds the current sheet volume is considered.

The collision frequency required for the Joule heating of a volume $V > V_J$ in time t_r is found from Eqn. 22 of H85 to be

$$\nu_e = 4.36 \times 10^6\ \alpha(EM)_{44}(T_{o(8)})^{1/2}(B_2)^{-1}(n_{11})^{-1}(t_{r(-2)})^{-3} \cdot$$

$$\cdot(v_e/v_d) \quad s^{-1}. \tag{4}$$

With B = 300 gauss, n = 10^{11} cm^{-3}, and (v_e/v_d) = 16, the collision frequency $\nu_e = 1.4 \times 10^7$ s^{-1} is obtained. This is well above the classical collision frequency, but an order of magnitude smaller than the maximum effective collision frequency expected from the ion acoustic instability. The ion acoustic instability will be driven by this current when $T_e/T_i \sim 10$, and this current and resistivity will result in significant electron acceleration. The length and width of the X-ray emitting region have been taken to be 6,000 km (ct_r), and the thickness of the emitting region is found from the emission measure to be 1.7 km. Hence, the rise time of the X-ray fluctuations can be attained with Joule heating if the resistivity in the current sheet is highly anomalous and the volume of the X-ray emitting region exceeds that of the current sheet. It is interesting, however, that, because of the strong dependence of ν_e upon t_r, rise times shorter than 10 msec rapidly become more difficult to obtain.

Since $V > V_J$, for the 20 msec rise time to actually be achieved the heat generated in the current sheet must be transported to the larger emission volume in 20 msec or less. Both classical and anomalous (Bohm) cross-field conduction are too slow to do this. This could easily be achieved with classical conduction along field lines, however. Hence, a bent or tangled field structure would allow the source volume to be achieved. Alternatively, if the heat is transported convectively or behind a shock or conduction front, a propagation speed of at least 40 km/sec is required.

Producing the X-ray fluctuations requires a mechanism for interrupting the enhanced heating of the flare plasma. If the current is driven so that E remains constant, and the plasma resistivity decreases with increasing temperature, as for classical resistivity, the fluctuations can be produced as follows. The Joule heating rate is E^2/η, where η is the resistivity in the current sheet, and, hence, is regulated by η. The current density $J = nev_d$ in the sheet is $J = E/\eta$ and, therefore, is also regulated by η. Hence, if the resistivity decreases as the temperature in the sheet increases, both the heating rate and J increase as T increases. The number of electrons accelerated out of the thermal plasma increases as well. If a new instability sets in because of the increased current of either thermal or accelerated electrons, η will increase, causing both the heating rate and J to decrease. The fall time of the fluctuation will be determined by either (a) the growth time of the new instability, (b) the time required for heat to be transported out of the emitting volume, or (c) the size of the emitting region ($t_f \sim L/c$). The longest of these time scales will dominate. After the enhanced turbulence dissipates, heating will be occurring at the initial lower level and, as T increases again, the process can repeat itself.

It should be noted that the rise time of the fluctuation can also be determined by either (b) or (c) if the heating time is shorter than t_r. If the rise is dominated by heating and the fall by heat transport, then the X-ray spectrum is expected to harden during the rise and soften during the falling phase. If heat transport dominates both the rise and fall, the spike will be fairly symmetric ($t_r \sim t_f$) with the X-ray spectrum becoming softer throughout the spike. The spike (0.25 sec rise time) studied by Kiplinger et al. (1984) may be of this type.

A likely source of the anomalous resistivity during the rise phase of the fluctuation is ion acoustic turbulence, since it can provide the required collision frequency, and the current drift speed is likely to be near the threshold for the ion acoustic instability. Whether or not the effective resistivity has the required temperature dependence will most likely be determined by how the instability saturates. The instability required to interrupt the heating must also be strong, since the turbulence level required in the sheet to attain the 20 msec rise time is already high. The oscillating two-stream instability, associated with the accelerated electrons, is a likely instability that can generate the required level of turbulence. Determining when the oscillating two-stream instability will occur is difficult, since it depends upon the details of the electron distribution. Since the instability grows rapidly compared to the msec time scale of the X-ray bursts, the growth time of the instability is not likely to be the time scale that determines the fall time of the fluctuations.

A variation upon this scenario might be to have the initial level of turbulence determined by the oscillating two-stream instability, and the heating interrupted by the ion acoustic instability when J reaches the instability threshold. It is not apparent that the oscillating two-stream effective resistivity can have the required temperature dependence, however, since it is proportional to the number density of accelerated electrons. Other likely sources of anomalous resistivity in the current sheet are the electrostatic ion cyclotron instability and the lower hybrid drift instability. One of these may be able to supply the required initial level of turbulence if the plasma density is higher and B is larger or v_e/v_d is smaller than assumed above. In the extreme case of $v_e/v_d \sim 1$, the Buneman instability could be the interrupting instability.

An alternative mechanism for interrupting the plasma heating has been studied by Krishan and Kundu (1985; see also Spicer 1977, 1981). In direct analogy to the sawtooth oscillations seen in Tokamaks, the current is interrupted by the onset and nonlinear growth of the m=1 tearing mode. A difficulty with this analogy is that the tearing mode is driven by an internal kink instability, requiring that the system oscillate about the threshold for this instability, $q = 1$, where

$$q = rB_z/LB_\theta = cB_z/2\pi LJ_z = (cB_z/2\pi enLv_e)(v_e/v_d) \qquad (5)$$

is the system safety factor. A cylindrical current channel of radius r with uniform current density, J_z, is assumed here, as for the Tokamak. B_z is the magnetic field strength in the direction of the current, and B_θ is the azimuthal magnetic field associated with the current. For solar parameters, however, q is found to be orders of magnitude smaller than one and, therefore, the oscillations cannot occur (the system is very unstable, however). This mechanism may still be able to operate as required if, instead of being distributed throughout a cylindrical volume, the current is concentrated in a thin sheet at the surface of the cylinder. The right side of Eqn. 5 then becomes multiplied by the factor $\pi(r/\delta r)$, where δr is the thickness of the sheet, and, for the parameters used above, $r \sim 10^6 \delta r \sim 10^3$ km is obtained for $q = 1$. Hence, although the formal analogy with the Tokamak disruption is no longer valid because of the different current geometry, this mechanism may also be able to provide the required interruption of the current heating.

