RHESSI Observation of the Solar Annihilation Line

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Abstract

RHESSI has observed the positron-electron annihilation line at 511 keV produced during the 2002 July 23 solar flare. The shape of the line is consistent with formation of positronium by charge exchange in flight with hydrogen in a quiet solar atmosphere at a temperature of $\sim$ 6000 K. However, the measured upper limit to the $3\gamma/2\gamma$ ratio (ratio of annihilation photons in the positronium continuum to the number in the line) is only marginally consistent with what is calculated for this environment. The annihilation line can also be fit by a thermal Gaussian having a width of 8.1 ± 1.1 keV (FWHM), indicating temperatures of $\sim 4 - 7 \times 10^5$ K. This would require the formation of a substantial mass of atmosphere at transition-region temperatures during the flare.

1. Introduction and Observations

Flare-accelerated protons, α-particles, and heavier ions interact with the solar atmosphere and produce radioactive nuclei that decay with the release of a positron [1]. The positrons slow down by coulomb interactions and directly annihilate with electrons or form positronium by attaching to an electron [2]. Positronium is formed in either the singlet or triplet spin state. Both direct annihilation or annihilation from the singlet state give rise to two 511 keV photons. When annihilation takes place from the triplet state three photons are emitted with varying energies, producing a continuum. The number of photons observed in this continuum divided by the number of photons in the line is known as the $3\gamma/2\gamma$ ratio. The temperature, density, and composition of the ambient medium where the positrons slow down, form positronium, and annihilate, determine the $3\gamma/2\gamma$ ratio, line width, and time profile of the radiation [2].

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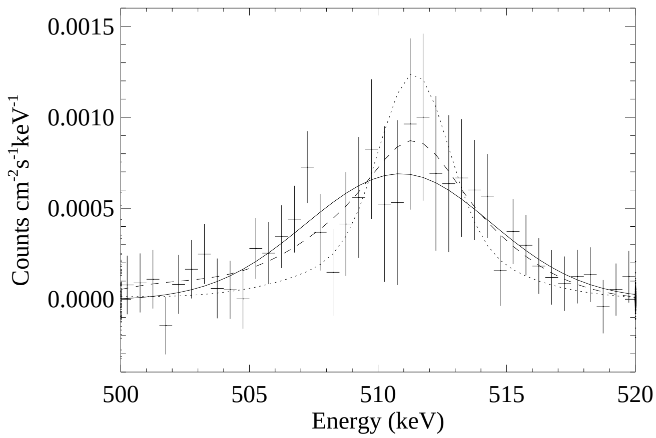

Fig. 1. Spectrum of the solar 511-keV annihilation line derived by subtracting the instrumental and background components from the total spectrum observed during the flare. Solid curve, best-fitting Gaussian; dashed curve, line-shape expected at 6000 K; dotted curve, line-share expected at 5000 K.

(*RHESSI*), $\geq$ 2 keV line widths can now be measured [3]. In this paper we summarize *RHESSI*'s observation of annihilation radiation from the 2002 July 23 X4.8 class flare (AR0039; S13E72)[4]. We accumulated 960 s of spectral data from 00:27:20 to 00:43:20 UT and estimated the background during the flare using comparable spectral accumulations on the previous and subsequent days ($\pm$ 15 orbits). We then constructed a model solar photon spectrum, passed it through the instrument response function, and fit the background-corrected data from 150 to 8500 keV. This model spectrum included a double power law, a nuclear de-excitation line function made up of 15 narrow and broad Gaussians, the neutron-capture line, the α-^{4}He fusion line complex between ~400 - 500 keV, and the solar annihilation line and its positronium continuum. In Figure 1 we plot the solar annihilation-line spectrum after subtracting all locally-produced components from the background-subtracted spectrum. The line is significantly broader than the ~2.5 keV widths of the locally-produced or background annihilation lines; it is fit best by an 8.1 $\pm$ 1.1 keV (FWHM) Gaussian (solid curve). Its time profile is well fit using the nuclear de-excitation lines as a proxy for the accelerated-particle interaction rate at the Sun, if one includes the life times of the flare-produced positron emitters [1].

2. Discussion

The 2002 July 23 flare was a prolific emitter of annihilation line radiation. The measured fluence over the entire flare, $\sim 83 \pm 14$ γ cm^{-2}, is higher than all but 5 of the 31 flares with annihilation radiation observed in ten years by the

SMM spectrometer.

