Is Positron Escape Seen In the Late-time Light Curves of Type Ia Supernovae?

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Abstract. At times later than 200 days, Type Ia SN light curves are dominated by the kinetic energy deposition from positrons created in the decay of ^{56}Co. In this paper, the transport of positrons after emission are simulated, for deflagration and delayed detonation models, assuming various configurations of the magnetic field. We find the light curve due to positron kinetic energy has a different shape for a radially combed magnetic field than it does for a tangled field that traps positrons. The radial field light curves fit the observed light curves better than do the trapping field light curves for the four SNe used in this study. The radial field permits a much larger fraction of the positrons to escape, perhaps enough to explain a large percentage of the 511 keV annihilation radiation from the Galactic plane observed by OSSE.

INTRODUCTION

Type Ia supernovae possess two qualities that make them attractive as a potential source of positrons; the large amount of positron-producing ^{56}Ni synthesized in the explosion, and the occurrence of Type Ia SNe in bulge populations. Their spectra and light curves show evidence of the $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$ decays. In 19% of the $^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$ decays, a positron is produced. The large number of positrons produced in a single SN combined with realistic Type Ia SN rates show that they can easily account for the 511 keV annihilation flux observed by SMM and other detectors if enough can escape from the SN into the ISM. All models of the galactic distribution of 511 keV annihilation emission that fit the OSSE observations contain a bulge component. Supernova searches in other spiral galaxies confirm that Ia SNe occur in the bulge populations [1].

Heterogeneity does exist within the Ia paradigm. Different models are created to fit the light curves and spectra of individual SNe. The mass of ^{56}Ni produced in models varies from 0.1 -0.9 $M_\odot$ [2]. The amount and location of ^{56}Ni in the ejecta has an obvious effect upon the fraction of positrons that escape. The magnetic field geometry is a less obvious, but even more important determinant of positron escape. If the field is tangled such that positrons are eternally trapped within the ejecta, the fraction of positrons that escape is zero. A small fraction may survive non-thermally in the expanding ejecta ($\leq 10^{-3}$ survival fraction). If the homologous expansion stretches the field lines to the extent that they are essentially radial, then many more positrons may escape (5% -15%). This subject was explained in detail by Chan and Lingenfelter (1993) [3]. While extreme SN Ia models vary in nickel mass by a factor of less than 10, the ratio between positron survival in the radial field geometry and positron survival in the knotted field geometry can vary by a factor of 200. Thus, the field geometry is the dominant determinant of positron survival. The problem is to determine which field geometry approximates the SN ejecta the best.

LIGHT CURVES

Six times as much energy goes into the γ-rays ($\simeq$3.6 MeV per decay) as goes into the kinetic energy of the positron ($\simeq$0.632 MeV) [3] For positron KE deposition to play a significant role, the gamma-ray opacity must drop to below one-sixth the effective opacity of the positron KE deposition. The gamma-ray transport was treated with a Monte Carlo simulation which estimated the fraction ($f_{dep,\gamma}$) of the decay energy that is deposited via Compton scattering and photoelectric absorption processes. $f_{dep,\gamma}$ is published for a number of SN models, including W7, in The, Bridgeman, Clayton (1994) [4]. The radial positron KE deposition was calculated by emitting positrons isotropically relative to the field lines and slowing them via ionization and excitation, inverse Compton scattering, synchrotron emission, and bremsstrahlung emission. Ionization and excitation dominates at all but the highest energies. The trapped positron KE deposition was calculated by emitting the positrons in the center of their respective zones and confining them to evolve co-located with the ejecta.

Figure 1 shows the various contributions to the bolometric light curve of the SN Ia model W7 [5]. The opacity to γ-rays drops quickly, so by 200^d only a small fraction of the γ-rays interact with the ejecta, and the KE deposited by the positrons as they slow down dominates the light curve. Escaping positrons take some of their KE with them creating a deficit in the light curve versus the “In Situ” approximation. Trapped, non-thermal positrons will store energy temporarily, giving it back at later times. The radial curve falls off more sharply than does the In Situ curve; the trapped curve crosses over above the In Situ curve and remains slightly above that curve.

