SEARCHING FOR ANNIHILATION RADIATION FROM SN 1006 WITH SPI ON INTEGRAL

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ABSTRACT

Historical Type Ia supernovae are a leading candidate for the source of positrons observed through their diffuse annihilation emission in the Galaxy. However, search for annihilation emission from individual Type Ia supernovae has not been 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 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 $3\sigma$ flux upper limit of $0.59 \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$ for $\sim$1 Msec exposure time, assuming a FWHM of 2.5 keV. This upper limit corresponds to a 7.5% escape fraction, 50% higher than the expected 5% escape scenario, and rules out the possibility that Type Ia supernovae produce all of the positrons in the Galaxy ($\sim$12% escape fraction), if the mean positron lifetime is less than $10^5$ years. 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: ISM: individual (SN1006), supernova remnants, gamma rays: observations

1. INTRODUCTION

Search for $\gamma$-ray lines from supernovae (SNe) remains one of the primary goals of $\gamma$-ray astrophysics, and also INTEGRAL (Winkler et al. 2003), as $\gamma$-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 $\gamma$-ray lines in young SNe also produce positrons, making them a prime candidate for 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 SNe Type Ia, the lifetime of a positron will be small in the initial SN, but may become as high as $>10^5$ years as the SN expands. The mean positron lifetime will be even longer, $>10^5$ years, in cases where the thermalization takes place in the interstellar medium (ISM), rather than in the ejecta (Guessoum, Ramaty, & Lingenfelter 1991). If the ejecta's magnetic field is weak, and/or radially combed, then 95% of the $^{56}$Co decay positrons annihilate promptly, and 5% escape to annihilate on a longer time-scale (Chan & Lingenfelter 1993). Alternatively, a tangled and strong magnetic field would confine $\sim100%$ of the $^{56}$Co positrons resulting prompt annihilation, leaving much smaller annihilation radiation flux from the delayed $^{44}$Ti decays ($\tau \sim 85$ years).

Simulations of late optical B & V light curves of Type Ia SNe indicate that the 5% escape of the $^{56}$Co positrons is the most probable scenario, assuming the optical light curves trace the bolometric luminosity (Milne, The & Leising 1993). A later study also showed that 16 of 22 SNe Ia observed at late epochs exhibit the same shape BVRI light curves as the initial sampling of 10 SNe Ia, strengthening the conclusion of 5% escape fraction (Milne, The & Leising 2001). However, excess 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 magnetic field configurations in these objects, as well as determine their role in producing the diffuse Galactic annihilation emission.

The positrons are initially hot, and slow down by Coulomb losses, ionization, and excitation. Once they are cool enough (less than a few hundred eV), the positrons can have 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, Ramaty & Drachman 1979, Guessoum, Jean & Gillard 2005). The fraction of the photons that are emitted in the line and the continuum depends on the properties of the annihilating medium. The recent analysis of the SPI data yields positronium fractions close to 0.95 for the diffuse Galactic annihilation radiation (Churazov et al. 2005; Jean et al. 2005). For the width of the line, SPI finds $2.4\pm 0.3$ FWHM, if the line is approximated as a simple Gaussian (Churazov et al. 2005). Note that the positronium fraction and the FWHM values for the Galaxy are not necessarily appropriate for individual SNe annihilations. The positronium fraction depends on the temperature and the ionization state of the medium (Guessoum, Ramaty, & Lingenfelter 1991; Jean et al. 2005), and the FWHM can be broadened by Doppler effects if the annihilation takes place in the ejecta.

