THE ASTROPHYSICAL JOURNAL, 595:L85–L88, 2003 October 1

HIGH-RESOLUTION OBSERVATION OF THE SOLAR POSITRON-ELECTRON ANNIHILATION LINE

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Received 2003 March 26; accepted 2003 April 29; published 2003 September 8

ABSTRACT

The *Reuven Ramaty High Energy Solar Spectroscopic Imager* (*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 annihilation in two vastly different solar environments. It can be produced by formation of positronium by charge exchange in flight with hydrogen in a quiet solar atmosphere at a temperature of ~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 fitted by a thermal Gaussian having a width of 8.1 ± 1.1 keV (FWHM), indicating temperatures of $\sim(4–7) \times 10^5$ K. The measured $3\gamma/2\gamma$ ratio does not constrain the density when the annihilation takes place in such an ionized medium, although the density must be high enough to slow down the positrons. This would require the formation of a substantial mass of atmosphere at transition-region temperatures during the flare.

Subject headings: Sun: flares — Sun: particle emission — Sun: X-rays, gamma rays

1. INTRODUCTION

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 (Kozlovsky, Lingenfelter, & Ramaty 1987). Positrons are also produced in decay of positively charged pions created in flares with accelerated protons ≥200 MeV (Murphy, Dermer, & Ramaty 1987). The positrons slow down by coulomb interactions and directly annihilate with electrons or form positronium by attaching to an electron. Positronium is formed in either the singlet or the triplet spin state. Both direct annihilation and 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. There are several different reactions that contribute to the formation of positronium (Crannell et al. 1976). At temperatures $\geq 10^4$ K, positronium begins to break up via ionization or charge exchange. Transition from the triplet to the singlet state at densities $\geq 10^{12}$ H cm^{-3} (ionized) or $\geq 10^{14}$ H cm^{-3} (neutral) reduces the continuum significantly.

Annihilation radiation measurements in flares have been made by moderate resolution spectrometers on *OSO 7*, the *Solar Maximum Mission* (*SMM*), *Yohkoh,* and the *Compton Gamma Ray Observatory*. The gamma-ray spectrometer on *SMM* made the most extensive solar observations but could only measure line widths ≥10 keV (FWHM). With the launch of the *Reuven Ramaty High Energy Spectroscopic Imager* (*RHESSI*), ≥2 keV line widths can now be measured. Lin et al. (2002) describe the overall *RHESSI* instrument and Smith et al. (2002) discuss the spectrometer and its performance in orbit. In this Letter, we describe *RHESSI*'s observation of annihilation radiation from the 2002 July 23 solar flare.

2. OBSERVATIONS

Soft X-ray emission from the X4.8-class flare (NOAA Active Region 0039; S13°, E72°) on 2002 July 23 was observed by *GOES* beginning at 00:18 UT and peaking at 00:34 UT. *RHESSI* observed the flare until about 01:16 UT when it was occulted by the Earth. Plotted in the top panel of Figure 1 is the *RHESSI* hard X-ray time profile observed at 150 keV covering the impulsive phase of the flare. We accumulated 960 s of spectral data in the time interval defined by the dashed lines to study the solar annihilation line from 00:27:20 to 00:43:20 UT.

There is a strong annihilation line in the background spectrum that comes from radioactive nuclei and electromagnetic showers produced in the detector and spacecraft by radiation-belt protons and cosmic rays, and from the Earth's atmosphere (Share et al. 2002). We estimated the background during the flare using 960 s spectral accumulations on the previous and subsequent days (±15 orbits) when the satellite passed over similar geographic locations. In Figure 2 we plot the flare-count spectrum observed between 500 and 520 keV, after background subtraction. The fluence in the background-subtracted 511 keV line was ~15% of the fluence in the background line.