OBSERVATIONS

A few SNe have occurred close enough that photometry was taken at 350+ days. A model is judged to satisfactorily represent the observed supernova if it reproduces the early-time spectrum and the multi-band light curve. The test of the field geometry is achieved by using models which fit at early time and determining

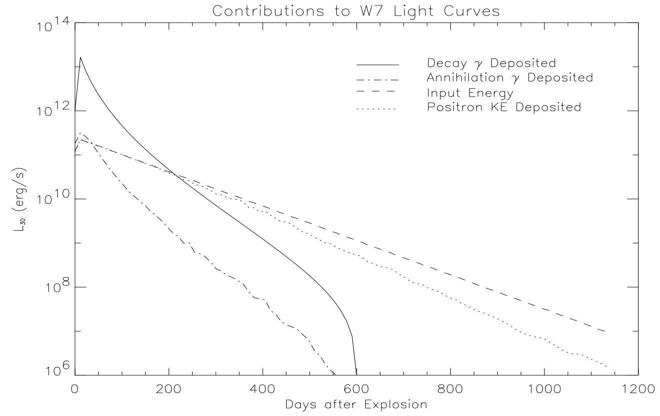

FIGURE 1. γ and e^+ KE deposition in units of 10^{30} erg/s. The "input energy" is the KE input to the ejecta by β^+ decay. The "In Situ" approximation is the assumption that all of the KE is deposited on-site, instantaneously. The energy deposited by γ-rays produced by positron annihilation in the ejecta is not significant.

whether the predictions of either of the two field geometries fit the late-time B band light curve. The B band is assumed to be proportional to the bolometric light curve during this phase. The bases of this assumption are two-fold. First, the observed light curves do not show color evolution in this phase [6]. Second, once the nebular phase begins, the continuum falls off and the B band is dominated by florescence lines [7]. The lines should scale with the KE deposition until very late times ($\sim 1000^d$) at which time freeze out becomes an issue [8]. Thus, the phase to observe positron driven light curves is between 400 and 1000 days.

The light curves are fit on a supernova-by-supernova basis. Four SNe were analyzed in this preliminary study. The first two, SN 1972E [9] and SN 1992A [10] were considered "typical" SNe and are thus fit with the deflagration model W7 to demonstrate the technique. The second two, SN 1990N [11] and SN 1991T [8] were peculiar and are fit by late detonation models created specifically to fit their early spectra and light curves, W7DN and W7DT [12]. The lines are scaled to fit the data at 200 days. The fits are shown in figure 2.

SN 1972E, SN 1992A and SN 1990N follow linear declines in magnitude after 200 days, and the slopes of these declines are better fit by the radial models. Other models have been suggested as better representatives of these individual SNe, in future, these other models will be used to strengthen the argument for these SNe. To fit W7DT to SN 1991T, we included a component with constant flux to account for the additional luminosity that is provided by light echoes, as identified by Schmidt, et.al.(1994) [8]. The existence of a light echo provides a luminosity source to offset the declining ^{56}Co input. Although it may still be possible to accurately model a light curve that contains a light echo, at present we caution against their use to discriminate between positron trapping and escape.

