Search for the Companions of Galactic SNe Ia

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Abstract. The central regions of the remnants of Galactic SNe Ia have been examined for the presence of companion stars of the exploded supernovae. We present the results of this survey for the historical SN 1572 and SN 1006. The spectra of the stars are modeled to obtain Teff, log g and the metallicity. Radial velocities are obtained with an accuracy of 5–10 km s\textsuperscript{-1}. Implications for the nature of the companion star in SNeIa follow.

1 Introduction

Type Ia supernovae have long been recognized as close binary systems where one of the stars, a carbon-oxygen WD (C+O WD), undergoes a thermonuclear runaway after reaching the explosive conditions at its center. While the remnants and the ejecta left by the explosion have been studied in great detail, little is known about companion stars. Motivated by the lack of definitive constraints on the progenitors of SNe Ia, a programme was started to find the moving companion of the exploding WD (Ruiz–Lapuente 1997; Canal, Mendez & Ruiz–Lapuente 2001).

Several possibilities for the companion have been proposed. It could be a white dwarf, giant, subgiant, or a main sequence star. Each of these possibilities and in particular the expected peculiar velocities are discussed below.

\textbf{White Dwarf.} A double–degenerate (DD) system, where the mass donor is a second WD, should not leave any companion. The companion is destroyed in the mass–transfer process. Although first estimates of the efficiency in producing SNe Ia disfavor this option, as reported in this conference (Napiwotzki et al. 2002), more double degenerate systems able to merge in less than a Hubble time are being discovered.

\textbf{Subgiant or Giant.} Close binaries consisting of WDs with subgiant or giant companions (also called Algol–like systems) can produce the growth in
mass of the WD until it reaches the explosive condition (Whelan & Iben 1973; Hachisu, Kato & Nomoto 1996, 1999; Hachisu et al. 1999). The transfer takes place when the subgiant or giant fills its Roche lobe due to its thermonuclear evolution and pours material onto the WD. The material transferred to the WD is H, and depending on the accretion rate the WD will either grow in mass up to the Chandrasekhar limit or ignite a detonation in an outer shell. Once the WD explodes, the ejecta hit the companion. That produces several effects: the system is disrupted, the companion moves with the orbital velocity it had before the explosion, plus the kick velocity it acquires from the impact of the ejecta. The interaction of the ejecta with the companion will also strip away part of its mass. In addition, the bound remnant of the companion will have its hydrostatic and thermal equilibrium altered (Marietta, Burrows & Fryxell 1999; Canal, Méndez & Ruiz–Lapuente 2001). Hydrostatic equilibrium will resume on a very short time scale, but thermal equilibrium will only be regained on a longer, global Kelvin–Helmholtz time scale (see as well the earlier calculations done by Colgate 1970; Wheeler, Lecar & McKee 1975; Fryxell & Arnett 1981; Taam & Fryxell 1985; Livne, Tuchman & Wheeler 1992). That means the companion will exhibit an increase in radius, increased surface temperature, and an increased luminosity, which should be observable in the most recent Galactic Type Ia supernovae. Depending on the separation between the two stars at the time of explosion, the companion will acquire different velocities. As a result of the orbital motion that the star had before the explosion and the kick velocity, we expect the star to be moving at velocities of a few hundred km s$^{-1}$ (see Table 1). That is one order of magnitude larger than the systemic velocities of typical stars at the same location in our Galaxy. The motion will be an identifying signature of the companion.

Main Sequence Star. The final possibility for a SN progenitor which has been proposed consists of a WD plus a main–sequence companion, i.e., a cataclysmic variable. Orbital shrinkage is driven in those systems by magnetic braking plus the emission of gravitational wave radiation (see Ruiz–Lapuente, Canal, & Burkert 1997, and references therein). In this case, the moving companion remaining after the explosion will be fainter than in the giant/subgiant case, but typical velocities will be higher.

