TEMPORAL EVOLUTION OF BREMSSTRAHLUNG-DOMINATED GAMMA-RAY SPECTRA OF SOLAR FLARES

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ABSTRACT

SMM/GRS- observations of the initial impulsive phase of the solar flare on 6 March 1989 are well suited for the study of temporal and spectral variations of bremsstrahlung caused by relativistic electrons. The bemsstrahlung-dominated spectra of the impulsive bursts are unique among gamma-ray spectra due to the strong electronic continua above 1 MeV. By estimating the nuclear contributions from narrow de-excitation lines, we find that the bremsstrahlung can be roughly approximated by power laws with spectral indices as low as n=1.5. This continuum extends to higher energies showing an exponential cutoff at several tens of MeV. Between 0.3 and 0.8 MeV, the spectra are steeper and can be well described by power laws with indices between n=2.4 and n=3.0 The degree of spectral flattening, losing its significance at later bursts, seems not to be correlated with the intensity of the radiation < 1 MeV. Ions are accelerated throughout the whole flare, even well before the onset of the intense bursts. The typical line structure however is suppressed by the dominant continuum during the initial bursts.

INTRODUCTION

The study of gamma-ray line spectra of solar flares allow a unique insight into high energy processes at the site of flaring loops. The interactions of flare accelerated electrons and ions in the solar atmosphere produce a large variety of secondary particles such as excited nuclei, neutrons, positrons and pions. The resulting gamma-radiation below $\sim$ 8 MeV consists of a characteristic nuclear line spectrum superposed on a continuum of bremsstrahlung which extends up to the highest energy of the creating primary electrons. The decay of neutral pions produced in nuclear reactions also forms a characteristic spectrum peaked at about 70 MeV. Charged pions and directly measured solar neutrons can further complicate the interpretation of the emission > 10 MeV. Spectra of events with dominant nuclear lines [1,2], π^o-emission [3] and bremsstrahlung from electrons [4] were reported. For details on the physical implications of the numerous solar flare observations the reader is referred to recent reviews [5,6].

To analyze the gamma-ray spectra one has to face two major problems: 1) the determination of the true photon distribution from the measured energy loss spectrum by means of a correct instrumental response model and 2) the unfolding of the complex superposition of the radiation components as discussed above. By using nuclear cross sections and by assuming different abundances for the target and the energetic particle beam [7,8], a forward-folding technique was applied successfully to the line spectrum of the flare on 27 April, 1981. It was shown that, even with the limited energy resolution of the SMM/GRS NaJ-scintillator, details in the elemental composition in target and beam can be discriminated.

To study such second order features, one needs to know the form of the underlying bremsstrahlung continuum to a high precision. As we will show in this paper, the dominant bremsstrahlung continua of the gamma-emission of the impulsive phase of the 6 March, 1989 flare can deviate strongly from simple power laws. Therefore, we analysed the spectra in a most model-independent way by applying a direct inversion technique.

ANALYSIS

The deconvolution of energy-loss spectra leads to matrix inversion problems widely known in all fields of astrophysics. Any applied technique must cope with the fundamental problem of numerical instabilities [9]. Most importantly, high frequent noise terms in count space must be kept in bay and should not appear in the recovered solution as spurious oscillations. The spectral resolution, given by the number and bin width of the data points in photon space, has to be traded for larger 1-σ uncertainity intervals. This leads to a reduction of the dimension in photon space compared to the oversampled 476 channel energy loss by at least a factor of 6. We found an inversion method which is based on the widely used singular value decomposition to be most useful [10,11]. For details on the applied iterative inversion see [12].

To include the SMM/GRS high energy matrix (HEM) data above 10 MeV, we calculate photon values by use of monte carlo calculations of [13]. The response model for the entire energy range up to 100 MeV is therefore not uniform. However work on such a model which differs slightly from the off-diagonal elements of the used UNH response (vers. 3.1) is under way [14].

Life-time measurements of some of the intense spectra reach values which are even below 50%. Such low values have a potential for gain change and pulse pileup. Although we did not find any sign for the latter, gain shifts were caused by a significant high voltage increase affecting slightly the structure of the nuclear lines during the later bursts (phases I3 and I4, see below). The derived line intensities were corrected for this instrumental effect. Due to strong gain shifts in the CsJ elements during the long life of the instrument we only use the NaJ elements.

