THE ABSENCE OF EX-COMPANIONS IN TYPE Ia SUPERNOVA REMNANTS

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ABSTRACT

Type Ia supernovae (SNe Ia) play important roles in our study of the expansion and acceleration of the universe, but because we do not know the exact nature or natures of the progenitors, there is a systematic uncertainty that must be resolved if SNe Ia are to become more precise cosmic probes. No progenitor system has ever been identified either in the pre- or post-explosion images of a Ia event. There have been recent claims for and against the detection of ex-companion stars in several SNe Ia remnants. These studies, however, usually ignore the angular momentum gain of the progenitor white dwarf (WD), which leads to a spin-up phase and a subsequent spin-down phase before explosion. For spin-down timescales greater than $10^5$ years, the donor star could be too dim to detect by the time of explosion. Here we revisit the current limits on ex-companion stars to SNR 0509-67.5, a 400-year-old remnant in the Large Magellanic Cloud. If the effects of possible angular momentum gain on the WD are included, a wide range of single-degenerate progenitor models are allowed for this remnant. We demonstrate that the current absence of evidence for ex-companion stars in this remnant, as well as other SNe Ia remnants, does not necessarily provide the evidence of absence for ex-companions. We discuss potential ways to identify such ex-companion stars through deep imaging observations.

Key words: accretion, accretion disks – ISM: supernova remnants – supernovae: general – white dwarfs

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1. INTRODUCTION

No progenitor system for a Type Ia supernova (SN Ia) has ever been identified, nor do we know the exact nature or natures of the progenitors. We do know that SNe Ia are explosions of carbon/oxygen core white dwarfs (WDs), and that is the extent of our current knowledge on the progenitor systems. We do not know the type of astrophysical system within which the WD comes to gain mass. One possibility is a binary in which the WD accretes mass from a non-degenerate companion star in the single-degenerate (SD) channel (Whelan & Iben 1973); another is through the merger of two WDs in the double-degenerate (DD) channel (Iben & Tutukov 1984; Webbink 1984). Yet another is the “double-detonation” model, in which a sub-Chandrasekhar-mass WD detonates following a detonation of an accumulated helium layer on the surface (Nomoto 1980; Woosley & Weaver 1994; Ruiiter et al. 2011; Sim et al. 2012 and references therein).

Resolving this issue is important because the characteristics of the companion and the mass-transfer process create the environment within which the explosion occurs.

Theoretical arguments can be marshaled to support or reject the hypothesis that most SNe Ia are produced through the SD channel, and the same is true for the DD channel. For example, SDs can produce explosions with the characteristic typical of SNe Ia (e.g., Hillebrandt & Niemeyer 2000; Livio 2000), while it has proved difficult to do the same for DD models. Even though the majority of the DD mergers may result in an accretion induced collapse to a neutron star (Nomoto & Kondo 1991), some of these mergers may instead produce SNe Ia (Yoon et al. 2007; Pakmor et al. 2010; Dan et al. 2011). While neither channel appears capable of reproducing the measured rates of SNe Ia in galaxies, the distribution of times after star formation associated with the DD models is a better fit to the measured delay time distribution (Maoz et al. 2010).

Observational evidence has not yet been able to provide a resolution. The mass distribution of WDs in the solar neighborhood provides some evidence that mergers occur (Liebert et al. 2005). Yet, while radial velocity surveys have identified a significant binary WD merger population (Kilic et al. 2010; Brown et al. 2012), there is no confirmed binary WD system with a total mass above $M_{\text{BD}}$ ($\approx 1.4 M_\odot$) and a merger time shorter than a Hubble time. Observational tests of the SD scenario would seem potentially more direct. Several post-explosion investigations, for example, detect circumstellar material likely to have been ejected from the progenitor binary (e.g., Patat et al. 2007; Sternberg et al. 2011). Observations of the supernova remnant, RCW 86, which appears to have been associated with an SN Ia, find features best explained by an explosion into a cavity created by an SD progenitor system. However, the true nature of RCW 86, whether it is a core-collapse or a Ia explosion, remains questionable (see the discussion in Williams et al. 2011).

