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Temporal and spectral characteristics of the June 11, 1991 gamma-ray flare *

G. Trottet[1], N. Vilmer[1], C. Barat[2], J.P. Dezalay[2], R. Talon[2], R. Sunyaev[3], A. Kuznetsov[3] and O. Terekhov[3]

[1] Observatoire de Paris, Section de Meudon, DASOP and CNRS-URA 324, 92195 Meudon, France
[2] Centre d'Etude Spatiale des Rayonnements , BP 4346 , 31029 Toulouse Cedex , France
[3] Space Research Institut , Profsoyuznaya 84/32 , 117810 , Moscow , Russia

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Abstract. — The June 11,1991 event is one of the major flares produced by AR6659 during its transit on the solar disk. In addition to bremsstrahlung emission this flare exhibits strong nuclear γ-ray lines.We report here PHEBUS observations of this flare and perform a detailed comparison of the time histories of both the prompt (4-7 MeV) and delayed 2.23 MeV GRL emissions. We derive for this flare preliminary values of the $^{3}He/^{1}H$ ratio and of the hardness of the ion spectrum and compare these values with the ones obtained from previous observations.

Key words: Sun:flares — Sun:gamma rays — Sun: abundances.

1. Introduction.

Unusual high solar activity has been observed during the first half of June 1991. It was mostly produced by active region n° 6659(NOAA number) during its transit across the solar disk. Between June 1 and June 15 this region has produced 6 >3B Hα flares each of them giving rise to X12.0 GOES X-ray bursts. The PHEBUS hard X-ray/gamma-ray spectrometer aboard GRANAT has recorded two of these six flares: June 1, 1991 at 13:58 UT and June 11, 1991 at 01:58 UT. Strong hard X-ray(HXR) continuum and nuclear γ-ray line(GRL) emissions were present in both flares but while the 1 June flare occurred when AR 6659 was about 9° behind the east limb (Barat *et al.* 1992), the 11 June event is associated to a flare located close to the disk center at N31 W17. We report here PHEBUS observations of the 11 June flare. Due to its location it is possible to perform a detailed comparison of the time histories of both the prompt (4-7 Mev) and delayed 2.23 Mev GRL emissions. The present measurements constitute one of the very rare data sets which allow such a study. This comparison allows us to derive parameters such as the $^{3}He/^{1}H$ ratio and the hardness of the ion spectrum.

2. Observations of the 11 June 1991 event.

The PHEBUS experiment has been described in Barat *et al.*(1988). It consists of 6 independent BGO detectors (78 mm in diameter, 120 mm in height) surrounded by a plastic anticoincidence jacket. The data discussed below deal with spectral measurements performed in 40 channels between 100 keV and 100 MeV with a time resolution of 1 sec during about 640 sec. The in-flight detector calibration has been used to determine the energy edges of the 40 channels (see Barat *et al.* 1988). The full detector response is still under study.

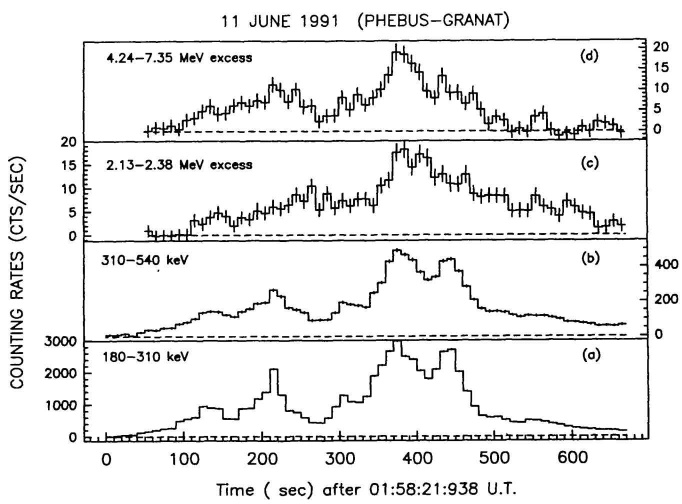

FIGURE 1. Temporal evolutions of the 180-310 keV (a), 310-540 keV (b) counting rates and of the 2.13-2.38 MeV excess (c) and 4.24-7.35 MeV excess (d) counting rates averaged over 10 sec for the 11 June 1991 event.

