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SEARCHING FOR ANNIHILATION RADIATION FROM SN 1006 WITH SPI ON *INTEGRAL*

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ABSTRACT

Historical Type Ia supernovae are a leading candidate as the source of positrons observed through diffuse annihilation emission in the Galaxy. However, a search for annihilation emission from individual Type Ia supernovae was not possible before the improved sensitivity of *INTEGRAL*. The total 511 keV annihilation flux from individual SNe Ia, as well as their contribution to the overall diffuse emission, depends critically on the escape fraction of positrons produced in ^{56}Co decays. Late optical light curves suggest that this fraction may be as high as 5%. We have searched for positron annihilation radiation from the historical Type Ia supernova SN 1006 using the SPI instrument on *INTEGRAL*. We did not detect significant 511 keV line emission, with a 3 σ flux upper limit of 0.59 $\times 10^{-4}$ photons cm^{-2} s^{-1} for ~1 Ms exposure time, assuming a FWHM of 2.5 keV. This upper limit corresponds to a 7.5% escape fraction, 50% higher than the expected 5% escape scenario, and rules out the possibility that Type Ia supernovae produce all of the positrons in the Galaxy (~12% escape fraction), if the mean positron lifetime is less than 10^5 yr. Future observations with *INTEGRAL* will provide stronger limits on the escape fraction of positrons, the mean positron lifetime, and the contribution of Type Ia supernovae to the overall positron content of the Galaxy.

Subject headings: gamma rays: observations — ISM: individual (SN 1006) — supernova remnants

1. INTRODUCTION

Searching for γ-ray lines from supernovae (SNe) remains one of the primary goals of γ-ray astrophysics, and also the *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*; Winkler et al. 2003a), as γ-ray line studies can probe the nucleosynthesis and explosion kinematics of these events. Many of the nuclear decay chains (^{56}Co, ^{44}Ti) that produce γ-ray lines in young SNe also produce positrons, making them a prime candidate as the source of positrons for the diffuse Galactic annihilation emission. However, there has not been a detection of positron annihilation radiation from an individual SN or a SN remnant (SNR). The main uncertainties on the expected annihilation fluxes from young SNe are the mean lifetime and escape fraction of positrons. For Type Ia SNe, the lifetime of a positron will be small in the initial SN but may become as high as 10^4 years or more as the SN expands. The mean positron lifetime will be even longer, over 10^5 years, in cases where thermalization takes place in the interstellar medium (ISM) rather than in the ejecta (Guessoum et al. 1991). If the ejecta's magnetic field is weak or radially combed, then 95% of the ^{56}Co decay positrons annihilate promptly, and 5% escape to annihilate on a longer timescale (Chan & Lingenfelter 1993). Alternatively, a tangled and strong magnetic field would confine ~100% of the ^{56}Co positrons, resulting in prompt annihilation and leaving a much smaller annihilation radiation flux from the delayed ^{44}Ti decays ($\tau \sim 85$ yr).

Simulations of late optical *B* and *V* light curves of Type Ia SNe indicate that the 5% escape of the ^{56}Co positrons is the more probable scenario, assuming the optical light curves trace the bolometric luminosity (Milne et al. 1999). A later study also showed that 16 of 22 Type Ia SNe observed at late epochs exhibit *BVRI* light curves of the same shape as the initial sampling of 10 SNe Ia, strengthening the conclusion of a 5% escape fraction (Milne et al. 2001b). However, excess near-infrared (NIR) emission at late epochs was reported recently from SN 1998bu and SN 2000cx (Spyromilio et al. 2004; Sollerman et al. 2004). This excess may be due to emission shifting into the NIR wavelength range from the optical range. The optical-NIR bolometric light curves for those SNe favor full positron trapping. Observations of positron annihilation radiation from individual SNRs can improve our understanding of the magnetic field configurations in these objects and also determine their role in producing the diffuse Galactic annihilation emission.