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For weak and/or radially combed magnetic fields that permit 5% escape, positron transport simulations estimate that roughly $8 \times 10^{52}$ positrons escape from a given SN Ia (Milne, The & Leising 1999). When combined with the rate of 0.5 Type Ia SNe per century, a steady state flux of $9 \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$ would be expected if the positrons are assumed to be annihilated at a distance of 8 kpc (distance to the Galactic center). The latest measurements of SPI yields a total Galactic 511 keV flux of $1.5\sim 2.9 \times 10^{-4}$ 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 OSSE on CGRO, SMM, and TGRS observations of 511 keV line emission (Milne et al. 2001). 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 maps of 511 should trace the recent SN Ia history. The bulge-to-disk flux ratio is confined to be within the range of 1–3 (and luminosity ratio of 3–9). This ratio is consistent with no 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 $\sim 1000$ ks, with the main goals of characterizing the hard X-ray emission using ISGRI and JEM-X instruments (Kalemci et al. 2005), and searching for 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 20 keV – 8 MeV band, and has an energy resolution of $\sim 2$ 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 52650 and MJD 52659 corresponding to INTEGRAL revolutions 30 and 32. These observations will be denoted as "Set I". The second 750 ks set was conducted between MJD 53024 and MJD 53034 during revolutions 155-158, which 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.

Before any analysis, we filtered out the pointings with high Anti-Coincidence 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 of 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. Maximum likelihood method in SPIROS was used for imaging. Note that SN 1006 is $\sim 30'$ in diameter, and is effectively a point source for SPI. Set I and Set II were analyzed separately. We used 5, 7, and 10 keV energy intervals encompassing 511 keV to factor in possibilities for both narrow and broad emission. We also searched for the positronium continuum in 200–500 keV band with SPI.

Fig. 1 shows the SPIROS sigma image in the energy band of 508.5–513.5 keV, using the mean count modulation method. We obtained similar images in larger energy bands, and 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 II shows the details of the search and $3\sigma$ sensitivity limits of SPI for the given energy band and observing time. The combined upper limit is for 18 detectors in Set I and Set II.

### Table I

| 511 keV Line | Set I (250 ks) | Set II (750 ks) | Combined |
|--------------|---------------|----------------|----------|
| FWHM (keV)   | Flux          | Flux           | Flux     |
| 2.5          | $1.15 \times 10^{-4}$ | $0.70 \times 10^{-4}$ | $0.59 \times 10^{-4}$ |
| 3.5          | $1.35 \times 10^{-4}$ | $0.81 \times 10^{-4}$ | $0.70 \times 10^{-4}$ |
| 5.0          | $1.66 \times 10^{-4}$ | $0.96 \times 10^{-4}$ | $0.83 \times 10^{-4}$ |

| Positronium Continuum | 350–500 keV band | $3.4 \times 10^{-4}$ | $3.0 \times 10^{-4}$ |

Note: All fluxes are $3\sigma$ upper limits, ph cm$^{-2}$ s$^{-1}$

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 $\sim 2.2$ kpc, the age is 999 years, the angular size is $\sim 30'$, and the ejecta’s current electron density is $0.7$ cm$^{-3}$ (Winkler, Gupta & Long 2003; Long et al. 2003; Milne 1971; Milne, The & Leising 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). Sim-
ulations have shown that positrons that escape from the SN ejecta typically have ∼500 keV of energy upon their escape (Chan & Lingenfelter 1993, Milne, The & Leising 1999). The range of 500 keV positrons in the ISM is such that few positrons would be expected to thermalize within 1000 years (Guessoum, Ramaty, & Lingenfelter 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, Ramaty, & Lingenfelter (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 argument against positrons crossing the shock in this fashion are circumstantial, as the distribution of annihilation radiation from SNNe would then trace the distribution of matter in the Galaxy. It has been shown that the diffuse 511 keV emission mapping results from OSSE and SPI (Purcell et al. 1997, Milne, The & Leising 2001) and the SPI upper limits for the emission 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 non-detection would still leave an ambiguity; the reason can either be ∼0% escape fraction from the ejecta, or very long thermalization timescale of 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 SN Ia are important contributors of galactic positrons.

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

![Predicted 511 keV line fluxes from SN 1006 as a function of positron mean lifetime.](image-url)