3. Nonthermal Microwave and Hard X-ray Spikes

In the above mechanism for generating thermal hard X-ray fluctuations the acceleration of electrons in the current sheet is modulated as well. The rate at which runaway electrons is produced is sensitive to the value of $v_e/v_d = E_D/E$, where E_D is the Dreicer electric field. With $\nu_e \propto T^{-3/2}$, $E_D/E \propto T^{-1}$ and the flux of accelerated electrons increases as the temperature in the current sheet increases. When the heating is interrupted by a sudden increase in resistivity, the rate of runaway production suddenly drops. For the parameters obtained above (§2), electrons can be accelerated to energies of up to 1 GeV. If the particles are pitch angle scattered within the current sheet, however (e. g., Holman, Kundu, and Papadopoulos 1982, Moghaddam-Taaheri et al. 1985), the maximum energy will be smaller, $\sim$a few MeV, since electrons with a perpendicular energy greater than a few MeV have gyroradii that exceed the thickness of the sheet.

Microwave emission generated by the accelerated electrons is not likely to directly mimic the X-ray fluctuations, since the rise and fall of the microwave spikes is likely to be determined by the growth and saturation of the emission mechanism. If the emission mechanism is gyrosynchrotron masering (Holman, Eichler, and Kundu 1980, Melrose and Dulk 1982, Sharma, Vlahos, and Papadopoulos 1982; for a review of possible emission mechanisms, see Holman 1983) a delay is also involved in the time required for the accelerated electrons to propagate to a mirroring point within the flaring loop. Only when conditions are right for both the X-ray fluctuations and the masering will both be seen simultaneously.

Generating the hard X-ray fluctuations at photon energies below $\sim$100 keV through nonthermal bremsstrahlung requires modulating simultaneously, to within the time scale of the fluctuations, electron acceleration within a large number of current sheets. For a typical electron flux requirement of 10^{35} electrons/sec for $\geq$25 keV X-rays, at least 10^4 sheets are required. For a typical sheet thickness of 100 cm, the total thickness of the sheets is $\sim$10 km if the sheets are arranged adjacently, well below ct_r = 6,000 km (and on the order of $v_A t_r$, where v_A is the Alfven speed). Hence the sheets can in principal be driven with the required degree of coherency. The interruption of the Joule heating within the sheets must keep the temperature (or emission measure) of the thermal X-ray source low enough so that it does not dominate the nonthermal emission.

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References

Gary, D. E., Linsky, J. L., and Dulk, G. A.: 1982, Ap. J. (Letters), 263, L79.

Holman, G. D., Eichler, D., and Kundu, M. R.: 1980, in IAU Symp. 86, Radio Physics of the Sun, ed. M. R. Kundu and T. E. Gergeley (Dordrecht: Reidel), p. 457.

Holman, G. D., Kundu, M. R., and Papadopoulos, K.: 1982, Ap. J., 257, 354.

Holman, G. D.: 1983, Adv. Space Res., Vol. 2, No. 11, p. 181.

Holman, G. D.: 1985, Ap. J., 293, 584.

Hoyng, P.: 1977, Astron. Astrophys., 55, 23.

Kaufmann, P., Strauss, F. M., Opher, R., and Laporte, C.: 1980, Astron. Astrophys., 87, 58.

Kaufmann, P., Correia, E., Costa, J. E. R., Sawant, H. S., and Zodi Vaz, A. M.: 1985, Solar Phys., 95, 155.

Kiplinger, A. L., Dennis, B. R., Emslie, A. G., Frost, K. J., and Orwig, L. E.: 1983, Ap. J. (Letters), 265, L99.

Kiplinger, A. L., Dennis, B. R., Frost, K. J., and Orwig, L. E.: 1984, Ap. J. (Letters), 287, L105.

Krishan, V., and Kundu, M. R.: 1985, in IAU Symp. 107, Unstable Current Systems and Plasma Instabilities in Astrophysics, ed. M. R. Kundu and G. D. Holman (Dordrecht: Reidel), p. 299.

Lang, K. R., Bookbinder, J., Golub, L., and Davis, M. M.: 1983, Ap. J. (Letters), 272. L15.

Melrose, D. B., and Dulk, G. A.: 1982, Ap. J., 259, 844.

Mòghaddam-Taaheri, E., Vlahos, L., Rowland, H. L., and Papadopoulos, K.: 1985, Phys. Fluids, submitted.

Sharma, R. R., Vlahos, L., and Papadopoulos, K.: 1982, Astron. Astrophys., 112, 377.

Slottje, C.: 1978, Nature, 275, 520.

Slottje, C.: 1980, in IAU Symp. 86, Radio Physics of the Sun, ed. M. R. Kundu and T. E. Gergeley (Dordrecht: Reidel), p. 195.

Spicer, D. S.: 1977, Solar Phys., 53, 305.

Spicer, D. S.: 1981, Solar Phys., 70, 149.

Spicer, D. S.: 1983, Adv. Space Res., Vol. 2, No. 11, p. 135.

Zhao, R., and Jin, S.: 1982, Scientia Sinica (Series A), 25, 422.