THE ASTROPHYSICAL JOURNAL, 425:L109–L112, 1994 April 20

EVIDENCE FOR INTENSE CORONAL PROMPT GAMMA-RAY LINE EMISSION FROM A SOLAR FLARE

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Received 1993 October 18; accepted 1994 February 9

ABSTRACT

We present hard X-ray/gamma-ray measurements, obtained with the PHEBUS experiment onboard *GRANAT*, of the intense solar flare which occurred on 1991 June 1 at 14:56 UT beyond the east limb. The gamma-ray spectrum displays strong prompt lines in the 1–2 and 4–7 MeV energy ranges but no significant neutron capture line. Although the flare location prevents emission at heights below (3000–7000) km from being observed, the total fluence due to prompt nuclear lines in the 4–7 MeV range is found to be one of the largest measured so far. We argue that the prompt gamma-ray line emission takes place in the lower corona at densities below (10^{11}–5×10^{11}) cm^{-3}.

Subject headings: gamma rays: observations — Sun: flares — Sun: X-rays, gamma rays

1. INTRODUCTION

Hard X-ray (HXR) and gamma-ray (GR) line and continuum measurements are the most direct signatures of the acceleration/interaction of energetic electrons and ions in the solar atmosphere. HXR imaging observations have provided information on the location, geometry, and temporal evolution of the <100 keV emitting region. For impulsive flares, the HXR source is generally located near the footpoints of flaring loops (e.g., Duijveman & Hoyng 1983). Statistical altitude measurements place the 14–23 keV emission at 9700 ± 2000 km above the photosphere and higher energy HXR sources are found at progressively lower altitudes, i.e., 6500 ± 2000 km for the 53–93 keV energy range (Matsushita et al. 1992). For gradual flares, the 30 keV HXR source is observed at higher altitudes, i.e., 4×10^4 km (Tsuneta et al. 1984). At energies greater than 100 keV, existing experiments cannot spatially resolve the HXR or GR emission. Stereoscopic observations by Kane et al. (1982) have shown that the >100 keV HXR source is extended in height but place the bulk of the emission at less than 2500 km for both impulsive and gradual flares. Measurements of GR line emission are generally consistent with a compact region located in the chromosphere at densities $>10^{12}$ cm^{-3} (e.g., Chupp 1984). Nevertheless, Hulot, Vilmer, & Trottet (1992) have shown that in some flares a fraction (>30%) of the prompt GR line emission originates from a coronal region with a mean density of 5×10^{10} cm^{-3}. Recently, the observation of a strong neutron capture line from a flare located beyond the limb has been reported by Vestrand & Forrest (1993). This result is in apparent contradiction with theoretical predictions which place the 2.22 MeV line emission in the photosphere (Hua & Lingenfelter 1987). This led Vestrand & Forrest to propose that the line emitting source comprises, in addition to the compact source, a spatially extended component that subtends a large range of heliolongitudes.

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In this *Letter*, we report on PHEBUS observations of >100 keV HXR and prompt GR line emissions from a flare (1991 June 1 at 14:56 UT) that occurred beyond the solar limb.

2. FLARE LOCATION

On 1991 June 1 a major soft X-ray (SXR) flare was observed by *GOES* from 14:56 to 17:26 UT. The SXR emission reached its maximum (*X*12.0) around 15:20 UT. This flare produced intense HXR and GR emission observed by PHEBUS from 14:56:40 to 15:19:36 UT. The Hα observations do not show any flare on the visible disk which could be associated with such a large event. Nevertheless, Hα material was first observed at 15:03 UT above the east limb at N26–27 by the Hα heliograph at Paris-Meudon observatory (Fig. 1 [Pl. L8]). This flaring arch is found to be associated with the NOAA active region 6659 located at about N25 and 7° behind the East limb (Z. Mouradian, 1993, private communication). This confirms the NOAA report of the *GOES* observations that the 1991 June 1 flare occurred in AR 6659. With the use of NOAA Solar Geophysical Preliminary and Comprehensive reports, the location of the 1991 June 1 flare has therefore been estimated from the position during the transit of AR 6659 across the solar disk of: (1) the centroid of the sunspot group; (2) all the Hα flares producing *GOES* events; and (3) Hα flares associated with *GOES* events of importance *X*. A linear least-squares fit and extrapolation of these locations as a function of time lead to the conclusion that the 1991 June 1 flare occurred between 6° and 9° behind the east limb. This corresponds to occultation heights ranging from 3000 to 7000 km above the photosphere.

