THE DECAY CHARACTERISTICS OF MODELS OF
SOLAR HARD X-RAY BURSTS

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Abstract. Models of solar hard X-ray bursts are considered in which non-thermal electrons are impulsively injected into a coronal magnetic trap. Recognising that the ends of the trap are likely to be rooted in the photosphere and that the density of the ambient atmosphere may thus be highly non-uniform along the field lines, it is shown that the X-ray spectra will initially soften with time, due to collisions, when this non-uniformity is strong enough. This removes a well-known discrepancy in models with uniform density.

It is shown also that non-uniformity steepens the electron spectrum required to produce a given observed X-ray spectrum. In consequence the total non-thermal electron energy involved in a given burst is greater than that previously inferred from impulsive injection models.

1. Introduction

It seems generally agreed in the literature that impulsive solar X-ray bursts in the energy range 20–100 keV are produced by bremsstrahlung emission from non-thermal electrons in the ambient flare plasma, (e.g. Peterson and Winckler, 1959; Takakura and Kai, 1966; Korchak, 1967). It also appears very likely that non-thermal electrons in this energy range are degraded mostly by collisions with ambient plasma particles (e.g. Takakura, 1969; Holt and Ramaty, 1969). However, it is not yet clear whether this degradation occurs in a characteristic time which is short or long compared to the decay time of the burst. In the former case, degradation occurs in a plasma of comparatively high density (\( \gtrsim 10^{11} \) electrons cm\(^{-3} \)), electrons being accelerated continuously throughout the X-ray burst by a mechanism whose time variations determine the time profile of the X-ray burst (Arnoldy et al., 1968; Acton, 1968; Brown, 1971). Models of this type are commonly referred to as continuous injection models. The alternative type of model is that originally proposed by Takakura and Kai (1966) in which acceleration of the electrons ceases quite abruptly at some instant, the electrons being subsequently degraded in a plasma of low density (\( \approx 10^9 \) electrons cm\(^{-3} \)) while trapped in a magnetic bottle in the flare field. In this model the decay characteristics of the X-ray burst are determined entirely by the gradual collisional degradation of the non-thermal electrons in the ambient plasma and not at all by the acceleration mechanism (except in so far as this establishes the initial electron spectrum). This type of model is commonly referred to as of impulsive injection (or simply ‘impulsive’) type. To prevent any confusion of this term with the ‘impulsiveness’ of the X-ray burst itself (indicating that the phenomenon is brief and confined approximately to the flare flash phase) the alternative term ‘trapping model’ will, however, be adopted throughout this paper.
In the discussion of the validity of the continuous injection and trapping models, one of the principal arguments levelled against the simple trapping model has been the discrepancy between the observed decay of the X-ray spectrum and some of the predictions of this model. Notably the burst decay rate, which is by hypothesis determined by collisional electron energy losses, should be greatest at low X-ray energies and least at high X-ray energies; i.e. the X-ray spectrum should be collisionally hardened with time (Takakura, 1969; Zirin et al., 1971). The decay spectrum is, however, observed to soften (Kane and Anderson, 1970). In trying to resolve this difficulty, several authors have invoked additional factors affecting the spectral decay, including the contribution of thermal X-rays at low energies (Takakura, 1969) and loss of electrons from the trap (e.g. Kane and Anderson, 1970; Zirin et al., 1971). These suggestions are discussed in Section 6 where it is shown that they are neither necessary nor sufficient to resolve the discrepancy in trapping models.

The discrepancy arises from the usual assumption that the collisional decay rate of electrons of different energy is inversely proportional to their energies to the power \( \frac{3}{2} \) (see Equation (3)). However, this is true only if the electrons decay in a plasma of uniform density. If, in fact, the higher energy electrons were allowed to reach far enough down the trap limbs, relative to those of lower energies, and hence to encounter sufficiently high ambient densities, then they would decay faster, and the X-ray spectrum would soften with time as observed. From Equation (3) it is evident that if the ambient density \( n \) encountered increased with electron energy \( E \) more rapidly than \( E^\frac{3}{2} \) then a softening spectrum would result.

Two physical phenomena give rise to a non-uniform density in a coronal trap. Firstly, any such trap is expected to have its 'limbs' rooted in the photosphere, possibly in a sunspot pair (see Takakura and Kai, 1966, and also Figure 1 of the present paper). Thus the trap limbs descend through an atmosphere with a gravitational density gradient, the density increasing with decreasing height. Secondly the ambient density \( n \) in a trapping model, as deduced from the decay times of bursts, does not exceed \( 10^{10} \) cm\(^{-3} \) (e.g. Kane and Anderson, 1970) while an upper limit of \( 30 \times 10^6 \) K has been set on the temperature \( T \) of thermal flare plasmas from soft X-ray observations (Neupert, 1969). Thus the trapped plasma pressure \( 2nkT \) could not exceed about \( 100 \) dynes cm\(^{-2} \) while a trapping field of only \( 100 \) gauss has a Maxwell pressure of \( 400 \) dynes cm\(^{-2} \). Thus the magnetic field in a trap with these parameters will be force free and may produce density variations in the trapped plasma, additional to the gravity gradient already present (c.f. Gold, 1964; Lighthill, 1966). Non-thermal electrons in the trapping region will, therefore, encounter considerable density variations, the densities encountered by any individual electron depending on its pitch angle. As the initial acceleration will be principally along the field lines, it is likely that higher energy electrons have lower pitch angles than low energy ones, so that electrons of highest energy would indeed encounter the highest ambient densities. By adopting a trial power-law expression for this variation of \( n \) with \( E \) (i.e. \( n \sim E^a \)) it proves possible to obtain analytically the initial X-ray spectrum emitted by a power-law electron 'injection' spectrum \( \sim E^{-\delta} \) in such a trap and, by neglecting scattering of