ON THE PRODUCTION OF HARD X-RAYS IN SOLAR FLARES

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Abstract. The problem of producing the hard X-ray burst at the onset of solar flares may be thought of in terms of the problem of producing the non-thermal electrons which emit the X-rays via bremsstrahlung. Electron acceleration to relativistic energies without similar ion acceleration is difficult to achieve, even in an ad hoc theoretical model. Yet from global energetic considerations, it is not feasible to accelerate the electrons as a minor constituent of the total energetic particle population. Therefore, it is necessary to invoke a more sophisticated process for the electron acceleration. In this paper we describe a mechanism for achieving this via an initial acceleration of a neutralized ion beam. When such a beam impacts the chromosphere, the electrons start to scatter while the ions continue downwards, rapidly setting up an electric field which is either cancelled by the inflow of background chromospheric electrons or results in the runaway acceleration of beam electrons. In the former case the result is simply heating, whereas in the latter case much of the ion kinetic energy is transferred into electron kinetic energy. The final electron energy may be similar to the typical energy of the ions. The electrons that are accelerated are those in the neutral beam that experience an electric field greater than the critical Dreicer field. Thus there will be a low-energy cut-off to the electron spectrum which overcomes the well-known energetics problem at low energies with certain other spectral forms.

1. Introduction

For several decades we have been endeavouring to understand the details of the physical processes occurring in the solar atmosphere at the time of solar flares. For a long time it was supposed that the energy transfer mechanism from the assumed magnetic energy source was a non-thermal electron beam, where the bulk of the energy was in the 10–100 keV region (Lin and Hudson, 1976); thermal sources were also in favour for a time (Brown, Melrose, and Spicer, 1979; Smith and Lilliquist, 1979). It was recognized by Colgate (1978) that the electron beam hypothesis was untenable and he proposed that all the flare energy should be carried by runaway protons, with energies above ~ 4 MeV. Simnett (1986) suggested a different approach, namely that the bulk of the energy should be carried by a neutralized ion (proton) beam where the bulk of the energy is in protons in the 0.1–1 MeV region. Neutralization would be by an accompanying electron current, analogous to the return current in an electron beam model, but moving in the same direction as the protons. Therefore, the self-magnetic energy problem identified by Colgate, Audouze, and Fowler (1977) is largely alleviated. The nuclear γ-rays, in flares where they are observed, may be explained by the scenario advanced by Ryan and Simnett (1989). Another problem with the electron beam hypothesis was...
the sheer number of electrons required. Calculation (Hoyng, Brown, and Van Beek, 1976) of the number of electrons needed to account for the hard X-ray burst placed almost an impossible burden on the actual supply of the electrons if the acceleration site was in the corona. With ions, the energy/particle is enhanced by the factor $m_i/m_e$ and, therefore, for the same energy budget, some three orders of magnitude fewer particles are needed if the energy/particle is similar. Although this does not solve completely the supply problem, it clearly greatly alleviates it. There is still a substantial hurdle to be overcome, namely the production of the hard X-ray burst.

There is no doubt that in the solar flare situation, immediately before the quantum of energy, $h\nu$, of the X-ray became an X-ray, the energy resided in an electron. The alternative way of producing an X-ray continuum directly from proton bremsstrahlung can be eliminated on account of the high, and not observed, gamma-ray yield that would result. The question now is how to produce energetic electrons from a non-thermal proton beam, where the bulk of the energy is in the 100–1000 keV region (Simnett, 1986) or $\geq 4$ MeV (Colgate, 1978). Both Colgate and Simnett could only endorse the original suggestion of Chubb, Kreplin, and Freidman (1966) that the high-energy X-rays originated in regions of very high plasma temperature and relatively small emission measure.

While we do not wish to rule out the thermal interpretation of hard X-ray bursts, there are many flares where the highest energy X-rays are $\geq 0.5$ MeV, thus straining the credibility of this explanation. We have, therefore, searched for an alternative hard X-ray production mechanism, while still retaining 0.1–1 MeV protons as the dominant energy transfer mechanism. It is the purpose of this paper to outline the concept that we have developed. The electrons which produce the hard X-rays are not a primary result of the fundamental acceleration process, which we suggest is common to all flares and results from magnetic reconnection. The acceleration is probably velocity dependent, or close to it (Decker and Vlahos, 1985; Pesses, Decker, and Armstrong, 1982; Tajima, Brunel, and Sakai, 1982; Sakai and Ohsawa, 1987) and the density will be enhanced in the reconnection region. This latter condition is needed in order to supply enough particles to the accelerator (see above). We further propose quasi-neutrality, and no net current, in the emerging beam. Martens (1988) has recently proposed an acceleration process based on Speiser's (1965) calculations of acceleration in the geomagnetic tail, and the output of this is a neutral beam with a typical proton energy of 200 keV, at approximately zero pitch angle, almost precisely what we advocate as an input to our model. The quasi-neutrality condition guarantees that the ions carry the bulk of the flare energy. In many flares the maximum ion energy need only be $\sim 1$ MeV, although with an elementary variation in the acceleration parameters, relativistic ions (and electrons) may be accelerated. Typically small flares show no evidence, from gamma-ray observations, for ions above a few MeV. When the plasma beam hits the chromosphere the beam electrons scatter. The ions continue downwards, setting up an electric field. This happens so rapidly that in a typical flare a steady-state model is applicable. Under the action of the electric field a significant fraction of the ion energy may be transferred to the electrons, which subsequently produce the hard X-ray burst by bremsstrahlung. As