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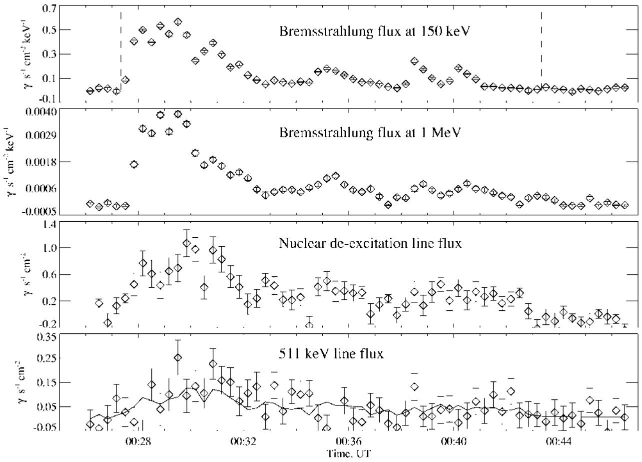

FIG. 1.—Time histories of the solar bremsstrahlung, nuclear de-excitation lines, and 511 keV annihilation line during the 2002 July 23 flare observed by *RHESSI* at 20 s resolution. The dashed lines indicate the time interval from 00:27:20 to 00:43:20 UT used for spectral studies. The solid curve shows the calculated annihilation line profile (see text).

We studied the effectiveness of our background subtraction, during orbits similar to the one in which the flare occurred, using data in the latter part of July. From this study we find that the uncertainty in the background line at the time of the flare creates a less than 15% (90% confidence) systematic error in the background-subtracted line shown in Figure 2.

Our next step was to separate the solar annihilation line from an ∼2.5 keV wide line at the same energy produced when the high-energy flare radiation interacted in the imaging grids and other passive spacecraft material above and around the detectors. The instrument response function (Smith et al. 2002) is used to calculate the strength of this locally produced annihilation line. We constructed a model solar photon spectrum, passed it through the instrument response function, and fitted the background-corrected data from 150 to 8500 keV (Lin et al. 2003). This model spectrum included a double power law, a nuclear de-excitation line function made up of 15 narrow and broad Gaussians (Smith et al. 2003), the neutron-capture line (Murphy et al. 2003), the α-^{4}He fusion line complex between ∼400 and 500 keV (Share et al. 2003), and the solar annihilation line and its positronium continuum. The results of this fit are shown in Figure 2; the dominant contributions to the locally produced line come from greater than 1 MeV solar bremsstrahlung and nuclear de-excitation radiation. The solar annihilation line is fitted best by an 8.1 ± 1.1 keV (FWHM) Gaussian (*thick solid curve*). In Table 1, we list all the parameters derived for the incident photon spectrum from our fits; the errors are statistical and were determined by mapping χ^2.

We feel confident of the solar origin of the annihilation line for two reasons. First, it is significantly broader than the ∼2.5 keV widths of the locally produced or background annihilation lines. Thus, systematic errors in the background subtraction or instrument model should not significantly affect our conclusions about the solar line (e.g., an incorrect background subtraction, using only data from July 22, increased the apparent line flux only by about 25% and decreased the line width by ∼1 keV). Second, its delayed time profile follows that calculated for a solar 511 keV line. We plot the fitted power-law fluxes at 150 and 1000 keV, the nuclear de-excitation line flux, and the solar annihilation line flux at 20 s resolution in Figure 1. From a cross-correlation analysis, we find that the 1000 keV bremsstrahlung and the nuclear de-excitation lines are delayed by at most 20 s from the 150 keV bremsstrahlung profile. In contrast, the solar 511 keV line appears to be delayed relative to the nuclear line emission (>97% confidence). Its time profile is well fitted using the nuclear de-excitation lines as a proxy for the accelerated-particle interaction rate at the Sun if one includes the less than 1 to greater than 10^4 s lifetimes of the flare-produced positron emitters (Kozlovsky et al. 1987). In this calculation, we assumed that the interacting accelerated particles had an impulsive solar energetic particle composition, an α/p ratio of 0.5, and a power-law spectrum with index 4, and that the ambient solar medium had coronal abundances with He/H = 0.1. The solid curve in Figure 1 shows the best-fitting time profile, calculated for a $3\gamma/2\gamma$ ratio = 1.9; it agrees well with the solar 511 keV line data without normalization. Thus, we feel confident that the broadened annihilation line originated at the Sun.