3. PHEBUS HXR AND GR OBSERVATIONS

A description of the PHEBUS experiment is presented in some detail in Barat et al. (1988), Barat (1993), and Talon et al. (1993). Briefly, PHEBUS consists of six actively shielded BGO (78 mm in diameter and 120 mm thick) detectors. Two of them face the Sun at an angle close to 90° (with respect to the detector axes), nearly independent of the pointing direction of *GRANAT*. High-time resolution data are recorded when a γ-ray burst is detected by the onboard system. This burst mode was triggered twice during the 1991 June 1 flare, at

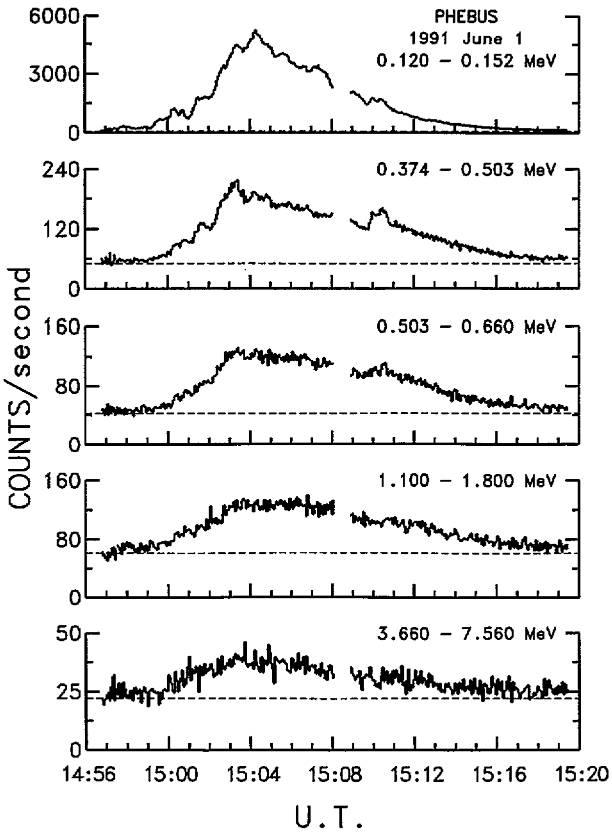

FIG. 2.—Time history of the 1991 June 1 event recorded by the PHEBUS experiment in five energy ranges. The dashed lines indicate the background levels. The time resolution is 4 s.

14:56:53 UT and at 15:08:48 UT, providing spectral information in the 0.12–90 MeV range from about 14:56:40 to 15:19:36 UT with a time resolution of 1 s below ~10 MeV and 4 s above. Only data from one detector are presented, although comparable results have been obtained from the other detector viewing the Sun. At energies below 0.5 MeV, the temporal evolution comprises numerous peaks of 1 minute typical duration until about 15:11 UT (Fig. 2). No significant delays in the peak times were measured in the 0.1–0.5 MeV energy range within the 1 s time resolution. However, such peaks are not visible above 0.5 MeV. After 15:11 UT, the emission decayed with an *e*-folding time ranging from 150 s around 0.1 MeV to about 200 s at energies above 1 MeV. Significant emission was detected in the 1.1–1.8 MeV and in the 3.7–7.6 MeV ranges. The time profiles in these two energy ranges display a smooth evolution, similar to the HXR emission above 0.5 MeV. No significant count rate was observed above 7.6 MeV.