RESULTS

Time profiles with high resolution [4] display a sequence of numerous individual bursts during the impuslive phases, the most exotic consists of coherent spikes on timescales of few seconds extending to energies up to 50 MeV. The individual data points in Fig. 1 (resolution of GRS-spectra limited to 16 s), starting at UT 13:56:23, are subdivided into the four impulsive burst-intervals I1-I4, a time interval of minimal intensity M and an end (decaying) phase E. The upper two panels show spectral indices and photon fluxes $\phi^B_{<0.8}$ of power law fits to the spectra between 0.3 and 0.8 MeV. The spectra, almost entirely dominated by bremsstrahlung, is well defined by a power law in this limited energy range. Above $\sim$ 0.8 MeV the spectra significantly hardened due to an increasing relative contribution from nuclear components and/or a flattening of the electronic continuum. We only use the extrapolation of the power laws as a line of reference for the analysis of the excess radiation above this line. At about 7.5 MeV the nuclear line spectrum posesses a cutoff due to the lack of strong lines above this energy [15]. Unless there is a strong production of charged pions which create by decay energetic positrons (and hence high energy bremsstrahlung), any significant excess between 7.5 and 8.5 MeV must be attributed to bremsstrahlung from primary electrons. The three panels in Fig. 1 therefore show the spectral characteristics of the bremsstrahlung. During the first burst I1, the peak excess flux $\phi^E_{7.5-8.5}$ of 1 Phot./(cm$^2\cdot$ s) exceeds values expected from nuclear lines by two orders of magnitude which implies a strong flattening of the electronic continuum. Strong evidence was found that the short spikes (2 s) have similar spectral form indicative of a non-power law distribution of the electrons formed during the process of acceleration [12]. The indices of I1 and I2 are on the average lower than during the later bursts. Considering all phases, no sign of a significant correlation between $\phi^B_{<0.8}$ and $\phi^E_{7.5-8.5}$ could be found.

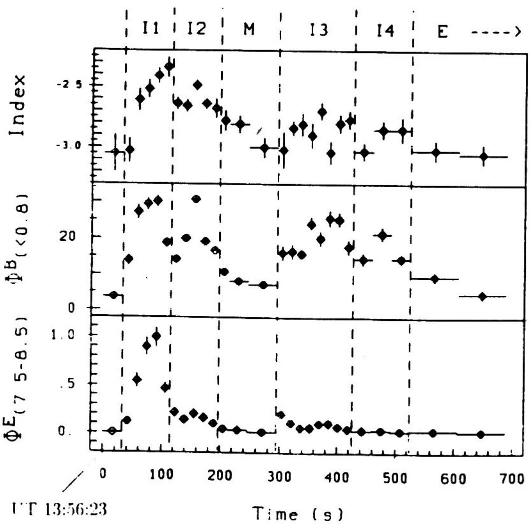

Fig. 1. *Time variation of the spectral indices, the fluxes below the fitted power laws $\phi^B_{<0.8}$ and excess fluxes $\phi^E_{7.5-8.5}$. Fluxes in units of Phot. cm^{-2} s^{-1}.*

The deconvolved spectra of the time intervals I1, I3 and E are shown for the entire energy range between 0.3 MeV and 100 MeV in Fig. 2. For reasons of presentation, the spectra of I1 and I3 were multiplied by 10^4 and 10^2, respectively. The fit of the low energy power law (solid line), the extrapolation C_1 (dashed line) and an estimation of the electronic continuum C_2 (dashed and dotted) for I1 and I3 between $\sim$ 1.5 and 9 MeV are plotted (see also discussion of Fig.3). Although in the case of I1 and I3 the two HEM data points between 25 and 60 MeV are in good agreement with the high excess values below 10 MeV, the data point between 10-25 MeV appears to be somewhat too low for a featureless continuum of bremsstrahlung at this spectral range. However, one has to keep in mind that this maybe be due to the use of two separate response models for GRS and HEM data (see above). This also has to be considered when interpreting the last data point between 60 and 100 MeV in the spectra of I1 and I3. They indicate a very steep exponential cutoff. In contrast to the bremsstrahlung-dominated spectra of I1 and I3, the broad feature in the spectrum of E, peaking around 60 MeV, indicates contributions from π^0-decay. This is in good agreement with results of [16] who applied a more sophisticated analysis to account also for direct registered neutrons and bremsstrahlung from charged pions. The characteristic nuclear line spectrum of the time interval E is very pronounced in the excess spectrum (C_1-continuum subtracted) in the third panel of Fig. 3. Prominent de-excitation lines and a dominant neutron capture line at 2.22 MeV are visible. Note that the line flux depends on the bin width which is scaled logarithmically. Curve N shows the 'nuclear continuum' consisting of doppler-broadend and unresolved lines. The shape of this continuum corresponds to model spectra [7] used to analyse the flare of April 27, 1981. The intensity is normalized relativ to the line fluxes of Ne (1.63 MeV) and C (4.44 MeV). The fluxes for E are 0.27 (± 0.10) and 0.22 (± 0.10) [$Phot./(cm^2 s)$] for the 1.64 MeV and 4.44 MeV lines, respectively. They are about a factor 2-3 lower than during I3. The ratios of the lines are relatively close to unity similar to results found for the flare on 27 April, 1981 [7]. Considering the crudeness of the applied method, the estimated continuum N agrees fairly well with the excess of E indicating that the excess is mainly produced by nuclear emission. The difference between a best fit and the continuum N is of the same