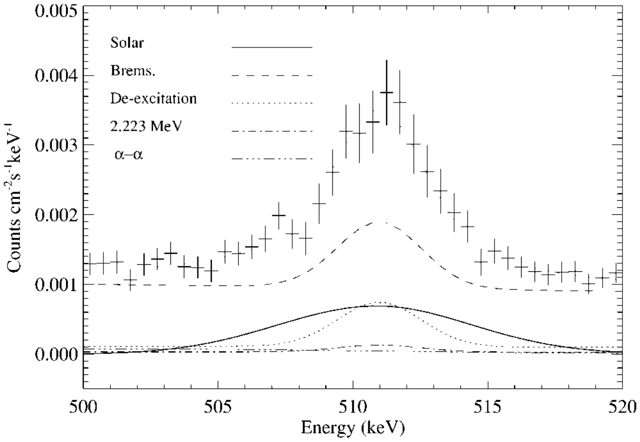

FIG. 2.—Fitted components of the 511 keV annihilation line observed during the time interval from 00:27:20 to 00:43:20 UT. The data points show the total background-corrected count spectrum and the best fit (*thin solid curve*). Instrumental contributions to the total line are plotted individually. The thick solid curve shows the Gaussian shape of the derived solar annihilation line.

3. DISCUSSION

The 2002 July 23 flare was a prolific emitter of annihilation line radiation. The measured fluence over the entire flare was ∼83 ± 14γ cm^{-2}. This fluence is higher than all but five of the 31 flares with annihilation radiation observed in 10 years by the *SMM* spectrometer (Vestrand et al. 1999). What is most important, however, is that this was the first flare for which the annihilation line may have been fully resolved. In Fig-

TABLE 1

FIT TO SOLAR SPECTRUM FROM 00:24:20 TO 00:43:20 UT

Component	Value
511 keV line energy	510.80 ± 0.45 keV
511 keV line width	8.1 ± 1.1 keV (FWHM)
511 keV line flux	0.075 ± 0.009γ cm^{-2} s^{-1}
Positronium continuum flux	−0.06 ± 0.11
$3\gamma/2\gamma$ ratio	−0.8 ± 1.5 (99% limit 3.3)
Nuclear de-excitation line flux	0.523 ± 0.023γ cm^{-2} s^{-1}
2223 MeV line flux	0.149 ± 0.004γ cm^{-2} s^{-1}
PL flux at 150 keV	0.161 ± 0.005γ cm^{-2} s^{-1} keV^{-1}
Low-energy PL index	2.92 ± 0.04
PL break energy	553^{+12}_{-35} keV
High-energy PL index	2.11 ± 0.03
α-^{4}He line flux	0.143 ± 0.032γ cm^{-2} s^{-1}

NOTE.—PL = power law.

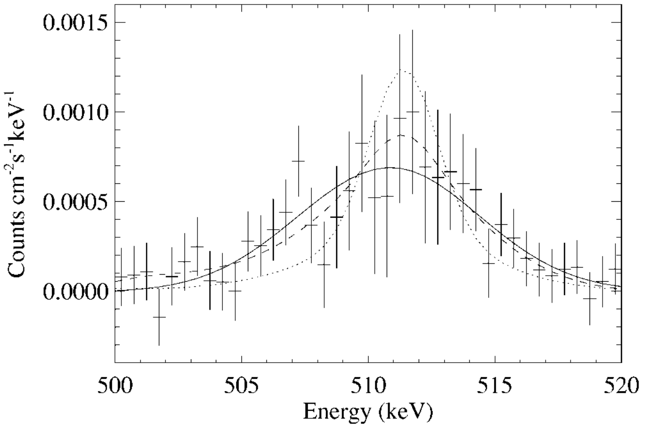

FIG. 3.—Spectrum of the solar 511 keV annihilation line derived by subtracting the instrumental and background components from the total spectrum observed during the flare. The uncertainties are too large for the scatter in the data; therefore, we use $\Delta\chi^2$ to compare the fits of different line shapes. The solid curve is the best-fitting Gaussian shown in Fig. 2. The dashed curve showing the calculated line shape formed in a quiet atmosphere at 6000 K fits the data equally well. There is only a 1% probability that the line shape at 5000 K (*dotted curve*) fits as well ($\Delta\chi^2 = 6.7$).