Several considerations lead to the selection of SNIa remnants for the detection of the companion star within this project. First, the X–ray shell morphology should be spherically symmetric with a well defined center of the remnant. The distance and the age of the SNeIa remnants should be in an adequate range to allow a reasonable search radius (see Table 1). SNe of Type Ia such as Tycho (SN 1572) and SN 1006, which have shell morphologies with high spherical symmetry preserved up to 1000 yr after the explosion seem to be the most natural targets for this study.
Table 1. Typical apparent magnitudes, proper motions, radial velocities, and maximum angular distance from explosion site (after $10^3$ yr) of SNeIa companions

| Companion type | $m_V$ | $\pi$ (arcsec yr$^{-1}$) | $v_r$ (km s$^{-1}$) | $\theta$ (arcmin) |
|----------------|-------|--------------------------|---------------------|------------------|
| Main sequence  |       |                          |                     |                  |
| 1 kpc          | 15.1  | 0.067                    | 320                 | 1.6              |
| 5 kpc          | 18.6  | 0.013                    | 320                 | 0.3              |
| Subgiant       |       |                          |                     |                  |
| 1 kpc          | 12.6  | 0.038                    | 180                 | 0.9              |
| 5 kpc          | 16.1  | 0.008                    | 180                 | 0.2              |
| Red giant      |       |                          |                     |                  |
| 1 kpc          | 10.5  | 0.015                    | 70                  | 0.4              |
| 5 kpc          | 14.0  | 0.003                    | 70                  | 0.1              |

2 SN 1572

SN 1572 (Tycho Brahe’s supernova) is close to the Galactic plane ($b = +1.4^\circ$). The field of the supernova is 3.8 $'$ in radius. In SN 1572 the radio shell is very regular and early radio and optical expansion measurements have found similar results on the ejecta expansion rate. The distance inferred by the expansion of the radio shell and by other methods lies between 2.25 and 4.5 kpc (Strom, Goss & Shaver 1982).

An estimate of the center is possible with an uncertainty less than 10 % of the radio shell. Therefore, it seemed a good strategy to complete observations down to a magnitude limit $m_R \sim 23$ of the stars within 0.7 $'$ of the center. In Figure 1 we show the spectra of some of the stars near the center of the remnant. A red giant is very near the geometrical center of SN 1572. Other stars in the vicinity range from supergiants to WDs.

We have obtained spectra with high enough resolution to allow detection of motions in the radial direction. Our spectra correspond to different epochs and this allows an additional check of variation of the velocities in those directions. Spectra were obtained with ISIS and UES at the William Herschel Telescope and with ESI at the Keck Telescope (see Table 2 for the observations).
Table 2. Observations of SN 1572

| Run | Rd ('') | $m_R$ | Telescope | $R$ | Spec Range (A) | stellar types |
|-----|---------|------|-----------|-----|---------------|---------------|
| (1) | 0.7     | 14   | WHT (UES) | 50,000 | 4000–7100     | red giant     |
| (2) | 0.7     | 23   | WHT (ISIS)| 15,000 | 4600–7500     | red giants to WD |
| (3) | 0.7     | 23   | Keck (ESI)| 7000   | 4000–10000    | as above      |

1 Radius of the search
2 Limiting magnitude
3 Telescopes (Instrumentation)

Table 3. Observations of SN 1006

| Run | Rd ('') | $m_R$ | Telescope | $R$ | Spec range (A) | stellar types |
|-----|---------|------|-----------|-----|---------------|---------------|
| (1) | 5       | 13   | NTT (EMMI)| 10,000 | 3950–7660     | red giants    |
| (2) | 5       | 15   | VLT (UVES)| 50,000 | 3500–9000     | all types     |

