HIGH RESOLUTION GAMMA LINE SPECTROSCOPY OF FLARES ON THE EAST AND WEST LIMBS OF THE SUN

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ABSTRACT

We present measurements in two flares of the energies of the de-excitation lines of ^{12}C and ^{16}O at 4.4 and 6.1 MeV by the Ge spectrometer SPI on board INTEGRAL, from which Doppler shifts are derived and compared with those expected from the recoil of ^{12}C and ^{16}O nuclei impacted by accelerated ions. An anomalous recoil Doppler measurement reported by *RHESSI* in a flare near the east limb has been explained by a tilt of the magnetic field lines at the footpoint of a magnetic loop away from the vertical, and towards the observer. This might imply a significant difference between the Doppler shifts on the east and west limbs. SPI observed both east and west limb flares and found no significant difference in Doppler shifts. The shapes of these lines, and their fluence ratio to the 2.2 MeV neutron capture line, when analysed using thick-target models parametrized by solar physical and geometric quantities, suggest that both flares studied here may also have magnetic fields tilted towards the observer.

1. INTRODUCTION

We start by using a simple picture of the origin of high-energy emissions from solar flares, where a magnetic loop rising from the solar surface undergoes a rapid energy release which accelerates ions and electrons. These are trapped in the loop and eventually encounter the dense solar surface material in its footpoints, with which they undergo nuclear reactions generating secondary particles and γ-ray lines from the de-excitation of the impacted nuclei.

The accelerated particles impart a recoil velocity to the impacted nuclei, giving rise to a Doppler shift of the γ-ray lines. If they are travelling in a generally downward direction in the loop this shift will be a function of heliocentric angle θ. In the simple loop picture, where the field lines are perpendicular to the surface at the footpoints, it will in general be red. At the centre of the disk the recoils are directly away from Earth and the red-shift is maximal, decreasing as θ increases towards the limb, becoming tangential (zero red-shift) at the limb.

Early measurements of γ-ray line shifts by *SMM* [8] agreed qualitatively with this picture. Recent measurements by *RHESSI* disagree with it in at least one case. The 2002 July 23 flare ($\theta = 73°$) lines had an anomalously large redshift, which [9] explained in terms of the loop model: if the field lines do not emerge vertically from the surface but are directed towards Earth, the accelerated particles moving downwards along them impel the recoils away from Earth.

Simple approximations from the loop paradigm imply that flares on opposite limbs of the Sun should have different Doppler line shifts (§3.1); the anomalous red-shift on 2002 July 23 was near the east limb, leading us to expect blue shifts in west limb flares.[1] We report here SPI observations of two flares, one on each limb, concentrating particularly on the line Doppler shifts. Measurements of other nuclear line properties are of low accuracy, since the flares had low count rates in SPI. However it is possible to obtain information on the same phenomenon of tilting of magnetic field lines in these two flares (§§3.2, 3.3).

2. OBSERVATIONS, ANALYSIS AND RESULTS

If SPI's pointing direction is the spacecraft $+x$ axis, constraints on the solar panels ($\pm y$ axis) and shadowing by IBIS ($+z$ axis) mean that SPI never observes the Sun directly; it is typically to the rear of the instrument, somewhere in the $(-x, +z)$ plane. Solar γ-rays must pass through the massive BGO shield, which is 5 cm thick and an efficient absorber toward

[1] A good analogy is the $preceding - following$ asymmetry of sunspot polarities: in an idealised picture, the preceding pole (N or S according to hemisphere and sunspot cycle) is always closer to Earth in regions coming into view round the east limb, but it disappears first in those going round the west limb, leaving the following polarity (S or N) closer to Earth.

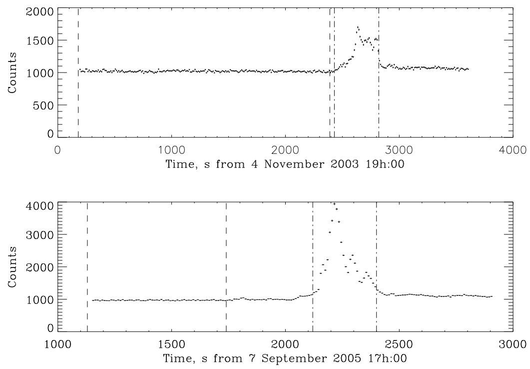

Figure 1. Count rate in the detectors during the two flares. Dashed lines — time intervals during which background rates were accumulated before the flare. Dot-dashed lines — time intervals of the flares.

