IDENTIFICATION OF THE COMPANION STARS OF TYPE Ia SUPERNOVAE

R. Canal,1,2 J. Méndez,1,3 and P. Ruiz-Lapuente1,4

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ABSTRACT

The nature of the binary systems giving rise to Type Ia supernovae (SNe Ia) remains an unsolved problem. In this Letter, we calculate, from the statistics of initial conditions (masses and binary separations), the mass, luminosity, and velocity distributions of the possible binary companions (main-sequence star, subgiant, and red giant) following the explosion of the white dwarf that gives rise to the SNe Ia. Those companions could be detected from either their proper or their radial motions by means of high-precision astrometric and radial velocity measurements in young, nearby supernova remnants. Peculiar velocities typically ranging from 100 to 450 km s\(^{-1}\) should be expected; these velocities place proper-motion measurements within reach of the Hubble Space Telescope instruments. Detections would solve the long-standing problem of which kinds of binaries produce SNe Ia and would clear the way for an accurate physical modeling of the explosions.

Subject headings: astrometry — binaries: close — supernovae: general — supernova remnants

1. INTRODUCTION

Nowadays, Type Ia supernovae (SNe Ia) are unanimously attributed to the thermonuclear explosion of a white dwarf (WD); this explosion is due to the accretion of matter from a companion in a close binary system. The mass-accreting WD is also generally thought to be made of carbon and oxygen (CO WD). There the agreement stops, and different kinds of systems are proposed as candidates for SNe Ia progenitors (see Iben 1997 for a review). The nature of the WD companion, the mass donor, is unclear: it could be either another WD (double-degenerate [DD] systems) or a still thermonuclearly evolving star (single-degenerate [SD] systems). The evolutionary stage of the companion in the SD systems could be anything from a main-sequence star to a supergiant, and mass accretion proceeds via Roche lobe overflow or by the capture of matter from the stellar wind. All that also bears on the explosion mechanism, i.e., on how the explosion is triggered and how it develops. Those uncertainties still raise doubts as to the use of SNe Ia as calibrated candles to probe the dynamics of the universe, the calibration being purely empirical and based on the nearby SN Ia sample (see, for instance, Drell, Loredo, & Wasserman 2000).

Recently, from the high efficiencies found in the production of SNe Ia from star formation, we have gathered evidence against the idea that the merging of WDs gives rise to SNe Ia. These efficiencies have now been measured at several redshifts and appear to be similar, every \(\approx 700 \pm 200 \, M_\odot\) going into star formation giving rise to one SN Ia (Ruiz-Lapuente & Canal 2001). No previously observed system has ever been identified as the progenitor of any SNe Ia. The historical SNe Ia took place at a time when astronomical instrumentation was rudimentary. Nonetheless, they can still give us important and decisive clues to the nature of the long-sought SN Ia progenitor systems (Ruiz-Lapuente 1997). If they were DD systems, there should be no companion left since it is destroyed in the accretion process already. On the contrary, in SD systems, the companion can survive the explosion in most cases and can show characteristics that allow us to identify it.

Of the historical SNe, from the records of light curves, only two have been identified as SNe Ia: SN 1006 and Tycho’s SN (SN 1572). From their X-ray morphology (spherically symmetric shell), X-ray spectra (showing high abundances of Fe, Ni, Si, Ca, and Ar), Fe enrichment in their optical filaments, and lack of any central X-ray source, a number of other nearby, young Galactic supernova remnants (SNRs) can also be attributed to SNe Ia (P. Ruiz-Lapuente et al. 2001, in preparation). As we will see, precise enough astrometric and radial velocity measurements of the central regions of such SNRs should allow us to detect the SN Ia companions from either their large proper motions or their high radial velocities because of the disruption of the binary orbit plus the kick from the impact of the SN ejecta on them. For SNRs with ages \(\approx 10^4\) yr, the companions should still exhibit in their outer layers the consequences of the strong perturbation of thermal equilibrium from the partial stripping of the envelopes and the deposition of energy from the ejecta into the layers that remain bound, and they may also show chemical contamination from the SN Ia ejecta.