In a neutral or partially ionized environment between 5000 K and 7000 K, the annihilation line is made up of narrow and broad components. The narrow $\sim$ 1.5 keV (FWHM) line is produced by annihilation of thermalized positrons with bound electrons. The broad component results from positronium formed via charge exchange in flight [5]. We have calculated its width using updated charge-exchange cross sections and obtain a width of 7.5 $\pm$ 0.5 keV for conditions at the Sun. There is a narrow range of temperatures, 5650 to 6270 K (90% confidence level), in the quiet solar atmosphere where the broad component can dominate and produce a shape (dashed curve in Figure 1) that fits the *RHESSI* spectra almost as well as a Gaussian (solid curve). In contrast, a line produced at 5000 K (dotted curve) is considerably narrower and has only a 1% probability ($\Delta\chi^2 =$ 6.7) of fitting as well as the 8.1-keV Gaussian.

Radioactive nuclei have the same depth distribution of γ rays and neutrons resulting from interactions with flare-accelerated protons and α-particles that peak at $\sim 10^{15}$ H cm^{-3} [6]. The fate of the emitted positrons depends on their energy and emission angle. One needs to explain how the positrons can slow down and annihilate at the relatively low densities of 2×10^{12} to 8×10^{13} H cm^{-3} corresponding to the temperature range deduced above for a quiet atmosphere. Higher densities, $\sim 3 \times 10^{15}$ H cm^{-3}, can occur in a flaring atmosphere [7] at 6000 K. However, our calculations from 5000 to 8500 K for this flaring atmosphere indicate that the broad line from charge-exchange in flight is never dominant enough to fit the *RHESSI* line shape. In the quiet atmosphere, where the broad line dominates, these calculations also require $3\gamma/2\gamma$ ratios > 2.7; the *RHESSI* upper limit on the flux in the positronium continuum is only consistent with this ratio with <4% confidence. The *SMM* Gamma Ray Spectrometer made measurements of the annihilation line and continuum in seven flares [8]; all the *SMM* measurements are consistent with the *RHESSI* line width. However, only two of the seven have $3\gamma/2\gamma$ ratios consistent with values > 2.7 expected if the annihilation line originates in a quiet solar atmosphere at a temperature of 6000 K. Thus, most of the *SMM* measurements are inconsistent with an annihilation line that is dominated by positronium formation via charge-exchange in flight.

If the broad line observed by *RHESSI* is formed in a warm or hot ionized medium, the best fitting Gaussian width of 8.1 $\pm$ 1.1 keV (FWHM) suggests temperatures ranging from $\sim 4 - 7 \times 10^5$K [2]. *RHESSI* and *SMM* line-width and positronium-continuum measurements are plotted in Figure 2. The *RHESSI* observation and all but perhaps two of the *SMM* measurements are consistent with densities $< 10^{12}$ H cm^{-3} that are necessary to be consistent with models of quiet or flaring atmospheres at temperatures $\geq 10^5$ K. But if the positrons are produced at densities $\geq 10^{14}$ H cm^{-3}, how do they slow down and annihilate at such low densities? Alternatively, all the observations are consistent with densities $\geq 10^{12}$

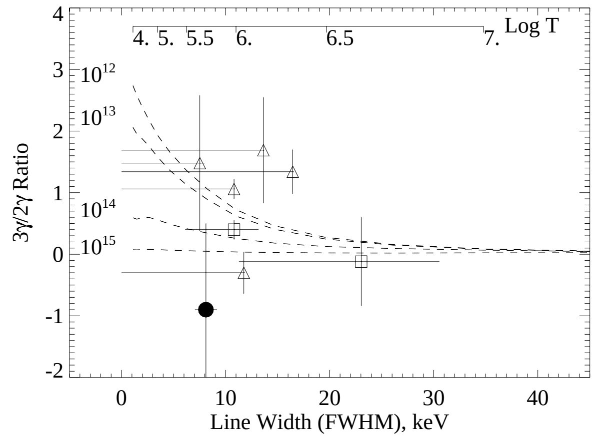

Fig. 2. Comparison of *RHESSI* (filled circle) and SMM measurements of the $3\gamma/2\gamma$ ratio versus 511 keV line width and temperature for a fully ionized medium. Triangles represent *SMM* 1σ upper limits on line width. The curves show the calculated $3\gamma/2\gamma$ ratio vs 511 keV width (temperature) for different densities.

H cm^{-3}. Such densities require formation of a substantial mass of atmosphere at transition-region temperatures during flares. There is some evidence for high temperatures at high densities in the dramatic enhancement over quiet Sun values of C IV and Si IV line emission in the transition region [9].

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