SNe Ia are rare, so we discover them at large distances from us. Furthermore, the progenitor systems, even in SD models, are predicted to be dimmer than typical progenitors of core-collapse supernovae, and therefore are impossible to detect in pre-explosion images of most SNe Ia host galaxies. Thus, nearby SNe Ia are particularly valuable to progenitor studies. The supernova 2011fe occurred in the galaxy M101, which, at 6.4 Mpc, is relatively nearby. Pre-explosion images were able to rule out the presence of a giant-donor star (Nugent et al. 2011; Li et al. 2011; Bloom et al. 2012; Horesh et al. 2012); the results of radio observations are consistent with this conclusion, placing limits on pre-explosion winds (Chomiuk et al. 2012). All other SD models, including those with subgiant or main-sequence donors, are allowed by the full complement of pre- and post-explosion observations.

One of the last SNe Ia to occur in the Milky Way was “Tycho’s” supernova (SN 1572), whose remnant is measured to be 2.5–3 kpc away. This is close enough to allow us to discover the widowed companion to the exploded WD, should it exist. Ruiz-Lapuente et al. (2004) identified a G2 dwarf as the...
ex-companion. However, this identification remains controversial (Kerzendorf et al. 2009; González Hernández et al. 2009).

Recently, Schaefer & Pagnotta (2012) extended the progenitor search to a supernova remnant in the Large Magellanic Cloud (LMC), SNR 0509-67.5. Based on a relatively short Hubble Space Telescope (HST) Wide-Field Camera 3 (WFC3) exposure of the SNR, they rule out any ex-companion star brighter than $V = 26.9$ mag in the central error circle. Given the distance to the LMC, this corresponds to sources brighter than $M_V = +8.4$ mag. Schaefer & Pagnotta (2012) argue that this magnitude limit excludes all SD progenitors and that the only remaining possibility is that of a DD merger system, with no companion left behind.

In this paper we point out that, if the effects of angular momentum carried by matter falling toward the WD are included, a wide range of SD progenitor models are allowed. These spin-up/spin-down models are reviewed in Section 2. In Section 3 we revisit the analysis of possible widowed donors in SNR 0509-67.5 and review the implications for the study of other SNe Ia remnants in Section 4.

2. SPIN-UP/SPIN-DOWN MODELS

2.1. Angular Momentum

The term “SD model” refers to diverse classes of binary systems within which a WD may accrete matter and achieve the critical mass. The donor may be drawn from a broad range of stellar types. Orbital separations may be close enough that the donor fills its Roche lobe, or wide enough that mass transfer occurs through winds. Matter may be accreted through a disk, or not. The common feature is that the WD should be able to retain enough of the matter it accretes to allow it to eventually achieve the critical mass needed for explosion.

Mass retention is generally thought to require that incoming matter undergo nuclear burning. Quasi-steady nuclear burning requires high rates of accretion, generally above a few times $10^{-7} M_\odot$ yr$^{-1}$ (Iben 1982; Nomoto 1982). Matter can also be retained with the somewhat lower accretion rates consistent with recurrent novae (Prialnik & Kovetz 1995). Note, however, that high rates of mass infall would be required even if nuclear burning were not an issue because the types of donors which can donate enough mass to a CO WD to allow it to achieve $M_{\text{crit}}$ would necessarily donate mass at high rates for extended periods (Rappaport et al. 1994).

In almost all accretion scenarios, infalling matter carries angular momentum. The WD therefore accretes both mass and angular momentum. While the accretion of mass has been considered in detail, in terms of both the burning of infalling mass and the evolution toward explosion, the increase in angular momentum is a difficult problem that has been less well studied. While results for some detailed models have been computed (e.g., Yoon & Langer 2004), there are uncertainties about important physical elements, such as the relative roles of viscosity, magnetic fields, and gravitational radiation in promoting both spin-up and spin-down (see, e.g., Piro 2008).

Recently, the significance of the issue of angular momentum transfer has been linked to the appearance of the progenitor binary both pre- and post-explosion, using physical arguments independent of the details of the relevant processes (Di Stefano et al. 2011; Justham 2011).