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Figures 1a and 1b show respectively the time profile of the HXR emission in the 180-310 keV and in the 310-540 keV energy ranges, with a 10 sec integration time, for the detector which recorded the highest counting rate. The HXR emission lasts for more than ten minutes and presents well defined peaks with durations of typically 1 mn. No energy dependent delays are observed in the peak times even with a 1 sec integration time. This implies that possible coronal trapping of energetic electrons does not substantially affect the observed time profiles (see e.g. Hulot *et al.* 1989). Hence the HXR emission may be considered in the thick target approximation where the HXR time profile mostly reflects that of the acceleration. This is further confirmed by the fact that the counting rate spectrum, thus the electron spectrum, is found to remain roughly constant during the whole event. This spectrum is well represented by a power law of spectral index 3.0 ± 0.4 in the 300 keV- 1 MeV energy range.

In order to estimate the intensity of GRL emission, the electron bremsstrahlung component has been determined for each spectrum, extrapolated up to 10 MeV and subtracted from the total counting rate recorded in the 2.13-2.38 MeV channel and in the (4.2-7.3) MeV band. The resulting excess counts are shown in Figures 1c and 1d.

The 4.2-7.3 MeV excess (Fig. 1d) represents more than 80% of the total counting rate recorded in this energy band. This is in agreement with earlier results (e.g. Chupp 1984, Forrest & Chupp 1983, Yoshimori 1989). The time history of the 4.2-7.3 MeV excess is very similar to that of the HXR (electron) emission. As the 4.2-7.3 MeV excess is entirely due to prompt GRL emission produced by the interaction of 10-50 MeV ions (see e.g. Ramaty & Murphy 1987 and references therein), this implies that electrons and ions are accelerated simultaneously on time scales of a few tens of sec. This is in agreement with earlier findings by e.g. Forrest & Chupp 1983.

Though a full deconvolution of the detector response would be necessary to get the 2.23 MeV line flux, the 2.13-2.38 MeV excess displayed on figure 1c represents ~ 85% of the total counting rate in this channel and can be considered as a good measurement of this line intensity. Indeed: (i) this energy band corresponds to the only channel which contains the line; (ii)using the 2.313 MeV line and the (4-7) MeV yields given by Murphy 1985, the observed 4.2-7.3 MeV excess leads to a contribution of prompt GRL in the (2.13-2.38) band which is one to two orders of magnitude below the excess observed in this band,thus completely negligible.

The 2.23 MeV line results from the radiative capture of energetic neutrons on ambient ^{1}H after thermalization in the medium. The 1-100 MeV neutrons are produced by nuclear interactions of accelerated ions with the ambient atmosphere (see e.g. Wang & Ramaty 1974). As it takes time for the neutrons to be thermalized, the 2.23 MeV line emission is delayed compared to the prompt GRL emission and both types of lines are expected to have different time histories. This is effectively observed for the 11 June 1991 event(see figures 1.c and 1.d). The 2.23 MeV time profile shows peaks which are smoother than the ones in the 4.2-7.3 MeV band and decays more slowly than the 4.2-7.3 MeV prompt GRL intensity.

3. Discussion and summary.

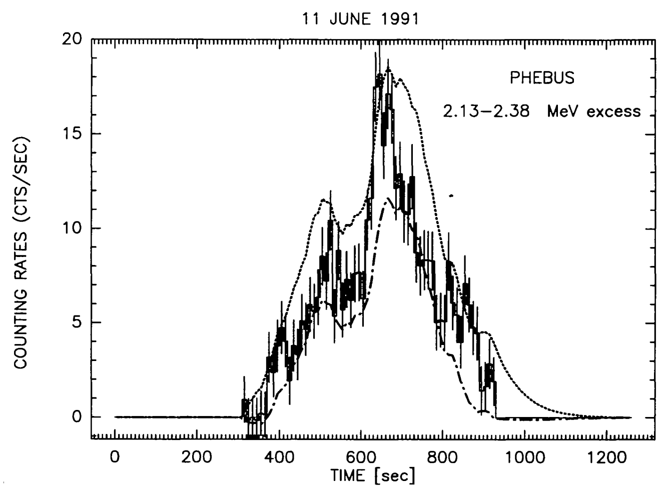

FIGURE 2. Observed temporal evolution of the 2.13-2.38 MeV excess counting rate (solid) for the 11 June 1991 event. Also shown for comparison are the computed high (dotted) and low (dash-dotted) limits of the 2.23 MeV time profile deduced from Equation (1) (see text for more details).