2. MODELING, RESULTS, AND DISCUSSION

The SD scenarios thus far proposed to explain the origin of SNe Ia involve different kinds of systems. We will only consider Chandrasekhar-mass explosions, which are generally thought to produce the bulk of SNe Ia, so the SN ejecta impinging on the companion will always be identical (differences due to the explosion mechanism should be minor and will be left aside). However, depending on the kind of system, the mass and evolutionary stage of the companion, as well as the separation between the two stars at the time of explosion, will be different, and that will determine the space velocity and the mass, luminosity, surface temperature, and surface abundances of the surviving star.

We will consider the case of a main-sequence companion filling its Roche lobe because of the loss of angular momentum via magnetic braking (cataclysmic variable [CV] system) and the case of a subgiant or red giant companion filling its Roche lobe because of thermonuclear evolution (an Algol-type or cataclysmic-like [CL] system). The latter case is thought to show up as luminous supersoft X-ray sources before exploding into SNe Ia. In the modeling of CL systems, the stabilizing
effects on the mass transfer of the strong wind generated in the WD surface have been taken into account as in Hachisu, Kato, & Nomoto (1996). The cosmic SN Ia rates thus predicted give the best agreement with the observations (Ruiz-Lapuente & Canal 2001). Our purpose here is to derive the statistical distribution of velocities, masses, and luminosities of the companions after the explosion. We first run an updated version of the Monte Carlo scenario code that we used to model SN Ia rates in previous work (Ruiz-Lapuente, Burkert, & Canal 1995; Canal, Ruiz-Lapuente, & Burkert 1996; Ruiz-Lapuente & Canal 1998) in order to obtain the distributions of companion masses and orbital separations at the time of the explosion for the systems considered. These are displayed in Figure 1 for the CV systems (main-sequence [MS] companion) and the CL systems (distinguishing between subgiant [SG] and red giant [RG] companions). Note that, in the upper panel, the mass distributions of the SG and RG stars in the CL scenario are the same, the SG case corresponding to the narrow range of final separations shown in the lower panel while the RG case covers a much broader range with an almost flat distribution (Fig. 1, lower panel). In the CV scenario, the much narrower distribution of final masses, peaking at ~0.6 $M_\odot$, also means a narrow distribution of the final radii of the MS star. Making contact with the Roche lobe while having a companion (the WD) that always has the Chandrasekhar mass produces the sharp peak in the distribution of the final separations that we see in the lower panel of Figure 1.

From the initial conditions described above, the effects of the impact on the companion are calculated in a semianalytical approximation that is equivalent to that used by Wheeler, Lecar, & McKee (1975), based on the previous work by Colgate (1970). The companion star is divided into concentric cylinders, and the ejecta are treated as plane slabs. If the momentum incident on a cylinder can accelerate it to the escape velocity, the corresponding mass is directly stripped. A strong shock wave is driven into the rest of the star; this will impart momentum to it (kick), and the heating will make the internal energy exceed the gravitational potential energy by extra layers that will thus be expelled. The approximation is made that the fluid velocity just behind the shock is equal to the mean velocity of all the shocked stellar material. The energy per unit mass rapidly increases as the mass per unit area in the cylindrical shells decreases; energy deposition is thus concentrated in the outer layers, which ensures that the companion is never entirely disrupted. The results have been compared with the two-dimensional hydrodynamic simulations of Marietta, Burrows, & Fryxell (2000). Specifically, this has been done for the cases of a 1 $M_\odot$ MS companion at separation $a = 3 R_\odot$, a 1.1 $M_\odot$ SG companion at $a = 4.9 R_\odot$, a 2.1 $M_\odot$ SG companion at $a = 6.5 R_\odot$, and a 1 $M_\odot$ RG companion at $a = 430 R_\odot$. The agreement in the stripped masses (with a maximum discrepancy below 20%) is good enough to confirm our approximation as a reliable tool for the statistical evaluation of the characteristics of the SN Ia companions after the explosion, which would be hard to do by means of detailed hydrodynamic calculations. Note that, in Marietta et al. (2000; see their Table 4), the combinations of companion masses and separations at the time of the explosion are just adapted from examples proposed by Livio & Truran (1992; the CV system) and Li & van den Heuvel (1997; the CL system), whereas in the present work the actual distributions of those parameters have been calculated for each scenario. That is why the cases above (with the exception of the 1.1 $M_\odot$ SG companion at $a = 4.9 R_\odot$) are not typical of the predicted distributions. However, Marietta et al. (2000) have compared their results with an approximation similar to ours and find the best agreement for binaries near the Roche lobe overflow, which is always our case. That reinforces the significance of our comparisons.