It is important to note that much theoretical and observational work needs to be done to understand the effects of angular momentum. For example, several sets of calculations (e.g., Iben 1982; Nomoto 1982; Shen & Bildsten 2007; Prialnik & Kovetz 1995) have been conducted to determine the range of accretion rates that allow the WD to burn incoming material or that are associated with nova. These have all assumed spherical symmetry, which does not hold if the WD spins at a rate of a few tenths of a Hertz. Furthermore, the calculations apply to WDs with mass below the Chandrasekhar mass. Thus, the accretion calculations must be extended if we are to understand the details of how matter accretes onto spinning WDs of all masses, including massive WDs. Several other questions must also be addressed, including the effects of a delay time to explosion on the internal state of the WD. On the observational front, searches for fast spinning WDs are needed. In this paper we focus on the specific issue of the effects spin-up/spin-down would have on the detectability of the widowed companion to a WD that explodes.

2.2. Spin-up/Spin-down Models

Di Stefano et al. (2011) introduced classes of spin-up/spin-down binary models for accreting WDs, and studied their implications for the detectability of the widowed companions. Briefly, in the SD channel, SNe Ia explosions result from WDs retaining the accreted mass. The angular momentum of the WD must increase because of accretion. There are several examples of fast spinning WDs in close binary systems, mostly in intermediate polars, e.g., the dwarf nova WZ Sge (27.87 s), the nova-like AE Aqr (33.06 s), and the nova remnant V842 Cen (56.82 s). The likely progenitors of SNe Ia have mass-transfer rates that are several orders of magnitude higher than those inferred for intermediate polars. The retention of should spin mass-gaining WDs to even shorter periods than measured for intermediate polars. The WD in HD 49798 is one such system; it has a 13 s spin period $1.28 M_\odot$ WD with a hot subdwarf companion (Mereghetti et al. 2011).

Spin-up can increase the value of the critical mass, $M_{\text{crit}}$, needed for explosion (Ostriker 1966; Anand 1965; Roxburgh 1965). If $M_{\text{crit}}$ has increased, the WD may not explode even after its mass has become equal to $M_{\text{Ch}}$. If the mass of the WD cannot reach $M_{\text{crit}}$, then the explosion must be delayed until the WD can spin down, reducing the value of $M_{\text{crit}}$ to the actual value of the WD’s mass. By “spin-down” we mean that the WD has either lost angular momentum or changed its internal angular momentum profile so that the required central density can be achieved. Spin-down begins when the mass-transfer rate becomes low enough that genuine mass gain is no longer possible.

The need for a spin-down time can mean that the donor has different properties at the time of explosion from those it would have had the explosion occurred at the time when the mass of the WD reached $M_{\text{Ch}}$.

2.2.1. Giant Donors

Consider the case in which the donor is a giant during the phase in which it contributes mass at a high-enough rate to promote nuclear burning. Because a giant loses mass at higher rates as it evolves, the WD is very likely to continue gaining mass and angular momentum until the envelope of the giant donor is exhausted. At that point, mass transfer ceases, and the first-formed WD can begin to spin down and to cool after mass transfer, just as its companion, the degenerate core of the donor star, also begins to cool. At the time of explosion, the remnant of the donor is a WD, less massive than the one that exploded. It has been cooling for a time equal to the time the massive WD needed...
to spin down. Its mass and temperature can therefore be used to measure the spin-down time. Justham (2011) argues that the amount of hydrogen left on the donors in these systems is below the current detection limits, providing a potential explanation for the lack of hydrogen in SNe Ia spectra.