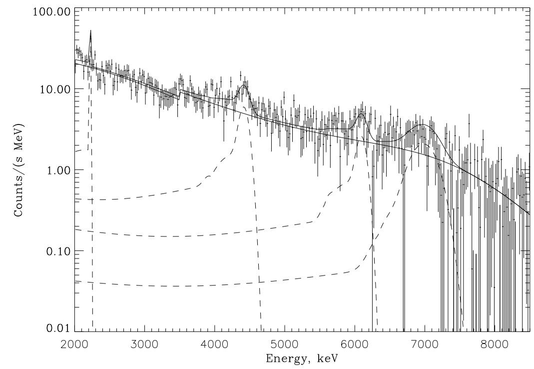

Figure 2. Background-subtracted spectrum of the 4/11/2003 flare. Dashed lines — γ-ray lines from neutron capture and ^{12}C and ^{16}O de-excitation. Full lines — (lower) continuum, (upper) line plus continuum.

the side and rear directions. This represents a considerable loss of efficiency to the Ge detectors when detecting solar flare photons.

The two limb flares analyzed here occurred on 2003 4 November (S19W83) and on 2005 7 September (S06E89). The former was spawned by the same active region as the strong flare of 2003 28 October, results from which have been published already [3]. The aspect of the Sun was similar on 4/11/2003 to that on 28/10/2003. During the 7/9/2005 flare the Sun was close to the z-axis. For background subtraction we defined periods of flare activity and preceding background periods when the Sun was assumed to be quiescent (Fig. 1). For the 7/9/2005 event we took into account the loss of 2 of the 19 detectors during 2004.

Our analysis was essentially that of [3]. From event-by-event detector-by-detector data files, we accumulated spectra of the background and flare periods over 10 s intervals. The events were binned into energy intervals of either 1 keV or 20 keV. These spectra were corrected for dead time and energy-calibrated using instrumental lines at known energies. The background subtraction was performed by measuring the ratios of the intensities of instrumental lines during the background periods to those in the flaring periods. The background-subtracted flare spectra (Fig. 2) were fitted by spectral models consisting of two continuum components and five lines at 2223, 4438, 6129, 6916 and 7115 keV. We used analytic approximations to two known flare continuum components: a steep underlying electron-bremsstrahlung spectrum and a flat component at 2–7.5 MeV due to nuclear reactions involving accelerated heavy ions. The line models included pair production and escape and Compton scattering in the BGO absorber and (for the 2223 keV line) in the Sun. The two lines around 7 MeV were fixed in an amplitude ratio of 1:1 and in relative position.

Our results are given in Table 1. The closeness of the neutron capture line energy to its rest energy (2223 keV) suggests that our energy calibration is valid, since neutrons must thermalize before capture and will not cause any recoil.

3. DISCUSSION

3.1. Line energies and Doppler shifts

The 4438 and 6129 keV line energies in Table 1 are compared with previous results [4] and with the expectations of recoil theory in Fig. 3. The trend which would be expected in this diagram according to the recoil model follows from a very simple treatment of the component of the recoil velocity in the direction towards or away from Earth: $-V cos\theta$ at heliocentric angle θ, assuming a downward pencil beam geometry. The recoil velocity V is then $V \cong \frac{v}{1+\frac{M}{m}}$, where v is the incoming proton velocity, m its mass and M the ion's mass. In the more realistic case of an isotropic beam in the downward hemisphere [7] the same naive treatment yields $V \cong \frac{\frac{1}{2}v}{1+\frac{M}{m}}$, which is shown in Fig. 3 (dash line) for accelerated 10 MeV protons.

The *SMM* measurements follow a trend which agrees qualitatively with the dashed line. The *RHESSI* measurements, however, suggest a constant redshift as a function of θ. In particular the *RHESSI* point at cosθ=0.29 has too large a redshift to be brought into agreement with either the *SMM* trend or the dashed line. Reference [9] therefore suggested that the accelerated ions were beamed in a downward direction in this flare, but the magnetic field was tilted by an angle $\sim 50°$ to the surface, instead of 90°. In terms of the naive recoil model above, when the magnetic field is tilted the redshift $-V cos\theta$ is replaced by

Table 1. Line results (amplitudes in counts s^{-1}, other values in keV)