1 Radius of the search
2 Limiting magnitude
3 Telescopes (Instrumentation)

3 SN 1006

SN 1006 is at a Galactic latitude $b = +14.6^\circ$, about $\sim 550$ pc above the Galactic plane. The field of this supernova extends 15′ in radius. An examination of all the centers given in the literature up to now (Winkler & Long 1997; Reynolds and Gilmore 1986; van den Bergh 1976) and our inspection of the geometry of the SNIa, suggest that within 1′, the center of SN 1006 should be at $\alpha = 15^h 02^{m}55^{s}$, $\delta = -41^\circ 55^{\prime}12^{\prime\prime}$ (J2000) as given by Allen et al. (2001). The distance estimates to this SNR are in the range between 1.5 and 2.5 kpc. Recently Winkler, Gupta & Long (2002) measure a distance of $2.17 \pm 0.08$ kpc to SN 1006 from the expansion rate of the remnant as derived from the optical filaments. Given the predictions for the movement of the companion, at a distance between 1.5 and 2.5 kpc, a search around 5′ at the best determined center of the remnant should find the companion of this SNIa.

Our search goes down to mag 15 in $R$. At the distance to this remnant, this means to reach stars of solar luminosity. Thus, an exhaustive test of the hypothesis of supergiant, giant and main sequence stars is obtained in this way (see Table 3 for a summary of the observations).
Fig. 1. Calculated synthetic spectra compared with the observed spectra of the SN companion candidates near the center of SN 1572. These are the closest red giants and supergiants to the center of the explosion, their surface gravity goes from log $g=2$ for Tycho A to log $g=0$ for C and E. The effective temperatures for those stars are similar. They are in the range 4200–4500 K. Model atmospheres with solar chemical abundances give a good account of the spectra. The overall spectral comparison allow us to exclude overabundances of the Fe–peak elements. Moreover, the stars show no enhancement of iron–peak elements versus intermediate–mass elements in the spectra. Synthetic spectra are shown with bold continuous lines.
Fig. 2. DA WD near the center of Tycho remnant. A preliminary analysis suggests log \( g = 6 \), and \( T_{\text{eff}} = 25,000 \) K.

4 Modeling

We have compared calculated LTE spectra with the observed spectra of the SN companion candidates. We have used Kurucz’s grids of model atmospheres (Kurucz 1993), a spectral synthesis code based on the Uppsala Synthetic Spectrum Package (Gustafsson et al. 1975), and the atomic data from the linelists in Kurucz. The profiles of the Balmer lines of H, calculated separately for the model atmospheres of the grids, have also been used in the spectral fits. The comparison of the synthetic spectra with the observations is shown in Fig. 1 for some of the stars in our sample of candidates to SN companion. Identifications of the most significant lines are given. Good agreement is achieved assuming solar abundances (Anders & Grevesse 1989). Moreover, none of the closest stars
to the center show signs of any spectroscopic anomaly. Radial velocities have also been measured from the wavelength shifts of several lines in each observed spectrum: they are in the range $-40$ to $-60$ km s$^{-1}$, which is perfectly attributable to Galactic rotation alone.

The low–velocity tail of the ejecta of a thermonuclear (Type Ia) supernova is made of Fe–peak elements (Fe, Co, Ni, Mn, Cr, V, Ti), as it comes from the material at the center of the exploding star and it thus reached the highest temperatures ($\sim 10^{10}$ K), being then processed to Nuclear Statistical Equilibrium (Thielemann 1989). Since this material is the most likely to have contaminated the surface of a binary companion (see papers cited in section 1), especial care has been given to the determination of the abundances of those elements in the atmospheres of the stars in our sample. An overabundance of those elements in relation to intermediate–mass elements is expected.

The giants at the core do not show any signs of contamination and are consistent with solar metallicities (or slightly lower solar metallicities). This result disfavors the subgiant possibility and that of a red giant closely bound to the WD prior to the moment of explosion.

Strong constraints can be placed also on the main sequence star candidates. No main sequence star moving at high radial velocity has been detected in SN 1572. An examination over a more extended radius around the center is being done.

For SN 1006 we have found radial velocities in the range $30$–$120$ km s$^{-1}$ for the giant stars within the radius of search. Stars show a larger dispersion in radial velocity than in the field of the remnant of SN 1572. A full account of the observations, the measurement of the reddening, the overall spectral modeling and a discussion on the distance to those candidates will be presented elsewhere.
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