2.2.2. Main-sequence Star Donors

Consider the case in which the donor is a main-sequence star. In this case the donor must be more massive than the WD when it first fills its Roche lobe, in order for enough mass to be donated at an accretion rate high enough to promote nuclear burning and to bring a carbon–oxygen WD to the Chandrasekhar mass. As the mass of the donor star decreases and the mass of the WD increases, the rate of mass transfer declines. Once the mass ratio reverses, mass transfer continues at a high rate until the donor star achieves thermal equilibrium. During this interval, much of the accreted mass continues to be burned; instead of being processed in a quasi-steady manner, however, it may burn episodically during recurrent novae. Once the donor star achieves thermal equilibrium, its thermal readjustment no longer drives mass transfer, which must then proceed through the agency of magnetic braking, producing a mass-transfer rate that starts at about $10^{-8} \ M_\odot / \text{yr}$ and declines as the donor continues to lose mass. The WD can no longer retain the accreted mass and is free to spin down. By the time of explosion, the companion star may still be donating mass at a low rate. Just prior to explosion, the system will be a cataclysmic variable (CV), with a low-mass donor. The mass of the donor can provide a rough measure of the spin-down time.

2.2.3. Subgiant Donors

If the donor is a subgiant at the time during which it donates mass at a high-enough rate to promote lasting mass gain by its WD companion, then elements of both scenarios apply. Like the case in which the donor is a main-sequence star, the mass accretion rate will decline sometime after the mass ratio reverses. But, as in the giant-donor case, the donor will run out of envelope after an interval of mass transfer. Thus, depending on the spin-down time, the system may be a CV (similar to AE Aqr, which we will discuss below) just prior to explosion, or else it may consist of a WD (likely an He WD) orbiting the massive WD.

2.2.4. Spin-down Time

The general trend is that the donor star will be less massive and less luminous at the time of explosion if spin-up/spin-down occurs. The physical characteristics of the system are determined by the spin-down time. The relationship between the properties of the widowed donor to the spin-down time is fortunate because it has the potential to provide a way to estimate the spin-down time of real systems. First-principles estimates have proved difficult, and the spin-down time is not well constrained at present. Theoretically, spin-down times are uncertain by several orders of magnitude; estimates range from $10^3$ to $10^7$ years (Lindblom 1999; Yoon & Langer 2005). For example, van Amerongen et al. (1987) show that the timescale for the secular decrease of the spin rate of an accreting magnetized WD in CVs is $(6 \times 10^8 / P_{\text{orb}}/4\text{ hr})^{-2.2}$. Unfortunately, observations of spinning-down WDs are scarce. The best example of a WD currently spinning down is AE Aqr, which contains a $0.79 \pm 0.16 \ M_\odot$ WD and a $0.50 \pm 0.10 \ M_\odot$ K5 dwarf companion in a 9.9 hr orbit (Casares et al. 1996). The WD in AE Aqr is currently spinning down at a rate $P = 5.64 \times 10^{-14} \text{ s}^{-1}$ (de Jager et al. 1994), which corresponds to a spin-down time of $2 \times 10^7$ years (Mauche 2006). The evolutionary history of AE Aqr exactly parallels that of SD progenitors that experience spin up; it apparently had a high mass transfer rate, allowing the WD to gain mass; it is now spinning down. The mass gained was, however, not enough to bring the WD to a mass near $M_{\text{crit}}$. There is evidence that other WDs in CVs have gained mass. For example, Yuasa et al. (2010) study the mass distribution of WDs in intermediate polars and show that the average WD mass of their sample is $0.88 \pm 0.25 \ M_\odot$. This is significantly larger than the average mass of the WDs in the solar neighborhood (Tremblay et al. 2011). In addition, 7 of the 17 systems in the Yuasa et al. (2010) study have WD masses above $1 \ M_\odot$. AE Aqr is perhaps the best example of a CV with a WD of mass smaller than $M_{\text{crit}}$ that appears to have followed the evolutionary track we suggest. In fact, since binaries in which a WD achieves the critical mass must be a small minority of binaries in which the WD accretes matter, we expect AE Aqr to be an example of many other members of its class. This system demonstrates that, even though angular momentum and its attendant physics are difficult to compute, spin-up/spin-down is realized in nature.