Line rest		2003 Nov 4 $\theta = 85°$ W			2005 Sep 7 $\theta = 89°$ E	
	Amplitude	Energy	Width	Amplitude	Energy	Width
2223.2	0.44 ±0.09	2224.2±0.3	4.0±1.9	0.26±0.12	2223.5±0.8	3.7±1.8
4438	$0.92^{-0.18}_{+0.28}$	4423^{-13}_{+15}	161^{-29}_{+40}	1.42±0.36	4432^{-11}_{+13}	132^{-38}_{+46}
6128	$0.39^{-0.11}_{+0.16}$	6101±20	161^{-48}_{+50}	$0.83^{-0.14}_{+0.18}$	6076±34	239^{-32}_{+36}
6916	0.20±0.10	6894±22	124±65	0.36±0.14	6817±31	155±50

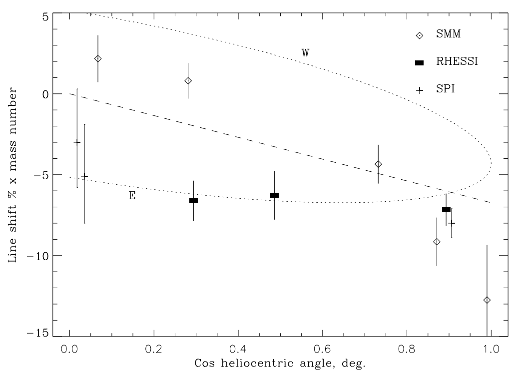

Figure 3. Mean Doppler shifts of ^{12}C and ^{16}O line energies multiplied by atomic mass of recoiling nucleus. Dashed line — expected Doppler shift from simple model of 10 MeV protons incident on ambient solar atmosphere nuclei in a downward isotropic beam. Dotted lines — expected shifts if the protons are incident along magnetic field lines tilted at 50° to the horizontal. Shifts follow the branches labelled "E" and "W" to the east and west of disk centre.

$-V sin(\theta + \phi)$ where ϕ is the angle between the field at the footpoint and the solar surface. This function is double-valued, corresponding to values of θ to the east and west of centre, splitting the dashed recoil line into two branches (dotted lines). The difference between the branches is greatest at the limbs, where the west limb ought to exhibit a substantial blue shift. Our measurements of the two limb flares however show no evidence for any difference between them. Our west limb point lies $\cong 3\sigma$ away from the blueshift which the simple model predicts. We conclude that the tilts of magnetic loop structures do not show a simple preceding-following pattern.

Our limb flare measurements lie in between the trends visible in the *SMM* and *RHESSI* data in Fig. 3. The SPI measurements are consistent with a redshift trend proportional to cosθ, as in the naive recoil model, but with a smaller slope than that shown by the *SMM* data. Due to the large error bars, they are also consistent with the suggestion in the *RHESSI* data of a constant redshift as a function of θ.

3.2. Line widths and shapes

The line shapes depend on multiple parameters of the incident beam, the ambient gas and the viewing geometry, which we analyzed using a thick-target interaction model [2]. We treated four of these parameters in detail — the beam geometry (downward pencil beam with variable opening angle, isotropic in the downward hemisphere, fan beam or a beam undergoing intense pitch angle scattering ($\lambda = 30$[1])) α/p ratio, power law spectral index s of the accelerated particles, and an "effective" heliocentric angle θ. The true heliocentric angle of these flares is known to be very close to 90°; however, were we to find our data better fitted by a different value, this would most easily be explained by a tilting of the field lines at the base of the loop. The lines and continuum were fitted separately, the continuum between 3.5–7 MeV being approximated by a power law.

Results for the α/p ratio in the 4/11/2003 flare are shown in Fig. 5; it is constrained only to be > 0.07 at the 2σ level Similarly we found the particle power law index could only be constrained to $s > 2.0$ in this flare. However Fig. 5 indicates an effective heliocentric angle $\theta = 60^{-19}_{+17}$, clearly not compatible with the known heliocentric angle 85° at about the 2σ level. For the 7/9/2005 flare the same is true at about the 1σ level ($\theta = 75^{-18}_{+19}$). The implication is that the magnetic field lines in the flare footpoints may be tilted, with angles of tilt $\phi \simeq 60°$–75° which are less than the 50° found by [9]. They are well within the error bars of the two points for these flares in Fig. 3. Thus our direct measurements of the tilt of the magnetic field lines support its existence at the 1σ–2σ level.