The positrons are initially hot and then slow down by Coulomb losses, ionization, and excitation. Once they are cool enough (less than a few hundred eV), the positrons can undergo charge exchange with neutrals, recombine radiatively with free electrons, and/or annihilate directly with free or bound electrons, producing a line at 511 keV and a positronium continuum (Bussard et al. 1979; Guessoum et al. 2005). The fractions of photons that are emitted in the line and in the continuum depend on the properties of the annihilating medium. Recent analysis of data from SPI (the Spectrometer aboard *INTEGRAL*) yields positronium fractions close to 0.95 for the diffuse Galactic annihilation radiation (Churazov et al. 2005; Jean et al. 2006). For the width of the line, SPI finds 2.4 ± 0.3 keV FWHM, if the line is approximated as a simple Gaussian (Churazov et al. 2005).[6] Note that the positronium fraction and the FWHM values for the Galaxy are not necessarily appropriate for individual SN annihilations. The positronium fraction depends on the temperature and the ionization state of the medium (Guessoum et al. 1991; Jean et al. 2006), and the FWHM can be broadened by Doppler effects if the annihilation takes place in the ejecta.

For weak or radially combed magnetic fields that permit 5% escape, positron-transport simulations estimate that roughly 8×10^{52} positrons escape from a given Type Ia SN (Milne et al. 1999). When combined with the rate of 0.5 Type Ia SNe

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[6] Recent analysis of the SPI observations of the Galactic center region suggest that the line may be composed of both a narrow (FWHM ~ 1.3 keV) and a broad (FWHM ~ 5.1 keV) component (Jean et al. 2006).

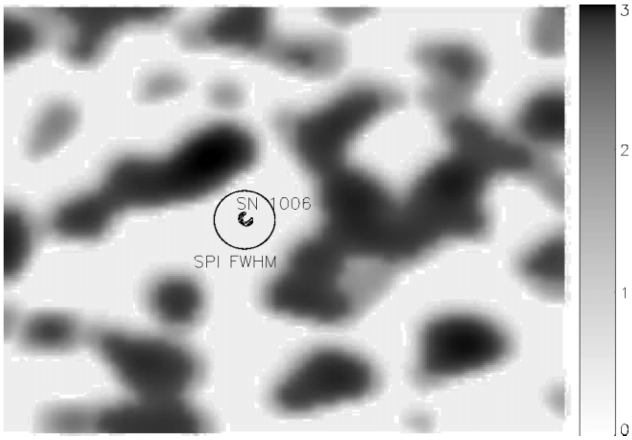

FIG. 1.—SPI significance image in the 508.5–513.5 keV band of the fully coded field of view. Contours of SN 1006 from the *Advanced Satellite for Cosmology and Astrophysics* are overlaid to indicate the extent and position of the source. The 3° FWHM of the imaging resolution of SPI is shown for comparison. The significance scale is shown at right.

per century, a steady state flux of 9×10^{-4} photons cm^{-2} s^{-1} is expected if the positrons are assumed to be annihilated at a distance of 8 kpc (the distance to the Galactic center). The latest measurements from SPI yield a total Galactic 511 keV flux of (1.5–2.9) $\times 10^{-3}$ photons cm^{-2} s^{-1} depending on the Galactic distribution model (Knödlseder et al. 2005). The higher end of that flux range is in agreement with observations of the 511 keV line emission by the Oriented Scintillation Spectrometer Experiment (OSSE) on the *Compton Gamma Ray Observatory*, the *Solar Maximum Mission*, and the Transient Gamma-Ray Spectrometer (Milne et al. 2001a). The expected flux from the 5% escape case is therefore 30%–60% of the total flux, with the higher fluxes producing the lower SN fractions. Therefore, if positrons escape the ejecta but are confined to local regions of the SNe, the 511 keV maps should trace the recent SN Ia history. The bulge-to-disk flux ratio is confined to be within the range 1–3 (and luminosity ratio of 3–9). This ratio is consistent with an absence of Galactic-scale diffusion and makes Type Ia SNe prime candidates for the source of Galactic bulge positrons, along with low-mass X-ray binaries (see Knödlseder et al. [2005] for a thorough discussion of potential candidates for diffuse annihilation radiation).

The most promising individual source candidate to search for a positron annihilation line is SN 1006, a recent SN thought to be of Type Ia. Our group observed SN 1006 with *INTEGRAL* for ∼1000 ks, with the main goals of characterizing the hard X-ray emission using the ISGRI and JEM-X instruments (Kalemci et al. 2006) and searching for the 511 keV emission line with SPI. In this Letter, we discuss the results of the analysis of the SPI data and place limits on the 511 keV line and positronium continuum emission from SN 1006.