Figure 3 shows the background-subtracted count rate spectrum accumulated between 15:00:40 and 15:03:10 UT. It consists of a continuum presumably from electron bremsstrahlung and of strong line structures above 1 MeV. The line emission comprises a broad feature in the 1.1–1.8 MeV energy range, which is probably due to a complex of lines mainly from ^{56}Fe, ^{24}Mg, ^{20}Ne, and ^{28}Si; this complex is not resolved by PHEBUS (the detector energy resolution is 9.8% FWHM at 1.63 MeV). In the 3.7–7.6 MeV range, the strong lines from ^{12}C at 4.44 MeV and from ^{16}O at 6.13 MeV are clearly observed, as well as the nuclear line emission cutoff at about 8 MeV. It should be emphasized that no significant 2.22 MeV neutron capture line is detected for the entire observation period. In particular, for the spectrum shown in Figure 3, the count rate at 2.22 MeV does not exceed the 3 σ count rate excess (corresponding to 1.7×10^{-2} photons cm^{-2} s^{-1}) expected for a neutron capture line emission. This is in agreement with earlier studies, which indicate that this line is strongly attenuated with respect to prompt GR line emission for flares located close to the limbs (e.g., Hua & Lingenfelter 1987). In order to separate the bremsstrahlung continuum and the nuclear contribution above 1 MeV, the count spectra accumulated every 8 s during the entire event were fitted to a double power law below 1 MeV. The break energy E_b is equal to 0.40 ± 0.02 MeV from 15:00 to 15:08 UT and then decreases between 15:09 and 15:12 UT to about 0.2 MeV, where it remains until

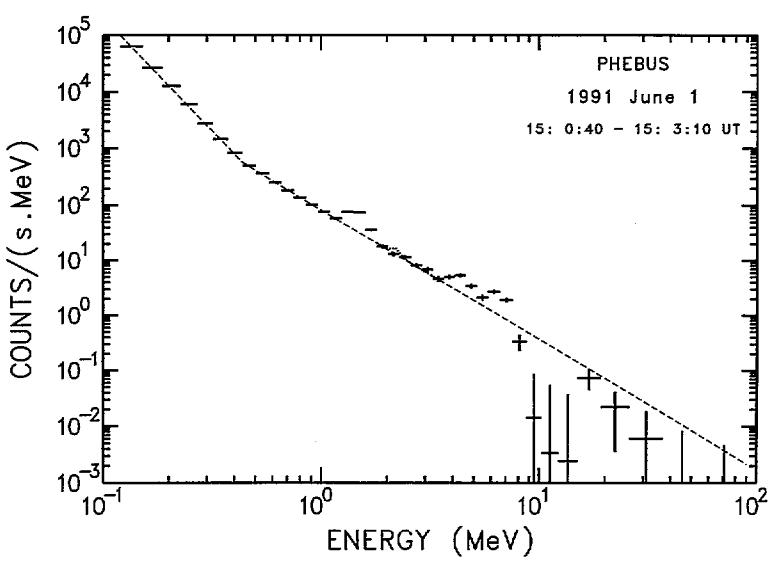

FIG. 3.—Count rate spectrum of the 1991 June 1 event accumulated between 15:00:40 and 15:03:10 UT. The dashed line represents a double power-law fit to the continuum below 1 MeV. The dotted line indicates the 3 σ count rate excess expected for a 2.22 MeV line emission.