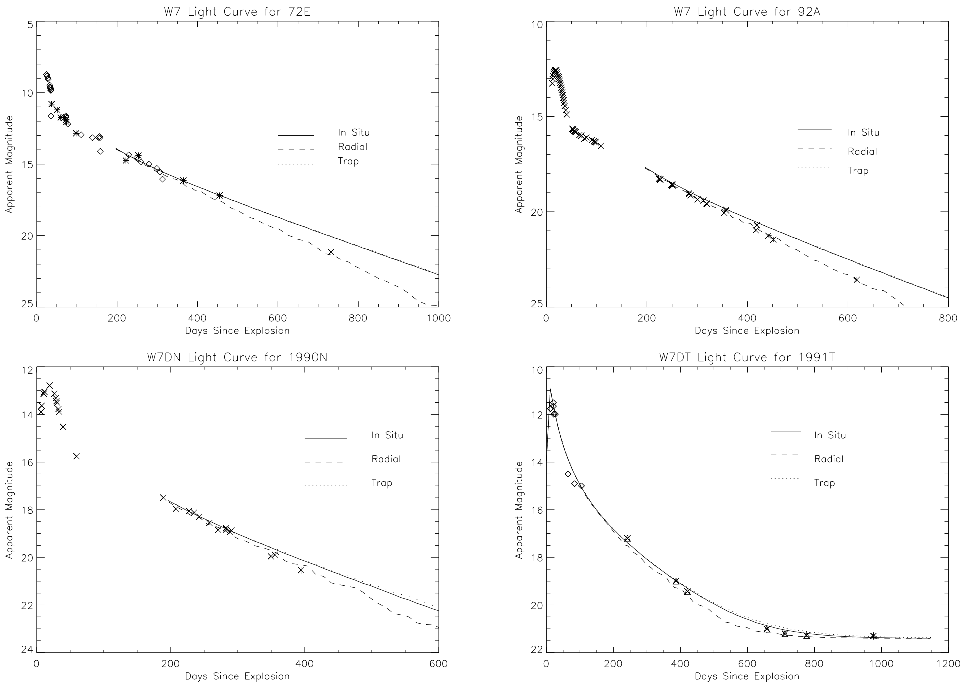

FIGURE 2. Model fits to four SNe observed at late-times. See text for references

SURVIVAL FRACTIONS AND 511 KEV FLUX

TABLE 1. Positron survival 3 years post-explosion.

Model Name	Radial %	Radial #	Trapped %	Trapped #
W7	5.5	1.3 x 10^{53}	2.0 x 10^{-2}	4.8 x 10^{50}
W7DN	10.4	2.6 x 10^{53}	5.2 x 10^{-2}	1.3 x 10^{51}
W7DT	11.7	3.6 x 10^{53}	5.9 x 10^{-2}	1.8 x 10^{51}

Table 1 shows the survival fraction of positrons emitted in the SN models W7, W7DN and W7DT for the two field geometries. The values are for 3 years (99.99% of the positrons have been emitted by then). Positrons that escape and/or survive until three years after the supernova explosion exist in an environment that is very diffuse. This is due to two facts. First, the rapid expansion of the supernova creates a tenuous bubble, and second, Type Ia SNe tend to occur in a very low density phase of the ISM. This tenuous environment means that a positron can survive so long that the contributions from many supernovae can combine to produce a diffuse positron annihilation radiation source. Numerically, if the galactic 511 keV flux is 2.3 x 10^{-3} γ cm^{-2} s^{-1} [13], then a Type Ia SN rate of 0.2 -1 SN Ia [100 y]$^{-1}$ would produce the necessary number of positrons, for a survival fraction of 5% from the SN model W7.

SUMMARY

This paper motivates the use of late-time light curves as a probe of positron transport in type Ia SN ejecta. A few SNe have been observed well enough to begin to discriminate between radial and trapping field geometries. Preliminary observations suggest that the field lines are radially combed, but future observations are required to solve this problem.

Determining the positron escape from typical Type Ia SNe does not solve the 511 keV emission problem by itself. The issues of the galactic distribution of past Ia SNe as well as of the ISM transport and the annihilation of positrons must also be addressed. Nonetheless, it appears that Type Ia SNe must be considered a potentially large contributor to the 511 keV emission.

REFERENCES

1. Branch, D., *ApJ*, 000 (1996).
2. Hoeflich, P., Khokhlov, A., *ApJ* **457**, 500 (1996).
3. Chan, K.-W., Lingenfelter, R.E., *ApJ* **405**, 614 (1993).
4. The, L.-S., Bridgman, W.T., Clayton, D.D., *ApJS* **93**, 531 (1994).
5. Nomoto, K., Thielemann, F.-K., Yokoi, K., *ApJ* **286**, 644 (1984).
6. Turatto, M., Cappellaro, E., Barbon, R., Della Valle, M., Ortolani, S., Rossino, L., *AJ* 100, 771 (1990).
7. Colgate, S.A., Fryer, C.L., Hand, K.P., in *Thermonuclear Supernovae*, Dordrecht: Kluwer Academic Publishers, pp. 273 (1997).
8. Schmidt,B.P., Kirshner,R.P., Leibundgut, B., Wells, L.A., Porter, A.C., Ruiz-Lapuente, P., Challis, P., Filippenko, A.V., *ApJ* **434**, L19 (1994).
9. Kirshner, R.P., Oke, J.B., *ApJ* **200**, 574 (1975).
10. Suntzeff, N.B., *Unpublished*,(1997).
11. Lira, P., *Master's Thesis: Univ. Of Chile*, (1995).
12. Yamaoka, H., Nomoto, K., Shigeyama, T., Thielemann, F.-K., *ApJ* **393**, L55 (1992).
13. Share, G.J., Leising, M.D., Messina, D.C., Purcell, W.R., *ApJ* **358**, L45 (1990).