2. OBSERVATIONS, ANALYSIS, AND RESULTS

SPI is a coded-aperture telescope using an array of 19 cooled germanium detectors for high-resolution spectroscopy (Vedrenne et al. 2003). It works in the 20 keV to 8 MeV band and has an energy resolution of ∼2 keV at 511 keV. The fully coded field of view is 16°, and the angular resolution is 3°.

The *INTEGRAL* observations of SN 1006 took place in two sets. The first, 250 ks set was conducted early in the mission, between MJD 52,650 and MJD 52,659, corresponding to *INTEGRAL* revolutions 30 and 32. These observations will be referred to as “set I.” The second, 750 ks set was conducted between MJD 53,024 and MJD 53,034 during revolutions 155–158 and will be denoted as “set II.” For SPI, set I has all 19 detectors working, whereas for set II the active detectors were reduced to 18 after the loss of detector 2.

TABLE 1
SPI UPPER LIMITS

511 keV Line FWHM (keV)	Set I (250 ks) Flux	Set II (750 ks) Flux	Combined Flux
2.5	1.15×10^{-4}	0.70×10^{-4}	0.59×10^{-4}
3.5	1.35×10^{-4}	0.81×10^{-4}	0.70×10^{-4}
5.0	1.66×10^{-4}	0.96×10^{-4}	0.83×10^{-4}
Positronium Continuum			
350–500 keV band	5.8×10^{-4}	3.4×10^{-4}	3.0×10^{-4}

NOTE.—All fluxes are 3 σ upper limits, photons cm^{-2} s^{-1}.

Before any analysis, we filtered out the pointings with high anticoincidence-shield rates, mostly occurring during the entry and exit of the radiation belts. We used OSA 4.2, SPIROS 6.1, and single-detector events for the analysis. Several background models were tried with “GEDSAT” as the main model, which assumes that the background level is proportional to the product of saturated detector trigger rate and live time. We used the continuum energy band at 523–545 keV for normalization. We tried normalization with an OFF observation (empty-field observation in revolution 130), and also using a template file (provided by J. Knödlseder). The details of the background methods and information about the template file can be found in Knödlseder et al. (2005). Finally, we tried the mean count modulation method in SPIROS, which does not require a prior background determination. The maximum likelihood method in SPIROS was used for imaging. Note that SN 1006 is ∼30′ in diameter and is effectively a point source for SPI. Sets I and II were analyzed separately. We used 5, 7, and 10 keV energy intervals encompassing 511 keV to factor in the possibilities of both narrow and broad emission. We also searched for the positronium continuum in the 200–500 keV band with SPI.

Figure 1 shows the SPIROS sigma image in the 508.5–513.5 keV energy band, using the mean count modulation method. We obtained similar images in wider energy bands, and with different background methods. We have not detected significant 511 keV line emission in any of the energy-band intervals around 511 keV. The positronium component was not detected either. Table 1 shows the details of the search and 3 σ sensitivity limits of SPI for the given energy band and observing time. The combined upper limit is for 18 detectors in sets I and II.

3. DISCUSSION

SN 1006 is an ideal candidate to search for 511 keV positron annihilation line emission, as it is a well-studied, historical Type Ia SN with relatively well determined characteristics. The distance is ∼2.2 kpc, the age is 999 yr, the angular size is ∼30′, and the ejecta’s current electron density is 0.7 cm^{-3} (Winkler et al. 2003b; Long et al. 2003; Milne 1971; Milne et al. 1999; Reynolds 1998).

