Solar Gamma-ray Lines at High Resolution with *RHESSI*

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Abstract

For the first time, gamma-ray lines from nuclear de-excitation in a solar flare have been resolved by an instrument with high energy resolution. The lines were observed by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) during an X4.8 solar flare on 23 June 2002. The lines show a surprisingly high degree of redshift considering the flare's position near the solar limb.

1. Introduction

Protons, alpha particles and heavy nuclei accelerated to energies of $\sim$ 1–100 keV in solar flares collide with ambient nuclei, creating short-lived excited nuclear states. These rapidly emit gamma-rays as they drop to the ground state. These gamma-ray lines are our only direct probe of ion acceleration and interactions in flares; many of the solar energetic ions detected in interplanetary space may be accelerated in processes taking place high in the corona, e.g. through interacting CMEs, rather than in a flare.

Each line is characteristic of particular ambient elements, so their relative intensities constrain the composition of the interaction region. Protons and alpha particles stimulate different lines with different efficiencies (some lines require alpha particles) and different lines also require different minimum ion energies. Thus the line ratios can also simultaneously constrain the spectrum and composition of the accelerated particles. These effects can be separated from the effect of the ambient composition if fluxes for enough different lines are detected.

Most of the excited nuclear states decay so quickly that the nucleus still

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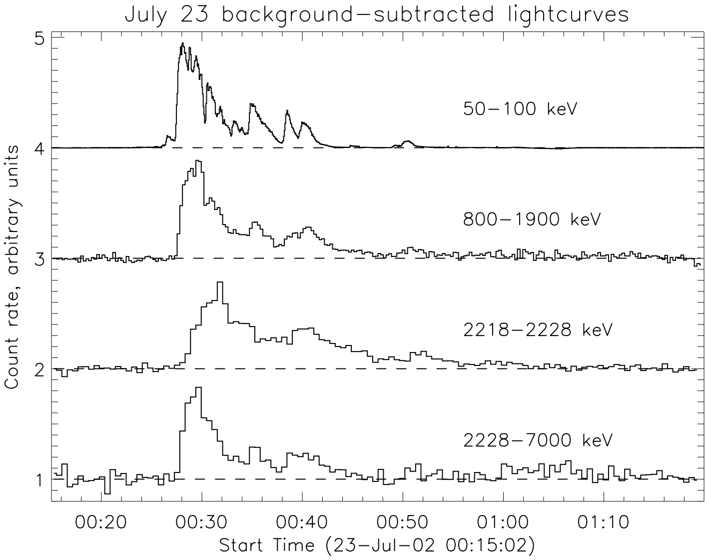

Fig. 1. Time profiles of the June 23, 2002 flare in four energy bands. Top panel: hard x-rays from electron bremsstrahlung. Second and fourth panels: energy ranges dominated by de-excitation lines. Third panel: the neutron-capture line (note the delay in the peak due to the neutron thermalization time).

has the recoil velocity it acquired during the exciting collision. Thus the angular distribution of the interacting ions is preserved in the Doppler profile of each gamma-ray line. Until now, all solar gamma-ray observations have been made with scintillation detectors with moderate energy resolution (FWHM no better than ∼4% of the line energy). Even the most sensitive flare spectrometer, the Gamma-Ray Spectrometer on the Solar Maximum Mission (SMM/GRS), has barely been able to constrain the Doppler widths and net redshifts of lines from flares, and only by combining many flares at once [1].

2. Observations and Discussion

The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) [2] was designed with detectors made from cryogenically-cooled ultrapure germanium, which have an energy resolution averaging around 0.2% FWHM in the range where gamma-ray lines appear (approximately 300 keV to 7 MeV) [3]. RHESSI, a NASA Small Explorer mission, was launched into low-Earth orbit on February 5, 2002.

On June 23, 2002, RHESSI observed an X4.8-class flare, the most energetic seen between its launch and the time of this writing. Nuclear de-excitation lines from C, O, Fe, Mg, Ne, Si, and possibly Al were observed, in addition to lines from positron annihilation (511 keV) and capture of thermalized neutrons on protons (2.223 MeV). Figure 1 shows the time profile of the flare in four energy bands, all

