PHYSICAL IMPLICATIONS OF INTEGRAL/SPI GAMMA-RAY LINE MEASUREMENTS OF THE 2003 OCTOBER 28 SOLAR FLARE

V. Tatischeff\(^1\), J. Kiener\(^1\) and M. Gros\(^2\)

\(^1\)CSNSM, IN2P3-CNRS and Université Paris-Sud, 91405 Orsay Campus, France
\(^2\)DSM/DAPNIA/SAp, CEA Saclay, 91191 Gif-sur-Yvette, France

The very powerful X-class solar flare of 2003 October 28 was detected with the INTEGRAL spectrometer as an intense \(\gamma\)-ray flash of about 15 minutes. Despite the non-standard incidence of the solar \(\gamma\)-rays, time-resolved spectra including several nuclear \(\gamma\)-ray lines were obtained. Such a measurement with a high-energy-resolution instrument can provide valuable information of the isotopic abundances of the ambient solar material, as well as the composition, directionality and energy spectra of the accelerated nuclei. First results on the measured \(\gamma\)-ray line ratios and time history of the neutron-capture line are presented.

1 Introduction

Although not devoted to solar physics, the INTEGRAL observatory can provide valuable measurements of the high-energy emission produced in the most powerful solar flares. In particular, the spectrometer SPI\(^1\) can allow fine spectroscopic analyses of the nuclear \(\gamma\)-ray line emission. These lines are produced by the interactions of flare-accelerated particles with the ambient solar material and their intensities can be used to determine isotopic abundances in the solar atmosphere\(^2\). In addition, measurements of the shape and redshift of some deexcitation lines can provide complementary information on the directionality and spectra of the accelerated ions\(^3\).

Very high solar activity was observed in late October and early November 2003, with several flares of class X originating from the same active region of the Sun. In this paper, we briefly review the data obtained with SPI for the X17.2 flare of October 28\(^4\). We then present a preliminary analysis of the measured \(\gamma\)-ray line fluence ratios and of the time history of the 2.22 MeV neutron-capture line.

2 Observations

The \(\gamma\)-ray emission from the 2003 Oct. 28 flare was detected with SPI as an intense flash of \(\sim 15\) minutes starting at 11:02 UT. The satellite was then observing the supernova remnant IC443, with the Sun at 122° from the instrument line-of-sight. Background-subtracted spectra were obtained by using both single and multiple events from the 19 Ge detectors. Four deexcitation \(\gamma\)-ray lines produced by the interactions of flare-accelerated protons and \(\alpha\)-particles with the solar atmosphere were detected: at 4.44 MeV from ambient \(^{12}\)C\(^*\), and 6.13, 6.92 and 7.12 MeV from ambient \(^{16}\)O\(^*\). In addition, we measured a strong line emission at 2.22 MeV from radiative capture of secondary neutrons by photospheric H. The relative fluences of these lines are given
Table 1: Relative line fluences for the 2003 October 28 flare

| Line Energy (MeV) | Relative Fluence |
|-------------------|------------------|
| 2.22              | 10.7±1.7         |
| 4.44              | 0.92±0.14        |
| 6.13              | ≡1.00±0.17       |
| 6.92              | 0.33±0.13        |
| 7.12              | 0.20±0.12        |

in Table 1. They were obtained from preliminary simulations of γ-ray transmission through the satellite material, for the configuration of INTEGRAL during the flare.

3 Line fluence ratios

Calculations of γ-ray line emission were performed assuming a thick target interaction model and a power-law source spectrum for the accelerated particles. We considered both photospheric and coronal compositions for the ambient medium. For the production of the neutron-capture 2.22 MeV line, we used the code developed by Hua et al. Whereas the emission of the $^{12}\text{C}$ and $^{16}\text{O}$ narrow lines is only due to accelerated proton and $\alpha$-particle interactions, neutron production also depends on the fast heavier nuclei. We assumed for these particles an impulsive-flare average composition obtained from measurements of solar energetic particle events, but allowed the $\alpha/p$ abundance ratio to vary between 0.02 and 0.5. The cross sections for the production of the $^{12}\text{C}$ and $^{16}\text{O}$ lines are based on Kozlovsy et al.

The neutron capture-to-deexcitation line fluence ratios strongly depend on the accelerated particle spectral index $S$, because, on average, the neutrons are produced at higher energies than the $^{12}\text{C}$ and $^{16}\text{O}$ lines (see Fig. 1). But these ratios also depend on the composition of the accelerated particles and the ambient material, as well as on the angular distribution of the interacting ions. We used the calculations shown in Fig. 1 to take into account these uncertainties.