3. SNR 0509-67.5

SNR 0509-67.5 is a 400 year old SN Ia remnant in the LMC. Based on its light echo and X-ray spectrum, Rest et al. (2008) and Badenes et al. (2008) demonstrate that SNR 0509-67.5 originated from an exceptionally bright SN Ia that synthesized $\sim 1 \ M_\odot$ of $^{56}$Ni. Its youth and location means that it provides a unique opportunity to determine the nature of its progenitor and to take an important step toward resolving the so-called progenitor puzzle. It is possible the WD whose explosion created SNR 0509-67.5 accreted mass from a companion. If so, that donor star likely survived the explosion, and is moving away from its site with a speed comparable to its former orbital speed. It would presently lie within about 0.3 of the explosion site, if its transverse velocity is smaller than 200 km s$^{-1}$. The LMC is close enough that we can, in principle, detect this newly “widowed” donor star.

Using 1010, 696, and 800 s exposures in the B, V, and I filters taken with the HST WFPC3, Schaefer & Pagnotta (2012) rule out ex-companion stars down to $V = 26.9$ mag in the central 1’ region. This magnitude limit corresponds to $M_V = +8.4$ mag at the LMC’s distance, ruling out a wide range of possible donors. This limit, however, does not take into account the extinction in the line of sight to the LMC ($A_V \approx 0.25$ mag; A. Pagnotta 2012, private communication). Hence, the absolute magnitude limit achieved by the current HST observations is at $M_V = 8.15$ mag, as shown in Figure 1.

To use this limit to place constraints on the flux from the widowed donor, it is important to locate the position at which the explosion occurred. We need to be certain that no stars lie close enough to the explosion site to be identified as possible ex-donors. Had the event occurred in a uniform medium, the supernova remnant would likely exhibit axial symmetry, making it possible to uniquely identify a center, which would be the most likely point of explosion. In the case of SNR 0509-67.5, it exhibits an asymmetric spatial pattern indicating that the surrounding medium is not uniform. Simulations can reproduce the pattern and identify the true site of the explosion (S. Reynolds 2012, private communication). Schaefer & Pagnotta (2012) instead studied the geometry of the remnant
3 However, helium-rich degenerate donor stars in the double-detonation model (e.g., Nomoto 1980; Woosley & Weaver 1994; Ruitert et al. 2011; Sim et al. 2012) cannot be ruled out.

to identify the likely explosion site, in a manner that also considers the asymmetry. Should the supernova have occurred at a position offset from the one identified geometrically, then, instead of a definite null detection, there could be a set of candidates for the widowed donor, shown in Figure 1 of Schaefer & Pagnotta (2012). In this case, each candidate would correspond to a possible binary model, and each would place different possible limits on the spin-down time. If one of these candidates was observed to have high proper motion and/or to be enriched in materials expected from the explosion, then the progenitor would be identified and the binary model could be unique. In the discussion below, we assume that the geometrical work produces the correct result, so that there are no candidate ex-donors down to the flux probed by the HST observations. If this is not the case, and there are candidate donors, then each would need to be studied separately. This more complex process will certainly apply to the sites of other remnants of SNe Ia.

Schaefer & Pagnotta (2012) conclude that all possible donor stars had been eliminated, proving that the progenitor was a DD system whose components merged.3 If, however, the WD gained mass from a companion, it would likely have also gained angular momentum. It may therefore have a higher critical mass and may need to spin down to decrease the value of \( M_{\text{crit}} \) to the current value of its mass.

After the spin-down episode, the donor star could be dim enough by the time of explosion that it would not have been detected in the existing data. The unknown spin-down timescales for fast spinning massive WDs are therefore extremely important for the visibility of ex-companion star in SNR 0509-67.5. Here we consider two cases, a red giant/subgiant companion and a main-sequence star companion.

### 3.1. Red Giant Companions

For giants and some subgiants, the mass-transfer rate will not decrease, and spin-down cannot start before the giant’s envelope is depleted. The giant donor becomes a WD that cools during spin down (Di Stefano et al. 2011; Justham 2011). Figure 1 displays the absolute magnitude versus the (cooling age) spin-down time for ex-companion WDs. If the spin-down takes longer than \( 10^7 \) years, such ex-donors are likely to be very dim today, requiring deep imaging observations. Ruling out present-day He-core (\( M < 0.45 M_{\odot} \)) WDs would rule out an ex-donor on the red giant branch; allowing higher mass present-day WDs would indicate ex-donors on the asymptotic giant branch.