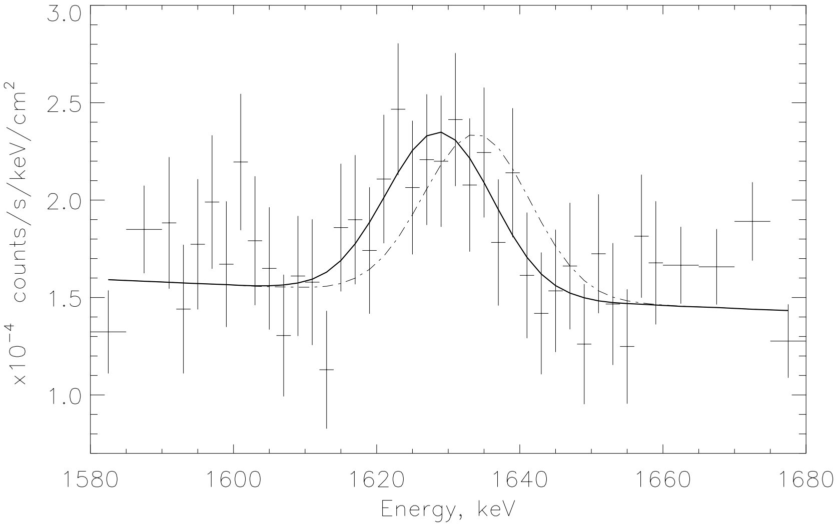

Fig. 2. The Ne de-excitation line from the flare of June 23, 2002.

but the lowest of which are dominated by emission related to ion acceleration.

Figure 2 shows the de-excitation line from Ne, integrated from 00:27:20 UT to 00:43:20 UT. The solid line is the best fit of a Gaussian to the data; the dashed line is the same Gaussian shifted until it is centered on rest energy of the line. A redshift of several keV is clearly required. The energy resolution (FWHM) of the instrument is about the width of a single data point in this plot, so Doppler broadening is even more clearly required.

Figure 3 shows the redshift and Doppler broadening of the most significantly detected lines, plotted vs. the inverse of the nuclear mass. The increasing trend is expected, since lighter nuclei will recoil at higher velocity. What makes this result unexpected is that the flare occurred close to the solar limb, at a heliocentric angle of 73°. For a flare loop exactly at the solar limb, minimal redshift would be expected even if the interacting ions were beamed directly down the field into the solar surface. For broader, more realistic distributions of ions, significant redshifts would only be expected for flares close to the center of the solar disk.

The only previous redshift/broadening results are for an ensemble of flares observed by SMM/GRS [1]. Shown in Figure 3 for comparison are their results for five flares which were near the heliocentric angle of the June 23 event. High energy resolution allows us to measure these parameters for more lines in a single flare than SMM/GRS could constrain for the ensemble.

The high redshifts in this flare are probably due to a tilt of the magnetic loop in which the ions interact toward the solar surface, so that the magnetic field at the footpoints is aligned more closely to the line of sight than would be the case

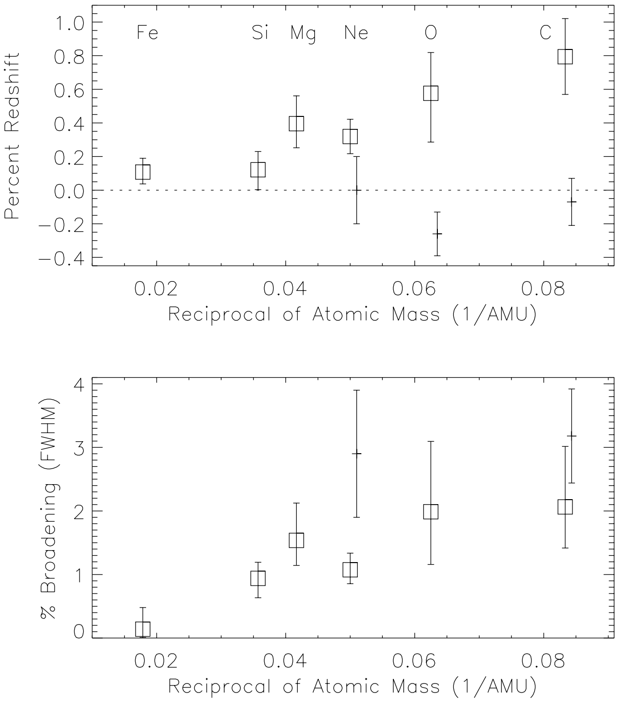

Fig. 3. Top: redshifts of de-excitation lines as a function of nuclear mass. Bottom: Doppler broadening. Data points marked by squares are from the RHESSI flare of June 23, 2002; points marked with dashes are from the combination of 5 flares observed by SMM/GRS.

if the field were perpendicular to the Sun. Bulk motion of the ambient medium away from us would give a redshift but would not reproduce the dependence on mass in Figure 3. Beaming of the interacting ions directly along the magnetic field would maximize the amount of redshift that could be produced without any tilt, but not enough to explain the data. Also, highly beamed angular distributions are inconsistent with other kinds of gamma-ray evidence from this flare and others [4,5,6].

3. References

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