The structures of the MS and SG companions prior to explosion have been obtained by the homologous transformations of a 1 $M_\odot$ model in the corresponding stages. Typically, 10%–20% of the companion mass is lost. The RG companion is modeled as a compact He core surrounded by an extended H-rich envelope, the latter having the structure of an $n = 1.5$ polytrope. The relationship between the RG mass, the radius at the time of explosion, and the core mass has been taken from the stellar evolution calculations by Politano (1988), which cover the initial mass range $0.1 M_\odot \leq M \leq 10 M_\odot$. We find that in all cases, the RG envelope is completely stripped off, as in the two-dimensional simulations of Livne, Tuchman, & Wheeler (1992). However, in their recent two-dimensional hydrodynamic modeling, Marietta et al. (2000) find that a small fraction of the envelope is retained; this would greatly help in the identification of possible SN Ia companions when exploring the central regions of young nearby SNRs, as discussed below.

The kick velocities imparted to the companions by their collision with the SN Ia debris are also calculated, but they are always much smaller than the typical orbital velocities at the time of explosion for the three types of companions (MS, SG, and RG). The predicted distributions of total velocities (orbital plus kick) are shown in Figure 2. The results corresponding to
than 100 km s\(^{-1}\). For the SG, there is a probability \(P > 90\%\) that it will move at a velocity larger than 100 km s\(^{-1}\). For the SG, there is a probability \(P > 90\%\) that it will move at a velocity larger than 200 km s\(^{-1}\), and for the MS, there is a probability \(P > 99\%\) that it will be moving at a velocity larger than 450 km s\(^{-1}\). The chances that the central regions of young SNRs produced by SNe Ia contain a star moving at a velocity larger than 200 km s\(^{-1}\) is 1 order of magnitude larger than the systemic velocities of field stars at the corresponding distances. The angular sizes of the regions to be explored (given by \(\theta\) in Table 1) ensure that the number of stars bright enough to be candidates for SN Ia companions, contained within their boundaries, is quite small. Detection of proper motion at the level of \(0.01\) yr\(^{-1}\), even at the magnitudes estimated in Table 1, is within the reach of the instruments on board the Hubble Space Telescope (HST), and detection of radial velocities in the 320–70 km s\(^{-1}\) range is feasible with ground-based telescopes (P. Ruiz-Lapuente et al. 2001, in preparation). Failure to detect any candidates within the currently known sample of SN Ia remnants (a total of eight) would be strong evidence that none are left after the explosion and would be strong evidence against the SD system hypothesis. The candidates selected for their high proper (or radial) motion should then be spectroscopically analyzed. As we have seen, MS and SG candidates should be swollen and overluminous, and RG candidates should have high effective temperatures. Moreover, Marietta et al. (2000) find that whereas no material from the ejecta should be accreted during impact, there is a possibility of a later accretion of material enriched in Fe and intermediate-mass elements from the low-velocity tail of the ejecta, long after impact.