3.3. Line fluence ratios

The 2.223 MeV line amplitudes in Table 1 are much smaller than those typically seen in flares. The reason is that the neutrons traverse a considerable thickness of matter before being captured by the ambient H. The resulting photons are absorbed by Compton scattering on their way out to the surface. We measured the ratio of the fluences in the 2223 keV line to the sum of the ^{12}C and ^{16}O de-excitation lines, finding values for (2223 keV)/(4438 keV + 6129 keV) of

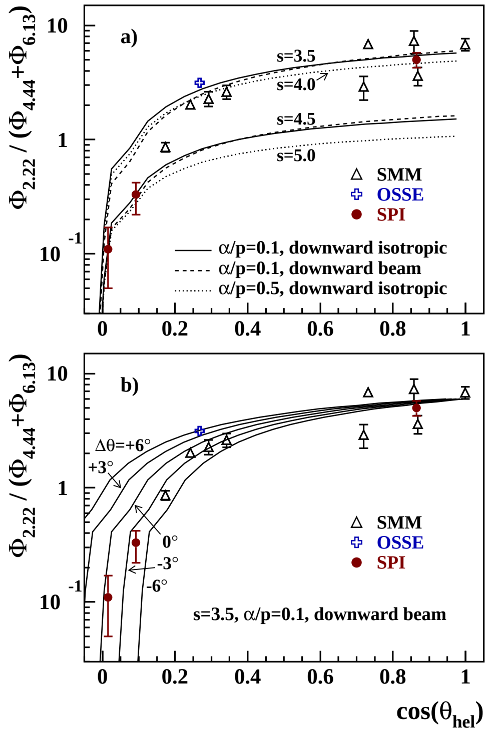

Figure 4. Ratio of 2.223 MeV line fluence to the 4.44+6.13 MeV line fluences as a function of cosθ. (a) Calculated ratios for various accelerated ion parameters. (b) Calculated ratios for shifts in heliocentric angle of 0, ±3° and ±6° to simulate a tilt of the magnetic field lines at the base of the loop. Parameters: s=3.5, α/p=0.1 and a pencil beam downward distribution.

$0.33^{-0.11}_{+0.09}$ for the 4/11/2003 flare, and 0.11 ± 0.06 for the 7/9/2005 flare (for the 28/10/2003 flare see [3]).

These ratios measured by SPI are shown in Fig. 4, together with the ratios measured with SMM for nine flares at heliocentric angles less than 80° [6] and the ratio measured with OSSE for the 1991 June 4 flare [5], and the theoretical predictions of a thick-target model incorporating the power law spectral index, α/p ratio and the angular distribution of the accelerated particles in the ion beam. The fluence ratios decrease with increasing θ due to Compton attenuation of the 2.223 MeV line. We see in Fig 4a that the theoretical curves for s=3.5 and α/p=0.1, and for s=4 and α/p=0.5 explain the data well for most flares. However, both the 1982 December 7 flare at θ=80° and our 4/11/2003 flare (θ=85°) fall significantly below these three curves. It is possible that the accelerated particle spectrum was softer in these two flares than in the general case (see Fig. 4a). But it is also possible that the low fluence ratios of these two events are due to an inclination of the magnetic loops that would lead to an increase of the 2223 keV line attenuation.

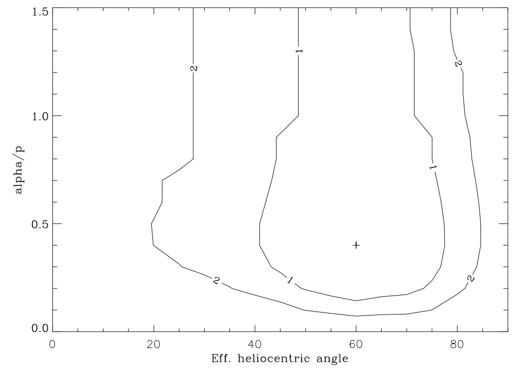

Figure 5. Best values of α/p and effective heliocentric angle for the 4/11/2003 flare (cross), with 1σ and 2σ contours. A downward isotropic beam with particle power law index $s = 3.5$ is assumed.

To simulate the expected effect of an inclination of the loop magnetic field on the 2223 keV line emission, we simply replaced the true θ by $\theta + \Delta\theta$, in such a way that positive/negative values of $\Delta\theta$ would correspond to a tilt of the magnetic loop away from/toward the observer. The results (Fig. 4b) suggest that the two limb flares observed with SPI may be tilted toward us and that the angle of tilt of the 4/11/2003 flare is larger that that of the 7/9/2005 flare, which agrees qualitatively with the conclusions of the line shape analysis (§3.2).

We arrive at the rather uncomfortable conclusion that all three of the tilts in the magnetic field lines deduced from flare γ-ray spectra are in the direction towards us. No blue shift such as would be expected from this scenario has yet been seen.

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