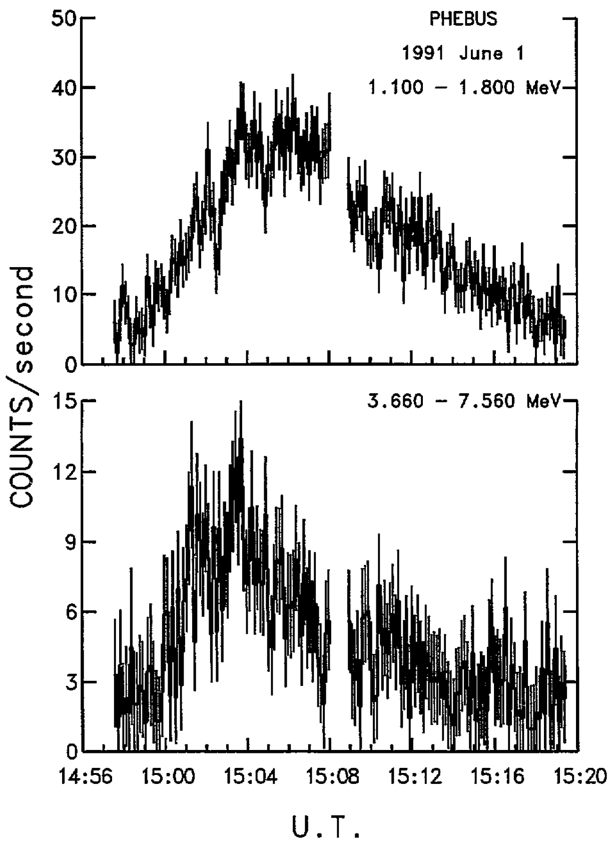

FIG. 4.—Count rate excesses above the continuum in the 1.1–1.8 and 3.7–7.6 MeV energy ranges. The time resolution is 8 s.

the end of the event. The power law which best fits each count spectrum between E_b and 1 MeV was extrapolated to estimate the number of bremsstrahlung counts in the 1.1–1.8 and 3.7–7.6 MeV ranges. The excesses due to prompt nuclear lines (Fig. 4) were obtained by subtracting this continuum contribution from the signal counting rates. It is noteworthy that no significant short duration (<1 minute) peaks are observed in the nuclear line excess time histories. The nuclear component contributes about 50% of the signal count rate integrated over the whole event in both energy ranges. On 1991 June 1, the incidence angle for solar photons was $80° \pm 1°$ for the detector analyzed. At this angle, the mean photopeak efficiencies are 0.58 ± 0.02 and 0.32 ± 0.02 in the 1.1–1.8 and 3.7–7.6 MeV ranges, and the total 1.1–1.8 and 3.7–7.6 MeV nuclear fluences are 419 ± 17 and 185 ± 14 photons cm^{-2}, respectively. However, these values are only lower limits. Indeed, Figure 2 clearly shows that the real continuum above 1 MeV may be softer than that deduced from the fit. A likely explanation lies in the existence of de-excitation lines in the 0.8–1 MeV region (see, e.g., Murphy et al. 1990), which are not resolved by the PHEBUS detectors but which may contribute to the continuum. The 4–8 MeV excess fluence derived for many flares lies in the 0.01–300 photons cm^{-2} range (Vestrand 1988). Thus, even though it is associated with a behind the limb flare, the 1991 June 1 event appears as one of the strongest GR line flares observed to date.

4. DISCUSSION AND CONCLUSION

The time evolution of prompt GR line events observed in many flares indicates that line emission is produced in a region with ambient densities $n_H > 10^{12}$ cm^{-3} (e.g., Chupp 1984) with a maximum production rate in the 10^{14}–10^{15} cm^{-3} region (e.g., Hulot et al. 1989). According to models of the flaring atmosphere, this places the prompt GR line-emitting region at heights less than 1500 km above the photosphere (e.g., Machado et al. 1980). In order to be captured, the neutrons producing the 2.22 MeV line must be thermalized at $n_H > 10^{16}$ cm^{-3} (Hua & Lingenfelter 1987). The location usually assumed for the >100 keV HXR and prompt GR line-emitting regions at heights <2500 km is doubtful, however, in the case of the 1991 June 1 event, since the flare location behind the limb implies that electromagnetic radiation can be observed only from regions at heights greater than 3000 km. Strong neutron capture line and weak prompt GR line emission have been reported so far only during the decay phase of the behind the limb 1989 September 29 event by Vestrand & Forrest (1993). They suggested that this neutron capture line could only be explained if, in addition to the compact emitting source which usually dominates the total GR line fluence, there is a spatially extended source which, in this peculiar event, subtends more than 30° on the solar surface. In contrast, no significant neutron capture line was detected during the 1991 June 1 flare. Moreover, the Hα observations show no evidence for the presence of a large-scale loop system connecting the flare site to the visible disk (Fig. 1). Under these conditions the simplest interpretation is that the >100 keV HXR and prompt GR line emissions originate from heights greater than 3000 km above the photosphere, i.e., from the lower corona.