For spin-down times of \( 10^6 \) years, the current HST observations allow ex-donors that are WDs with \( M > 0.6 M_{\odot} \). For spin-down times of \( 10^7 \) years, only low-mass He-core WDs are ruled out; higher mass WDs with \( M > 0.4 M_{\odot} \) would be hidden in the current data. For even longer spin-down times of \( 10^8-10^9 \) years, the current data cannot rule out even the lowest mass He-core WDs. Figure 2 displays the ruled-out ex-companion WDs for a given spin-down time; C/O core WDs may be hiding in the center of this remnant if the spin-down times are longer than about \( 10^5 \) years.

### 3.2. Main-sequence Companions

Figure 3 shows the evolution of the ex-companion main-sequence stars to (super-)Chandrasekhar-mass WD explosions. We consider 1.79 and 1.39 \( M_{\odot} \) WDs. For each value of the WD mass, we have assumed that the low-\( M \) phase begins when the donor star is 0.1 \( M_{\odot} \) less massive than its WD companion. This value is uncertain, since it depends on issues such as...
the readjustment of the donor star, the generation of radiation from the vicinity of the accreting WD, and its effect on the donor. Once magnetic braking becomes the dominant driver of orbital evolution and mass transfer, the system will have entered the realm of CVs, which have been well studied, using both theory and observations. Nevertheless, there are significant uncertainties about key issues such as magnetic braking, and the possible “bloating” of the donor star. To illustrate that there is a range of possibilities, we show for each value of the initial donor mass the results for two different values of the magnetic braking parameter, γ (cf. Equation (36) in Rappaport et al. 1983), as described in the caption.

The limits placed by a non-detection in the current data mean that a main-sequence star with mass larger than approximately 0.5 \( M_\odot \) would have been detected if the spin-down time is shorter than about \( 10^7 \)–9 years to \( 10^8 \) years. Thus, it is possible that the donor star would not have been detected, if the spin-down time is in this range or longer.

It is important to push the limit on the mass of the widowed donor to even lower values. The reason for this is that the evolution of the CV slows down considerably for values of the donor mass of about 0.3 \( M_\odot \). Magnetic breaking ceases, and the further evolution of the orbit is governed by gravitational radiation, which is generally a slower process. Thus, if we could establish that the donor had a mass of less than 0.2 \( M_\odot \), then the spin-down time would have to be larger than \( \sim 10^9 \) years.

4. DISCUSSION

Nearby SNe Ia remnants provide us the best opportunity to identify the progenitor systems. The discovery of an ex-companion star in these remnants would be direct evidence of an SD progenitor. Hence, any process that can hide such companions is important. Di Stefano et al. (2011) discuss one such mechanism, the spin-up/spin-down channel, in which the recently widowed companion has \( 10^5 – 10^7 \) years to evolve during the spin-down phase and before the explosion.

Revisiting the available data on SNR 0509-67.5, we demonstrate that the current magnitude limit of the HST observations, \( V = 26.9 \) mag, is relatively shallow to reject an SD progenitor that had to spin-down before an explosion. However, deeper imaging observations with the HST WFC3 can achieve magnitude limits that are more meaningful for ex-companion star searches. Figure 1 demonstrates that an \( M_V = 11 \) mag search, \( V \approx 29.5 \) mag at the LMC’s distance, would identify or rule out all C/O and He-core WDs for spin-down times of \( \lesssim 10^7 \) years and \( M \lesssim 1 \ M_\odot \) WDs for \( \lesssim 10^6 \) years. These observations would also be sensitive to all ex-companion main-sequence stars with \( M \geq 0.2 \ M_\odot \) for spin-down times of up to \( 10^7 \) years. Even deeper limits can be achieved with the James Webb Space Telescope. If the donor star is detected in such observations, this would be an important first, which would allow us to model the progenitor and determine the spin-down time. If no ex-companions are detected, this would suggest either a DD progenitor system or a double-detonation event with an undetectably faint present-day helium-core WD companion (Nomoto 1980; Woosley & Weaver 1994; Ritter et al. 2011; Sim et al. 2012).