In addition to radiative capture on ^{1}H, thermal neutrons may experience non radiative capture on ^{3}He (e.g. Wang & Ramaty 1974). The time dependence of the 2.23 MeV line provides a measurement of abundance ratio $r = ^3$He/1H (Wang &Ramaty 1974, Prince et al. 1983). The detector efficiency is constant within 20% in the(2-8) MeV band (see Barat *et al.* 1988). The ratio R of the time integrated (2.13-2.38) MeV to the (4.2-7.3) MeV excess counts is thus a good first approximation of the ratio of the total fluences of the 2.23 MeV line to that of the (4-7) MeV prompt lines. This procedure leads to R = 1.25± 0.10 where the error is only due to the statistics on both data sets. This is in good agreement with values generally obtained for flares close to the Sun's center (e.g. Hua & Lingenfelter 1987a).

Following Prince *et al.* 1983, the flux $I_{2.2}(t)$ of the 2.23 MeV line is related to the neutron production rate by:

$$I_{22}(t) = A \int_{-\infty}^{t} I_{obs4-7}(t') e^{(t-t'/T)} dt' \qquad (1)$$

$AI_{\mathrm{obs}4-7}(t)$ is the neutron production rate which has been taken proportional to the observed proton production history. The exponential is the simplest form that can be considered for the response function giving the 2.23 MeV photon contribution at time t due to neutrons produced at time t'. Using the (4.2-7.3) MeV excess counting rate shown in Figure 1c the excess counting rate in the (2.13-2.38) MeV band has been computed through Equation (1) with $A = R$. The comparison between observed and computed values of the (2.13-2.38) MeV excess allows us to determine the time constant T. The best model fit is obtained for T =70 s ± 10 s. This is illustrated in Figure 2 which shows that, despite the simplicity of the model and the complexity of the event time profile, the computed and observed (2.13-2.38) MeV excess counts are in good agreement within the error bars.

The time constant T can be written as:

$$T(\text{sec}) = \frac{1}{\left(\frac{n_{\rm H}}{1.4\times10^{19}} + \frac{r n_{\rm H}}{8.5\times10^{14}} + \frac{1}{T_{\rm d}}\right)} \qquad (2)$$

where $n_{\rm H}$ is the ^{1}H number density in cm^{-3} and $T_{\rm d}$ = 917 s is the mean neutron decay time. Taking $n_{\rm H} = 1.3 \times 10^{17}$ cm^{-3} (Prince *et al.* 1983, Hua & Lingenfelter 1987b) we find $2 \times 10^{-5} < r < 5 \times 10^{-5}$. The best fit is obtained for $r = 3\times10^{-5}$. The present values of r are in agreement with those obtained by Chupp *et al.* 1981 ($r = 5 \times 10^{-5}$) for the 7 June 1980 flare and by Hua and Lingenfelter 1987b ($r = 2.3 \times 10^{-5}$) for the 3 June 1982 event. They also agree with model calculations by Wang & Ramaty 1974 where $r < 5 \times 10^{-5}$. On the other hand Prince *et al.* 1983 obtained somewhat lower values and found r in the range 0.0-1.3 $\times10^{-5}$.

Using calculations performed by Hua & Lingenfelter 1987a for $r = 2 \times 10^{-5}$ the knowledge of R allows us to determine the hardness of the proton spectrum. For incident ions with an isotropic distribution we find that $T \simeq 0.02$ if the spectrum is a Bessel function and a spectral index $s \simeq 3.5$ for a power law spectrum. These values are in agreement with those obtained for 15 GRL flares: $0.01 < \alpha T < 0.04$ and $3 < s < 4$ (Hua and Lingenfelter 1987a).

In summary the 11 June 1991 flare has similar characteristics as most of the flares producing GRL emission. The PHEBUS observations have allowed us to perform a detailed comparison of the time histories of the neutron capture line and of the prompt nuclear gamma-ray lines.The ^{3}He/^{1}H ratio r found from this study is in the range (2-5)$\times10^{-5}$. The present preliminary result adds to the very few determinations of r and confirms that its solar value is larger than the protosolar ones (1.1-1.2 $\times10^{-5}$) derived by e.g. Anders& Ebihara (1982) and Cameron (1982).

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