Energetic Proton Spectra in the 11 June 1991 Solar Flare

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Abstract. We have studied a subset of the 11 June 1991 solar flare γ-ray data that we believe arise from soft proton or ion spectra. Using data from the COMPTEL instrument on the Compton Observatory we discuss the gamma-ray intensities at 2.223 MeV, 4-7 MeV, and 8-30 MeV in terms of the parent proton spectrum responsible for the emission.

INTRODUCTION

Flares and intervals within flares have been observed to have γ-ray spectra that are produced by soft proton spectra. Share and Murphy (1995) found evidence of soft proton spectra in several flares. During 1991 COMPTEL was used to measure the γ-ray spectra of several flares including some that exhibited features associated with soft proton spectra.

The 11 June 1991 flare observed with the COMPTEL instrument aboard CGRO shows several indicators of a soft proton spectrum. During a middle phase of the flare (Dunphy et al. 1999), there is low 4-7 MeV emission, no significant emission above 10 MeV, but a strong 2.2 MeV line (Rank et al. 1997). In addition, the 2.2 MeV line has a long (> 300 s) decay time. These two facts point toward an excess of lower energy neutrons and thus a softer parent proton spectrum (Ryan et al. 1996). Similarly, the 24 October 1991 flare shows a paucity of 4-7 MeV emission. There was a strong 2.2 MeV line and an even stronger ^{20}Ne line (Suleiman 1995). This ^{20}Ne line and other low threshold lines seen along with the 2.2 MeV line indicate low energy neutrons and thus a soft proton spectrum. The 11 June 1991 measurements were performed in COMPTEL's telescope mode, whereas the 24 October 1991 measurements were made in the burst mode.

COMPTEL has two modes that operate simultaneously. The telescope mode is a Compton imaging telescope that operates in the energy range of 0.75 MeV - 30 MeV. It consists of two detector planes. The top is a low-Z liquid scintillator that Compton scatters an incident photon to the bottom detector plane that is a

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set of high-Z NaI detectors. The second mode is the burst spectrometer and it operates from 0.1-1.1 MeV and 0.6-10 MeV, using two of the NaI detectors in the lower (D2) modules. The ideal analysis of the flares includes both data sets. The telescope mode provides spectral and imaging data so it has a high signal-to-noise ratio but a small effective area. The burst mode provides spectral information in an overlapping energy band with a lower signal-to-noise ratio but a much greater effective area. This provides two data sets that contain comparable information but with different systematics. In an earlier study (Young et al. 1999), we discussed the spectral deconvolution and its use with the burst mode data emphasizing the 24 October flare. Here, we discuss the analysis of the 11 June flare telescope data.

DISCUSSION

For analysis of the 11 June 1991 flare data, we divided the flare into 3 phases. Phase I covers 7030 to 7600 seconds (1:57:10 - 2:06:40 UT), Phase II is from 7600 to 8000 seconds (2:06:40 - 2:13:20 UT) and Phase III is from 8000 to 10400 seconds (2:13:20 - 2:53:20 UT). These phases differ slightly from those used by Dunphy et al. (1999). Fig. 1 shows the flare lightcurve uncorrected for background and deadtime and Fig. 2 shows the flux time profiles for the 2.2 MeV, 4-7 MeV, and 8-30 MeV energy ranges (Rank 1996) with background and continuum subtracted.

As seen in Fig. 2, during Phase I there is a larger flux in the 4-7 MeV range than in 2.2 MeV line with a significant 8-30 MeV component. This is consistent with a high-energy population of ions. During the transition from Phase I to Phase II the relative amounts of 4-7 MeV and 2.2 MeV emission are reversed with an order of magnitude more 2.2 MeV emission. This would normally indicate a very hard ion spectrum. This, however, is inconsistent with the lack of significant 8-30 MeV emission. Alternately, the spectrum could have been produced by a softer population of ions. This would better explain the extended 2.2 MeV emission which has a decay time of >300 s. Aside from extended production, a long decay time requires a low hydrogen density which would imply a smaller penetration depth for the neutrons. The neutrons would penetrate deeper if they were more energetic (Hua and Lingenfelter 1987).

The three plots in Fig. 3 show the deconvolved photon spectra (using the Maximum Entropy Method (Gull and Skilling 1991) and a Monte Carlo simulated effective area (Schönfelde et al. 1991)) for the three phases. We have included with each a best fit powerlaw for the bremsstrahlung continuum. The powerlaw indices were based on a single measurement from the PHEBUS instrument by Trottet et al. (1993). The normalizations where based on the COMPTEL data at 600 keV and above 10 MeV. The 2.2 MeV emission is the most prominent feature in all three phases. The measurements with EGRET-TASC (Dunphy et al. 1999) and COMPTEL (Rank 1996) both show spectral hardening from Phase I to Phase III. Also, both indicate two independent ion populations in Phase I and Phase III due to the low value of the nuclear line flux in Phase II.