In either case, the result would be the most concrete clue to the nature of any SN Ia progenitor, and would provide the most direct insight yet to the solution of the SNe Ia progenitor puzzle. Another complication in the studies of SNe Ia remnants arises due to the unknown center of the explosion. Based on hydrodynamic simulations, Dohm-Palmer & Jones (1996) demonstrate that in the presence of a nonuniform external density region there can be a significant shift in the apparent geometric center of a remnant away from the explosion center. If the remnant is smaller than the width of the density transition, it maintains a circular shape but the apparent center shifts. Borkowski et al. (2006) and Williams et al. (2011) detect a large asymmetry in the infrared brightness profile of SNR 0509-67.5; one hemisphere of this remnant is brighter than the other side by a factor of five in the Spitzer 24 \( \mu \)m images. This brightness difference is most likely due to the forward shock running into material that is several times denser than in other places (Williams et al. 2011). Therefore, there is indirect evidence from the infrared observations that the interstellar medium in the explosion site is nonuniform and the apparent center of this remnant has likely shifted from its original location.

A comparison of the HST images of SNR 0509-67.5 (see Figure 1 in Schaefer & Pagnotta 2012) and the hydrodynamic simulations (see Figures 10 and 11 in Dohm-Palmer & Jones 1996) show that the apparent center is likely to shift toward the low-density side. Hence, the real explosion site for SNR 0509-67.5 is likely to the right of the current geometric center. Schaefer & Pagnotta (2012) consider such a shift based on the geometric appearance and the ellipticity of the remnant. However, Dohm-Palmer & Jones (1996) argue that the geometric center corrected for the ellipticity of the remnant may not represent the actual center of a Ia remnant and that detailed hydrodynamical simulations are required to constrain the actual explosion site (S. Reynolds 2012, private communication). There are several targets, e.g., stars B, C, E, and I, to the right of the 3σ error circle as measured by Schaefer & Pagnotta (2012). The absolute magnitudes and the \( V-I \) colors of these stars are consistent with \( 0.5-1 \ M_\odot \) main-sequence stars. Hence, one of these could be the ex-companion star to SNR 0509-67.5 that evolved as a CV during the spin-down phase of the exploding WD. Until hydrodynamic simulations for this remnant are...
available, a main-sequence ex-companion cannot be ruled out for SNR 0509-67.5.

5. CONCLUSIONS

Recent studies based on the delay time distribution of SNe Ia (Maiz et al. 2010) and the merger rate of double WD systems (Brown et al. 2011; Badenes & Maoz 2012) suggest that double WDs may contribute significantly to SNe Ia events. Therefore, there is a tendency in the community toward searching for more evidence for such progenitor systems. One way to identify a double WD progenitor is to search for and rule-out ex-companion stars in SNe Ia remnants. Proving that something does not exist is obviously difficult, and such claims require extraordinary evidence. In this paper, we revisited the evidence for absence of an ex-companion star in the young LMC SNe Ia remnant SNR 0509-67.5. We demonstrate that in the spin-up/spin-down model, the WD needs $10^5-10^6$ years before a Ia explosion, which lets the companion evolve into either a faint WD (if the companion starts as a subgiant) or a low-mass main-sequence star (if the companion starts as a main-sequence star). The current limits on the ex-companions are not stringent enough to rule out faint WDs and $M < 0.5 M_\odot$ main-sequence stars in SNR 0509-67.5. Hence, the absence of evidence for an ex-companion star in this remnant, as well as other SNe Ia remnants, does not provide the evidence of absence for such companions.

Future deep imaging observations can detect or rule out the majority of the C/O WD ex-companions and low-mass main-sequence stars for plausible spin-down times of $\lesssim 10^5$ years. If a companion is detected, this would be a first, and it would constrain the uncertain spin-down times for WDs near the Chandrasekhar mass. A non-detection can, in principle, rule out the SD channel even in the spin-up/spin-down models. However, until such observations are obtained, we consider an SD progenitor for SNR 0509-67.5 still possible.

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