TABLE 2

MEASUREMENTS OF THE SOLAR ANNIHILATION LINE AND CONTINUUM

Flare	Width (FWHM) (keV)	$3\gamma/2\gamma$ Ratio
1982 Jun 3	<16.5[a]	1.34 ± 0.36
1984 Apr 24	<10.8[a]	1.06 ± 0.16
1986 Feb 6	<13.6[a]	1.69 ± 0.86
1988 Dec 16	<11.8[a]	−0.30 ± 0.34
1989 Mar 6	<7.5[a]	1.48 ± 1.10
1989 Aug 16	21 ± 10	−0.12 ± 0.72
1989 Oct 19	9.6 ± 3.5	0.4 ± 0.16
2003 Jul 23	8.1 ± 1.1	−0.9 ± 1.5

[a] *SMM* line limits are 68% confidence limits.

ure 3, we plot the broadened solar annihilation line spectrum after subtracting all the fitted locally produced components from the background-subtracted spectrum shown in Figure 2. We can conceive of two vastly different solar environments in which such a broad line would be produced: (1) a limited range of chromospheric densities and temperatures in a quiet solar atmosphere and (2) a warm or hot ionized medium.

In a neutral or partially ionized environment between 5000 and 7000 K, the annihilation line is made up of narrow and broad components. The narrow ∼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. Bussard, Ramaty, & Drachman (1979) determined that this component has an effective width of ∼6.5 keV (FWHM) in an astrophysical environment. We have calculated the width using updated charge-exchange cross sections and obtain a width of 7.5 ± 0.5 keV for conditions at the Sun. We find that there is a narrow range of temperatures, 5650–6270 K (90% confidence level), in the quiet solar atmosphere, where the broad component can dominate and produce a shape that fits the *RHESSI* spectra (Fig. 3, *dashed curve*) almost as well as a Gaussian. 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.

We have concerns about the charge-exchange origin for the solar annihilation line observed by *RHESSI*. Hua et al. (1989, 2002) have calculated the depth distribution for production of γ-rays and neutrons resulting from interactions with flare-accelerated protons and α-particles. The depth distribution peaks at $\sim 10^{15}$ H cm^{-3} for harder spectra and for angular distributions of interacting particles with a strong downward component; however, significant γ-ray production occurs at lower densities for broader angular distributions. Radioactive nuclei have the same depth distribution, and the fate of the emitted positrons depends on their energy (<2 MeV) and emission angle. For example, a 700 keV positron has a range of 0.13 g cm^{-2} in neutral hydrogen, equivalent to the amount of overlying atmosphere at a density of 5×10^{14} H cm^{-3}. Detailed calculations have not yet been made that follow these positrons in the solar atmosphere to determine where they are likely to annihilate.

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 (Machado et al. 1980) 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. These calculations also require $3\gamma/2\gamma$ ratios greater than 2.7 where the broad line dominates in the quiet atmosphere; the *RHESSI* upper limit on the flux in the positronium continuum is only consistent with this ratio with less than 4% confidence. The *SMM* gamma-ray spectrometer made measurements of the annihilation line and continuum in seven flares (Share, Murphy, & Skibo 1996; Share & Murphy 1997); we list these measurements in Table 2. Because of its moderate spectral resolution, *SMM* was able to measure the line width only at a significance greater than 1 σ in two flares; 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 greater than 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 shape is a thermally broadened Gaussian of width

$$\mathrm{FWHM} = 1.1\ \mathrm{keV}\sqrt{\frac{T}{10^4\ \mathrm{K}}} \qquad (1)$$

(Crannell et al. 1976). The best-fitting Gaussian plotted in Figure 3 (*thick solid curve*) has a width of 8.1 ± 1.1 keV (FWHM) and suggests temperatures ranging from ~ 4 to 7×10^5 K. *RHESSI* and *SMM* line width and positronium-continuum measurements are both consistent with a thermal origin in an ionized medium. This is clear from Figure 4, where we plot the measured $3\gamma/2\gamma$ ratios versus the line width and temperature; the dashed curves show the calculated relationship for densities from 10^{12} to 10^{15} H cm^{-3}. However, we also have concerns about annihilation in an ionized medium. The *RHESSI* observation and all but perhaps two of the *SMM* measurements are consistent with densities less than 10^{12} H cm^{-3}, which 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