Therefore, SN Ia companions that were left by recent nearby explosions should in fact be detectable at magnitudes significantly brighter than those shown in Table 1. To illustrate this, we also give, within parentheses, the magnitudes expected for the MS companions (the less luminous ones) at \(t \approx 10^3\) yr after the explosion. The peculiar velocities predicted are 1 order of magnitude larger than the systemic velocities of field stars at the corresponding distances. The angular sizes of the regions to be explored (given by \(\theta\) in Table 1) ensure that the number of stars bright enough to be candidates for SN Ia companions, contained within their boundaries, is quite small. Detection of proper motion at the level of \(0.01\) yr\(^{-1}\), even at the magnitudes estimated in Table 1, is within the reach of the instruments on board the Hubble Space Telescope (HST), and detection of radial velocities in the 320–70 km s\(^{-1}\) range is feasible with ground-based telescopes (P. Ruiz-Lapuente et al. 2001, in preparation). Failure to detect any candidates within the currently known sample of SN Ia remnants (a total of eight) would be strong evidence that none are left after the explosion and would be strong evidence against the SD system hypothesis. The candidates selected for their high proper (or radial) motion should then be spectroscopically analyzed. As we have seen, MS and SG candidates should be swollen and overluminous, and RG candidates should have high effective temperatures. Moreover, Marietta et al. (2000) find that whereas no material from the ejecta should be accreted during impact, there is a possibility of a later accretion of material enriched in Fe and intermediate-mass elements from the low-velocity tail of the ejecta, long after impact.

There are still many uncertainties concerning the close binary evolution, binary mass transfer, and process of mass growth of a WD from accretion until it reaches the Chandrasekhar mass. To what extent could these uncertainties affect our result that any SN Ia companion should be moving at high velocities after the explosion and be luminous enough to be detected in the central regions of young nearby SNRs?

In the case of the CV systems, the companions are MS stars that continuously fill their Roche lobes because of the loss of angular momentum via magnetic braking (plus the emission of gravitational waves when the orbits become very close). With the WD mass being equal to the Chandrasekhar mass, separation
is only a function of companion mass, which in turn is just the initial mass of the star minus the fraction transferred to the WD and the (minor) fraction lost to stellar wind. Here the efficiency of magnetic braking is the main unknown factor, but it hardly affects the distribution of final masses (and thus separations) shown in Figure 1 or the values predicted in Table 1.

Although the Algol-type systems (CL systems) involve companions in a more advanced evolutionary stage than do the CV systems, our main conclusions are equally robust. When the companion is a SG, the case is as clear-cut as for the CV systems. For the RG companions, the only worrisome possibility (that the companion velocities were actually much lower than in our modeling) can be reliably excluded; since \( v_{\text{orb}} \propto a_{\text{e}}^{1/2}(M + M_{\text{c}})^{1/2} \) and the WD mass is always equal to the Chandrasekhar mass, we approximately have \( v_{\text{orb}} \propto a_{\text{e}}^{1/2}(M_{\text{c}} + 1.4)^{1/2} \), with \( M_{\text{c}} \) being the companion’s mass. Increasing \( a_{\text{e}} \) (and, less efficiently, lowering \( M_{\text{c}} \)) would thus decrease \( v_{\text{orb}} \). But the companion is filling its Roche lobe \( R_L \), and we also have (from Paczynski 1971) \( R_L \propto a_{\text{e}}(0.35M + \log M_{\text{c}}) \) (where, in the numerical constant, we have again taken \( M_{\text{c}} = M_{\text{c}}(\odot) \)). Increasing \( a_{\text{e}} \) should therefore increase \( R_L \) faster than it would decrease \( v_{\text{orb}} \) (decreasing \( M_{\text{c}} \) cannot go very far since the companion’s initial mass must be \( M_{\text{c}} \gtrsim 0.8M_{\odot} \) in order to have evolved from the MS in less than a Hubble time), and a substantial increase should postpone the Roche lobe overflow at the red supergiant (RSG) stage, where a common envelope should form and be ejected, thus suppressing the mass transfer to the WD altogether and leaving a DD system rather than a SD one.

