ON THE NONTHERMAL EXCITATION AND POLARIZATION OF X-RAY LINES DURING SOLAR FLARES

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Abstract. The energy distributions of nonthermal electrons are derived from hard X-ray spectra taken during the impulsive phase of two 2B flares in February 1969. They are used to calculate the fluxes of nonthermally excited X-ray lines of hydrogen-like and helium-like ions. These fluxes are compared to the total line fluxes observed at the same time with crystal spectrometers. The nonthermal excitation is found to give only small contributions to the total line intensities. This implies that the impact polarization which is to be expected for anisotropic velocity distributions of the energetic electrons, will be low. Nevertheless it should be feasible to detect line polarization during the impulsive phase of strong X-ray flares.

1. Introduction

High-energy electrons are assumed to play a fundamental role in the diverse aspects of solar flares. The most direct information on the nature of these electrons is provided by observation of the hard X-radiation produced by them in collisions with ions of the solar atmosphere. Additional knowledge on the properties of the nonthermal electrons can be obtained by observing the polarization of the X-radiation (Korchak, 1967; Elwert, 1968; Elwert and Haug, 1970). In particular, the anisotropy of the electron beams can be inferred from such measurements (Haug, 1972). So far, all the attempts to measure solar X-ray polarization have involved a broad energy band, i.e., continuum radiation (Tindo et al., 1970, 1972, 1973, 1976; Nakada et al., 1974). Due to the extreme difficulty of the experiments the results obtained up to now are inconclusive. An alternative approach to this problem could be the measurement of line polarization. When atoms or ions are excited by collisions with electrons whose velocity distribution is anisotropic, the resulting emission lines are partially polarized (Percival and Seaton, 1958). The polarization of X-ray lines can be observed by means of the Bragg polarimeter (Novick, 1975). This instrument makes use of the dependence of the reflectivity of a Bragg crystal on the polarization state of the incident radiation, and has a high wavelength resolution which enables one to observe a single line. There arises, however, the question whether the degree of polarization of the lines will be sufficiently high to be detectable. Whereas the hard X-ray continuum above 20 keV is assumed to be predominantly bremsstrahlung from nonthermal (and probably anisotropic) electrons, a high percentage of the X-ray line emission originates from collisional excitation by thermal electrons. In the coronal plasma heated by a flare, temperatures of some $10^{7}$ K are quite common.

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(Neupert, 1971b; Milkey et al., 1971) so that even levels of highly ionized iron are excited thermally with sufficient frequency to generate strong line fluxes.*

In the present paper, observations of solar flare X-radiation by crystal spectrometers and the hard X-ray detector flown on the OSO-5 satellite are used to estimate the contribution of X-ray line emission excited by nonthermal electrons to the total radiation flux emitted in a line. Assuming the nonthermal radiation to be completely linearly polarized, one can derive an upper limit for the line polarization to be expected. This analysis is accomplished with the data from the two flares of Importance 2B on February 24 and February 27 1969.

2. Calculation of the Nonthermal Line Flux

Calculation of the actual nonthermal X-ray line flux emitted from a flare proceeds in two steps. First the flux \( F_e(E) \) of nonthermal electrons is derived from hard X-ray spectra, and then the resulting flux \( F_{kt} \) of line emission is obtained.

2.1. Flux \( F_e(E) \) of nonthermal electrons

Generally the hard X-ray differential flux can be well represented by a power law with spectral index \( \gamma \)

\[
F(k) = K k^{-\gamma} \text{photons cm}^{-2} \text{s}^{-1} \text{keV}^{-1},
\]

where \( k \) is the photon energy in keV; the parameter \( K \) gives a measure for the number of nonthermal electrons producing the hard X-radiation. In the thin-target model, neglecting directional effects, the relation between the electron flux \( F_e(E) \) and \( F(k) \) is given by

\[
F(k) = K k^{-\gamma} = \frac{V}{4 \pi R^2} \sum_i N_i \int_0^\infty F_e(E) \frac{d\sigma_i}{dk} dE,
\]

where \( E \) is the kinetic electron energy, \( V \) is the source volume, \( R = 1 \text{ AU} \) is the distance Sun–Earth, \( N_i \) is the number density of ions with atomic number \( Z_i \), and \( d\sigma_i/dk \) is the bremsstrahlung cross section for target ions \( i \). Employing the nonrelativistic limit of \( d\sigma_i/dk \) in Born approximation,

\[
\frac{d\sigma_i}{dk} = \frac{16}{3} \alpha Z_i^2 r_0^2 \frac{mc^2}{kE} \ln \left( \sqrt{E/k} + \sqrt{E/k} - 1 \right),
\]

where \( \alpha = e^2/\hbar c = \frac{1}{137} \), \( r_0 = e^2/mc^2 \), and \( e, \hbar, c, \) and \( m \) have their usual meaning. Equation (2.2) can be solved for \( F_e(E) \), resulting again in a power law (Brown, 1971)

\[
F_e(E) = A E^{-8} \text{electrons cm}^{-2} \text{s}^{-1} \text{keV}^{-1},
\]

* A nonthermal interpretation of flare line emission has been given by Landini et al. (1973).