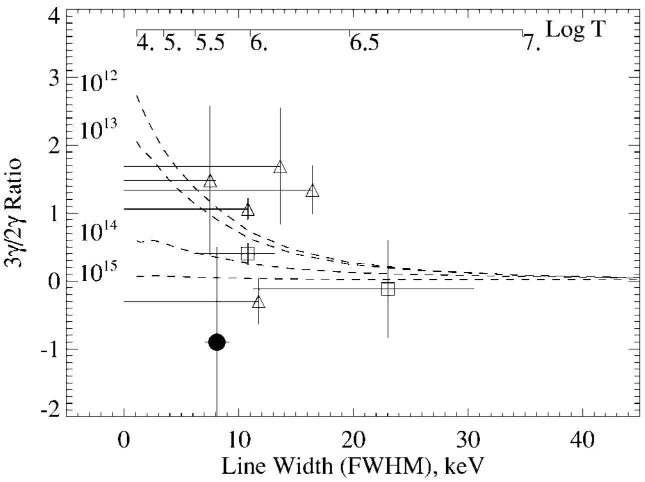

FIG. 4.—Comparison of *RHESSI* (*filled circle*) and *SMM* measurements of the $3\gamma/2\gamma$ ratio vs. 511 keV line width and temperature for a fully ionized medium. Triangles represent *SMM* 1 σ upper limits on line width. The curves show the calculated $3\gamma/2\gamma$ ratio vs. 511 keV line width (temperature) for different densities (curves for lower densities are similar to that for 10^{12}.

annihilate at such low densities? Alternatively, all the observations are consistent with densities $\geq 10^{12}$ 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 noted by Brekke et al. (1996).

With the possible exception of the 1989 October 19 flare, all of the *SMM* line measurements are consistent with a Gaussian width of ~1.5 keV (FWHM) calculated for temperatures less than 5500 K in either a quiet atmosphere (Vernazza, Avrett, & Loeser 1981) or a flaring atmosphere (Machado et al. 1980). For these temperatures we expect $3\gamma/2\gamma$ ratios less than 2.2 in a quiet atmosphere and less than 0.9 in a flaring atmosphere; the *SMM* ratios are consistent these values. Because of limited spectral resolution, the *SMM* observations cannot exclude annihilation occurring in the lower chromosphere at densities greater than 10^{14} H cm^{-3}. However, the 8.1 ± 1.1 keV line width measured by *RHESSI* appears to exclude this origin for the 2002 July 23 flare.

In conclusion, we find no single location where positron-electron annihilation takes place that both is consistent with our current understanding of the solar atmosphere and can explain all the observations. The broad solar 511 keV line observed by *RHESSI* is consistent with annihilation at ~6000 K in a quiet atmosphere (Vernazza et al. 1981), but *RHESSI*'s upper limit on the $3\gamma/2\gamma$ ratio is barely consistent with this origin (*SMM's* limits on the ratio in five of seven flares are inconsistent with annihilation at ~6000 K). A flaring model of the chromosphere (Machado et al. 1980) does not appear to produce the conditions for such a broad line. The *RHESSI* line width is also consistent with annihilation in an ionized medium between ~4 and 7 × 10^5 K. These temperatures are reached at densities $\leq 10^{12}$ H cm^{-3} for most atmospheric models; the *RHESSI* $3\gamma/2\gamma$ ratio is consistent with these densities. However, we have the vexing question of why the annihilations do not take place lower in the chromosphere at densities of 10^{14} H cm^{-3}, where the positrons are expected to be produced and where there is sufficient material to slow them down.

This work was supported NASA DPR W19746 and DPR W10049 at the NRL. The work at the UCB and NASA Goddard was supported by NASA contract NAS 5-98033. B. Kozlovsky acknowledges the Israeli Science Foundation for support. The positronium calculations used here were derived from a computer code written by Jeffrey Skibo while he was at NRL; a paper that he was preparing with coauthors Nidhal Guessoum and Reuven Ramaty has not yet been submitted for publication. We thank John Mariska for discussing evidence of high densities at transition-region temperatures during flares.

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