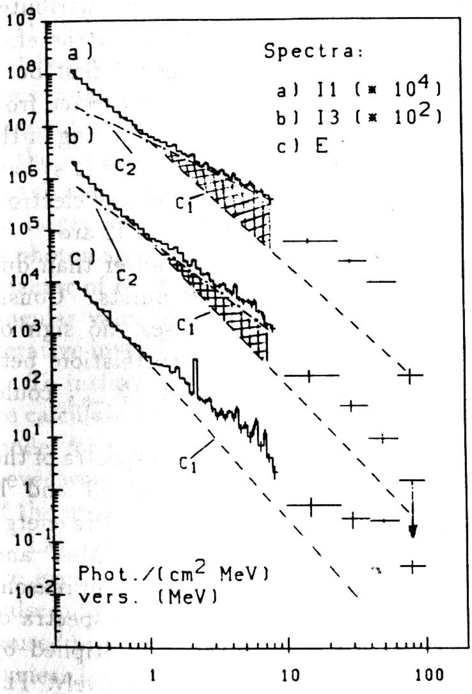

Fig. 2. *Deconvolved GRS and HEM (NaJ only) data for the phases I1 (UT 13.958-13.976), I3 (14.026-14.062) and E (14.092-14.177).* C_1: *extrapolated power law fit to the data below 0.8 MeV,* C_2: *estimated bremsstrahlung continuum between* ~ 1.3 *and 9 MeV.*

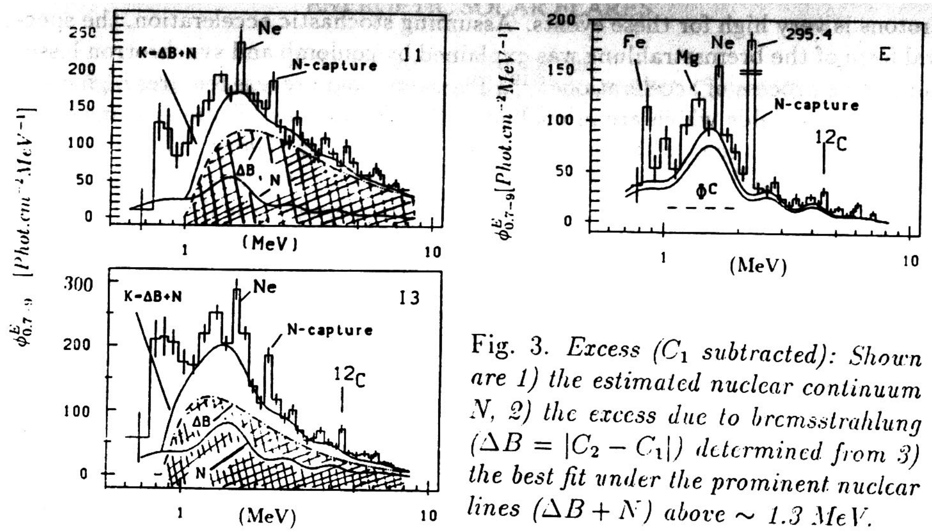

Fig. 3. *Excess (C_1 subtracted): Shown are 1) the estimated nuclear continuum N, 2) the excess due to bremsstrahlung ($\Delta B = |C_2 - C_1|$) determined from 3) the best fit under the prominent nuclear lines ($\Delta B + N$) above $\sim$ 1.3 MeV.*

order as the estimated continuum ϕ^c from photospheric compton-scattered 2.22 MeV photons (for details see [17]). The estimated nuclear continua N in the excesses of I1 and I3 obviously cannot account for the total continuum. Note that, because of the very low line-to-continuum ratio during I1, only an approximate value for the Ne-line flux at 1.63 MeV of $\sim$ 0.8 $[Phot./(cm^2 s)]$ could be determined. If we assume for the sake of simplicity an additional power law continuum C_2 which we attribute to bremsstrahlung, we can fit the total continuum successfully above $\sim$ 1.3 MeV. The shaded regions in Fig. 3 and Fig. 2 give the difference $\Delta B = |C_2 - C_1|$ above 1 MeV. As can be seen from Fig. 3, the relative contribution of bremsstrahlung to the excess in the 4-7 MeV range, usually considered as a measure for nuclear emission, decreases from about 90 % during I1 to about 45 % during I3, reaching finally a value around zero during E.

CONCLUSION

We showed that the bulk of gamma-emission during the impulsive bursts of the flare of March 6, 1989 is produced by bremsstrahlung continua with spectral forms, that flatten at about 0.8 MeV and extend as the dominant radiation component to almost 100 MeV. The bremsstrahlung-dominated spectra differ from ordinary gamma-ray spectra because of this flat and intense electronic high energy continuum above 1 MeV. Since these spectra can be produced within a second or less, a very efficient and fast process is required to accelerate the electrons to highly relativistic energies. The ratio of relativistic electrons to line-producing protons is very high for these events. Assuming stochastic acceleration, the spectral form of the bremsstrahlung was explained by coulomb and synchrotron losses during the process of acceleration [18,19]. The latter loss process requires high coronal magnetic fields which are in conflict with observations. There remains other observational findings which are difficult to explain by theory: 1) all the individually analysed spectra flatten in a very limited energy range around 1 MeV ($\pm$ 200 keV), and 2) there is no direct correlation between the degree of spectral flattening and the intensity and spectral form at lower energies ($<$ 1 MeV). Any successful model that includes acceleration, transport and interaction processes of the particles in flare loops ought to account for these detailed features in the bremsstrahlung-dominated spectra of the flare on 6 March 1989.

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