Observations of many flares strongly suggest that electrons and ions are accelerated simultaneously (e.g., Chupp 1990). It is thus assumed that electrons and protons are simultaneously and continuously injected into a region with a mean ambient density n_0, where they are prefectly trapped and where they lose energy through Coulomb collisions with the ambient medium. The HXR and GR line fluxes are then computed with the models developed by Vilmer, Kane, & Trottet (1982) and Hulot et al. (1989). The observed smoothing of the individual peaks of 1 minute typical duration above 0.5 MeV as well as the absence of delays in the times of maxima of these peaks below 0.5 MeV are found to be consistent with bremsstrahlung radiation of trapped electrons if the density in the region lies in the 10^{11}–10^{12} cm^{-3} range. Assuming that electrons are continuously injected into the trap as long as the individual peaks are seen at low energies (for about 12 minutes up to 15:11 UT), the decay times of computed X-ray fluxes at different energies after the end of the injection are, for these densities, in the 150–200 s range, in agreement with the observed values. These values of the density are only upper limits, since perfect electron trapping in the source and an electron injection spectrum without a high-energy cutoff are assumed. However, the predicted temporal evolution of the GR lines produced by perfectly trapped protons is consistent with that observed (smooth behavior, no trace of the 1 minute duration peaks observed at low X-ray energies) if the density in the coronal trap lies in the 10^{11}–5×10^{11} cm^{-3} range. This is in the range of densities obtained for the electrons. Assuming a proton injection spectrum with a power-law index of 3.5, usually observed in flares (Hua & Lingenfelter 1987), the total number of >30 MeV protons necessary to radiate the observed GR line fluence at 4.44 and 6.13 MeV in a coronal trap with a mean density of 10^{11}–5×10^{11} cm^{-3} is of the order of $2–3 \times 10^{33}$ for standard abundances.

In summary, the PHEBUS observations of the HXR/GR continuum and of the GR lines during the 1991 June 1 flare are consistent with the hypothesis that the emissions are produced at heights >3000 km by electrons and protons trapped in a low coronal region of density of the order of 10^{11} to 5×10^{11} cm^{-3}. The observed total line fluence is comparable to that measured for the largest flares detected on the visible disk. Nevertheless, the coronal production of the GR line emission does not require a substantially higher number of protons than the one usually assumed in other GR line flares. This implies that, at least in some flares, the GR line-emitting region extends over both the chromosphere and the lower corona, and confirms the model prediction by Hulot et al. (1992). Moreover, for this flare, the absence of a detectable neutron capture line does not support the suggestion, made by Vestrand & Forrest (1993), of the existence of a spatially extended chromospheric/photospheric GR line emitting region, unless this region spreads only eastward of the flaring site. Finally, it should be emphasized that the 1991 June 1 HXR/GR spectral characteristics are similar to those generally measured during GR line flares. In particular it exhibits, as usually observed (Vestrand 1998), a spectral break around 400 keV and the 1.1–1.8 to 3.7–7.6 MeV nuclear line fluence ratio (~ 2.3) is similar to that observed in many flares (~ 2–4), Marschhaüser 1992). This suggests that a coronal contribution to GR line emission may be present during more flares than the ones for which it has been detected or inferred so far. If this is the case, it would provide a natural explanation for the fact that relative elemental abundances, derived from the GR line spectrum of one flare (e.g., Murphy et al. 1990), are close to coronal values but inconsistent with photospheric ones.

At CESR and Meudon Observatory, this work was supported by CNES contracts 92/93-0208 and 92-0240/0241, respectively. The authors are indebted to I. Soru-Escaut and Z. Mouradian for the optical data and are grateful to the referee for his constructive comments.