A class of SD system that we have not included here as SN Ia progenitors is the one in which the WD accretes H-rich material from the wind of an RG or RSG that is not filling its Roche lobe, i.e., a symbiotic system. There the orbital separation could be larger, and the orbital velocities smaller. The difficulty in making the WD grow to a Chandrasekhar mass through such a low-efficiency accretion process, avoiding the explosive ignition of either H or He in the outer layers (which requires high accretion rates), led us to discard symbiotic systems as possible progenitors of the bulk of the SNe Ia at least (Kenyon et al. 1993). Recently, Hachisu, Kato, & Nomoto (1999) have suggested that recurrent novae (RNe) are likely SN Ia progenitors in their final presupernova stage. More than half of the known RNe (five out of nine) are made of massive \( (M \approx 1.37M_{\odot}) \) WDs plus MS or SG companions that are filling their Roche lobes. The rest consists of equally massive \( (M \approx 1.35 M_{\odot}) \) WDs plus RGs. Out of those four WD + RG systems, the RG is filling its Roche lobe in one of them (T CrB; Hachisu & Kato 1999) and is underfilling it in the other three (RS Oph, which is based on the modeling of the light curve of its outburst [Hachisu & Kato 2000], V745 Sco, and V3890 Sgr). In the latter cases, the WD must be accreting matter from the RG wind. With the separation being larger, the typical peculiar velocities would then be ~40% of those for the Roche lobe filling case, and the detection of proper and radial motions should thus be harder, with the other peculiar characteristics of the RG companions that are due to the SN explosion remaining the same. We see from the above statistics, however, that even assuming that every SN Ia progenitor should become an RN before exploding, such a reduction in the predicted velocities would affect ~2 of the cases at most. But from the observed frequency of RNe, Della Valle & Livio (1996) conclude that those systems can account for at most a few percent of the SN Ia rates, which would make the final fraction of systems with Roche lobe–underfilling companions almost negligible.

3. CONCLUSIONS

To the results from existing hydrodynamical studies of the impact of SNe Ia on their companion stars, we have added the statistical evaluation of the distribution of velocities to be expected for different kinds of companions. We have shown that they should be moving at velocities much higher than those of the surrounding stars: For RG companions, there is a probability \( P > 90\% \) that the velocities are higher than 100 km s\(^{-1}\) (the possible above-mentioned case excepted), for SG companions, there is a \( P > 99\% \) that \( v > 200 \text{ km s}^{-1} \), and for MS companions, there is a \( P > 99\% \) that \( v > 450 \text{ km s}^{-1} \). Such velocities make their identifications possible in the central regions of young nearby SNRs of SN Ia origin. For distances \( d \approx 5–8 \text{ kpc} \) and SNR ages \( \approx 10^{3}–10^{4} \text{ yr} \), detection of proper motion is within the reach of instruments on board the HST. The angular sizes of the regions to be surveyed are small enough that the numbers of stars within them, which are bright enough to be candidates for SN Ia companions, remains low. There are eight Galactic SNRs (including those of SN 1006 and SN 1572) that most likely formed from SN Ia explosions and whose distances and ages allow us to search thoroughly (P. Ruiz-Lapuente et al. 2001, in preparation). Candidates selected from their peculiar velocities and positions close to the centers of the SNRs could be confirmed by spectroscopic characteristics arising from their being out of thermal equilibrium because of heating by the impact of the SN debris, according to recent hydrodynamic simulations (Marietta et al. 2000). Contamination by material accreted from the low-velocity tail of the ejecta is also possible.

Our conclusions are largely independent of the unknowns that are still effecting the close binary evolution, mass transfer, and growth of WDs up to the Chandrasekhar mass. Therefore, it now appears feasible to test the SD system hypothesis for the origin of SNe Ia by means of observations of Galactic SNRs. Detection of confirmed companions would not only validate the SD system hypothesis but it would also allow us to physically model the SNe Ia on a firmer basis and, through that, make much more reliable use of SNe Ia in cosmology.

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