Figure 1: Neutron capture line to $^{12}\text{C}$ and $^{16}\text{O}$ line fluence ratios. Horizontal hatched areas: SPI data. Solid curves show calculated ratios as a function of power-law spectral index, for the following case: accelerated ions with $\alpha/p=0.1$ and downward-isotropic distribution, interacting with an ambient medium of coronal composition and $^{3}\text{He}/\text{H}=3\times10^{-5}$. Dashed and dotted curves show the effects of changing the ambient medium composition (panels a and e) the flare geometry (b and f) the ambient $^{3}\text{He}$ abundance (c and g) or the $\alpha/p$ ratio (d and h).
and obtained from the comparison with SPI data: $S = 3.15 \pm 0.55$, $3.65 \pm 0.55$ and $4.075 \pm 0.475$, for $\alpha/p = 0.02$, 0.1 and 0.5, respectively.

In Fig. 2, we compare calculated $^{12}$C and $^{16}$O line ratios for these 3 values of $\alpha/p$ with the SPI data for the corresponding values of $S$. We assumed that the $\gamma$-ray production region is of coronal composition, with $C/O = 0.46$ [6]. We see that the calculated $^{16}$O line ratios are in good agreement with the SPI data, given the large uncertainties due to the relatively low statistics obtained for the $\sim 7$ MeV lines. But we also see that the calculated 4.44-to-6.13 MeV line ratios overestimate the observed value, for all the $\alpha/p$ ratios. We have further compared our calculations with data obtained for other solar flares with SMM, CGRO/OSSE and RHESSI and found the theoretical $^{12}$C-to-$^{16}$O line ratios to overestimate the average of the measured flux ratios by a factor of $\sim 1.5$ [9]. This discrepancy suggests that the $^{12}$C and/or $^{16}$O abundances at the $\gamma$-ray production sites could be different from their generally-assumed coronal values.

### 4 Time dependence of the 2.22 MeV line emission

Time history measurements of the 2.22 MeV line can provide a unique determination of the photospheric $^3$He/H ratio, because neutron capture on $^3$He via the $^3$He($n,p)^3$H reaction can significantly shorten the delay of the radiative-capture line emission. But as recently emphasized by Murphy et al. [10], the time history of this line is also strongly dependent on the angular distribution of the interacting flare-accelerated particles. Following these authors, we calculated the 2.22 MeV line production by using a detailed magnetic loop model [7], for which this angular distribution is parameterized by the level of MHD pitch-angle scattering (PAS) occurring in the coronal portion of the loop. We assumed the neutron-production time history to be identical to the one of the prompt deexcitation $\gamma$-ray line emission, for which good quality data were obtained with SPI (Fig. 3a).

Fig. 3b shows the best fit to the measured count rate of the 2.22 MeV line and Fig. 4 the regions of $1\sigma$ and 90% confidence levels for the two free parameters. These results are in good agreement with those previously obtained with RHESSI [10]. However, the derived $^3$He/H ratio is still not well constrained. But the 4.44 and 6.13 MeV line shapes measured with SPI will allow an independent determination of $\lambda$, which should significantly reduce the uncertainty on the photospheric $^3$He abundance (Fig. 4).
Figure 3: Measured time dependences of (a) the sum of the 4.44 and 6.13 MeV line count rates and (b) the 2.22 MeV neutron-capture line emission. Also shown in panel (b) is the best fit with ±1σ uncertainties, obtained for the normalized PAS mean free path \( \lambda = 2000 \) and for \(^{3}\text{He}/\text{H} = 6 \times 10^{-5}\) (see text).

Figure 4: Regions of 68.3% (1σ) and 90% confidence levels for the two free parameters \( \lambda \) and \(^{3}\text{He}/\text{H}\). Also shown is the estimated solar \(^{3}\text{He}\) abundance obtained by multiplying the \(^{4}\text{He}/\text{H}\) ratio measured from heliosismology with the \(^{3}\text{He}/^{4}\text{He}\) ratio as determined for Jupiter’s atmosphere.

Acknowledgments

This work is based on observations with INTEGRAL, an ESA project with instruments and science data centre funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain), Czech Republic, Poland, Russia and the USA. We acknowledge A. Bykov for permission to use the data prior to their public release.

References

1. G. Vedrenne et al., *A&A* **411**, L63 (2003).
2. R. Ramaty, N. Mandzhavidze and B. Kozlovsky in *AIP Conf. Proc.* 374, *High Energy Solar Physics*, ed. R. Ramaty et al., (New York: AIP, 1996), 172.
3. D. Smith et al., *ApJ* **595**, L81 (2003).
4. M. Gros et al. in *Proc. of the 5th INTEGRAL Workshop, The INTEGRAL Universe*, ESA Publication SP-552, 669 (2004).
5. K. Lodders, *ApJ* **591**, 1220 (2003).
6. D. V. Reames, *Space Sc. Rev.* **90**, 413 (1999).
7. X.-M. Hua et al., *ApJS* **140**, 563 (2002).
8. B. Kozlovsky, R. J. Murphy and R. Ramaty, *ApJS* **141**, 523 (2002).
9. V. Tatischeff *et al.*, in preparation.
10. R. J. Murphy *et al.*, *ApJ* **595**, L93 (2003).