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FUTURE WORK

Several important features will be added to this analysis. The initial broad-banded work is based on the work of Rank (1997). Finer energy binning and an improved deconvolution method will enable a focus on individual lines. Improved power law fits based on BATSE (Rank 1999) and OSSE will provide better continuum subtraction. These improvements will allow a comparison of photon spectra from both the telescope and burst mode. The time intervals from the TASC analysis will be closer matched to allow a better comparison of the 2 data sets. This provides two independent measurements in the same energy band. Then using a nuclear γ-ray template model, the proton spectrum can be analyzed along with the associated low energy neutrons (Young and Ryan 1997).

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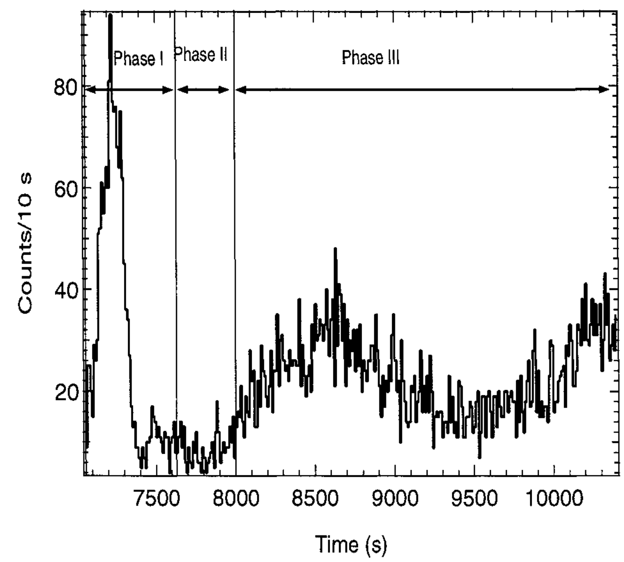

FIGURE 1. The 11 June 1991 solar flare uncorrected light curve showing the 3 phases. The odd shape is an effect of the deadtime from the middle of Phase I until a few hundred seconds into Phase III. This is due too the large soft x-ray flux that impinged upon the veto domes of COMPTEL.

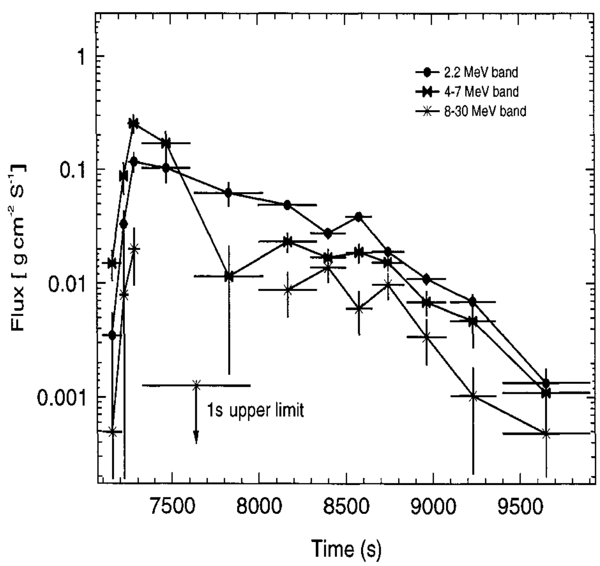

FIGURE 2. The 11 June 1991 solar flare flux time histories in the 2.2, 4-7, and 8-30 MeV energy bands with subtraction of background and continuum (based on Trottet et al. 1993).

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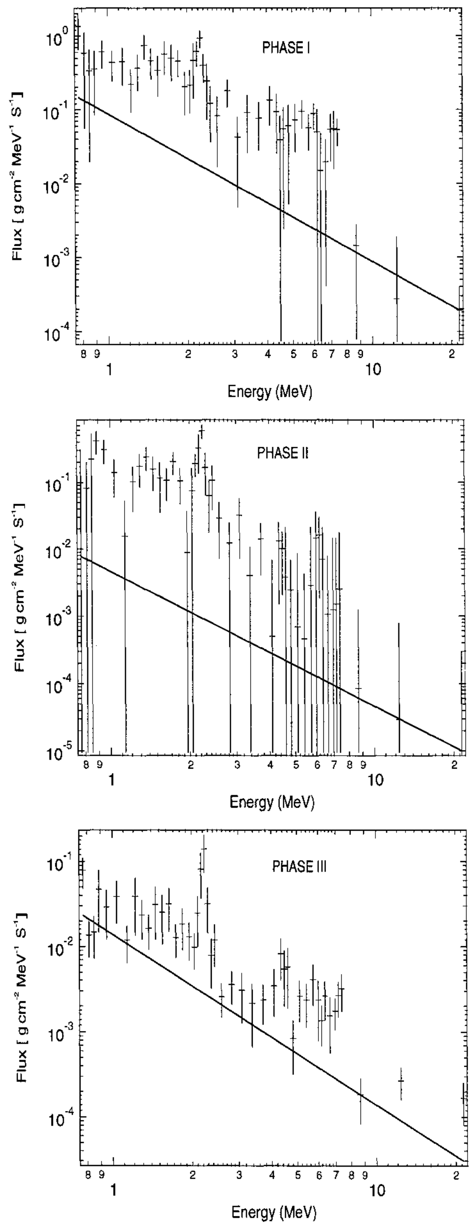

FIGURE 3. The 11 June 1991 solar flare photon spectra with bremsstrahlung power law fit for the 3 time phases.

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