Predictions of the current 511 keV line and positronium continuum fluxes from SN 1006 depend upon understanding the complicated interaction of the SN shock with the ISM and the resulting degree of magnetic confinement of positrons (Ruiz-Lapuente & Spruit 1998). Simulations have shown that positrons that escape from the SN ejecta typically have ∼500 keV of energy upon their escape (Chan & Lingenfelter 1993; Milne et al. 1999). The range of 500 keV positrons in the ISM is such that few positrons would be expected to thermalize within 1000 yr (Guessoum et al. 1991). This situation is even worse at the location of SN 1006, where the ISM density appears even lower than four media treated by Guessoum et al. (1991). Thus, if the shock fails to confine escaping positrons, perhaps even accelerating the positrons, then SN 1006 would be only a faint source of annihilation radiation, even if positrons escaped the ejecta. The primary arguments against positrons crossing the shock in this fashion are circumstantial, as the distribution of annihilation radiation from SNe would then trace the distribution of matter in the Galaxy. It has been shown that the results of diffuse 511 keV emission mapping from OSSE and SPI (Purcell et al. 1997; Milne et al. 2001b; Knödlseder et al. 2005; Teegarden et al. 2005) indicate a strong bulge component, with a bulge-to-disk luminosity ratio of 3–9. By contrast, the matter content of the Galaxy is concentrated in the disk (bulge-to-disk mass ratio of only 0.3–1.0; Robin et al. 2003), which appears to eliminate large-scale positron transport from source to annihilation site (not just from SNe, but in general).

If the magnetic field in the shock successfully confines the positrons, they will repeatedly traverse the inside of the bubble, being reflected numerous times. Preliminary simulations of this scenario suggest that the positrons will encounter a sufficient amount of matter to be thermalized and annihilate on a 1000 yr timescale. However, these simulations are too crude for us to confidently predict an annihilation rate at 1000 years after the SN event. A more detailed simulation will be conducted for analysis of the entire data set, including this and observations in the near future.

In Figure 2, we show the predicted 511 keV fluxes from SN 1006 as a function of mean positron lifetime for the 5% escape fraction. The figure also shows the current 3 σ SPI upper limit and the 3 σ sensitivity level that will be achieved after the approved future observations (2.5 Ms). If 5% of the positrons indeed escape the ejecta and are locally confined with a lifetime of less than 10^5 yr, then SPI is expected to detect 511 keV annihilation emission from SN 1006 once the additional observations are performed.

Figure 2 also shows the predicted fluxes for SN 1006 if the positron yield is increased by a factor of 2.5, so that SNe Ia could account for *all* Galactic positrons. The SPI nondetection suggests against this possibility if the mean positron lifetime is less than 10^5 yr. Note that in the case of no escape from the remnant, the expected 511 keV flux from only ^{44}Ti decays is

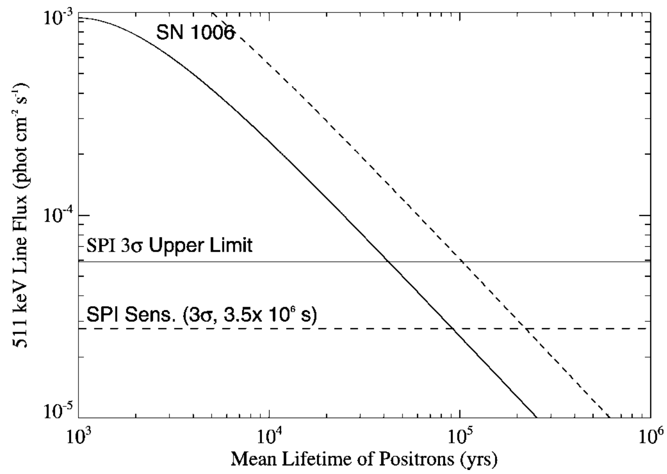

FIG. 2.—Predicted 511 keV line fluxes from SN 1006 as a function of positron mean lifetime. The solid and dashed curves are for 5% and 12% escape fractions, respectively. The expected SPI (5 σ) sensitivity to the 511 keV line for 3500 ks and the current SPI 3 σ upper limits for the emission from the SNRs are shown for reference.

no larger than 4×10^{-6} photons cm^{-2} s^{-1} from SN 1006, which is far too low to be detectable by SPI.

We stress that the conclusions above depend strongly on the assumption of no escape to the ISM and thermalization in the ejecta. The future observations of SN 1006, and other SN Ia remnants of different ages (both younger and older), will provide essential information for understanding positron transport in SNRs. A nondetection would still leave an ambiguity; the reason could be either ∼0% escape fraction from the ejecta or a very long thermalization timescale for positrons in the ISM. On the other hand, detection of annihilation radiation would be a strong indicator of thermalization in the ejecta and confirm whether SNe Ia are important contributors of Galactic positrons.

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