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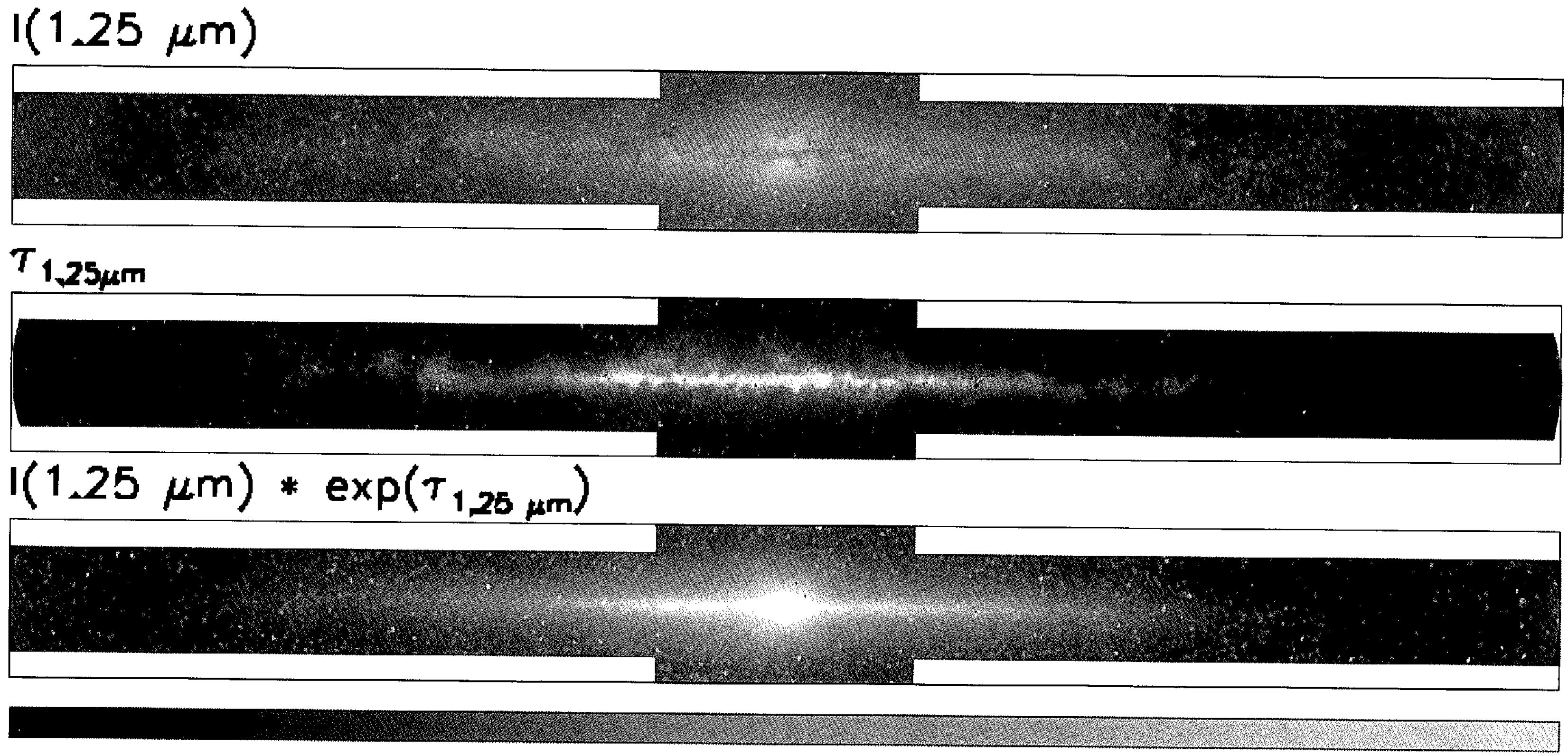

FIG. 3.—DIRBE images of (*a*) Galactic emission at 1.25 μm [I(1.25 μm)] with zodiacal light removed, (*b*) extinction at 1.25 μm ($\tau_{1.25}$), and (*c*) I_0(1.25 μm) with the effects of extinction removed [i.e. I(1.25 μm) * exp ($\tau_{1.25}$)]. Intensities are displayed on a logarithmic scale $\log_{10}$ [I (MJy sr^{-1})] = [−0.2, 1.5], and optical depths are displayed on a linear scale $\tau_{1.25}$ = [0, 2.5]. The extinction correction in Fig. 3*c* is not strictly valid in the Galactic plane where $\tau_{1.25} > 1$.

ARENDT et al. (see 425, L87)