A Quadruple or Triple Origin For Tycho B and SN 1572

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1 INTRODUCTION

The progenitors of Type Ia supernovae remain unknown (Maoz & Mannucci 2012). Recent searches for possible binary companions in their remnants have strongly constrained the single-degenerate model (Li et al. 2011; Schaefer & Pagnotta 2013). The lack of obvious companions points to the double-degenerate model, wherein the merger of WD-WD binaries produce Ia supernovae (Iben & Tutukov 1984; Webbink 1984).

That Ia’s from the merger of WD-WD binaries might occur in higher-order multiple systems was first discussed by Iben & Tutukov (1999). Thompson (2011) showed that this “eccentric Kozai mechanism” (EKM), which is suppressed in nearly equal mass binaries, can be triggered by mass loss; after the AGB phase of an intermediate-mass star, this could bring a WD to tidal contact with its stellar companion via EKM. Katz et al. (2011) and Kerzendorf et al. (2012) recently reported the startling discovery of a metal-poor ([Fe/H] $\approx -1 \pm 0.4$) A-type star near the center of the Tycho supernova remnant. We propose two possible explanations. In the first, Tycho B is a blue straggler, formed from the merger of a close K- or G-type binary system, which was previously in a quadruple system with the binary that produced SN 1572. Both binaries were likely brought to tidal contact by Kozai-Lidov oscillations acting in concert with tidal friction. Analogous progenitor systems may include CzeV343, VW LMi, and KIC 4247791. In the second, Tycho B is the surviving tertiary of a triple system, which was also likely affected by Kozai-Lidov oscillations. Rates are briefly discussed. Problems with each evolutionary scenario are presented. Finally, a chance alignment between Tycho B and the supernova remnant is not excluded.

Estimates indicate that many Ia supernovae could occur in triple systems, motivating searches for the surviving tertiary in supernova remnants (Thompson 2011). However, since the semi-major axis of the tertiary is expected to be $\sim 1 \times 10^2$ AU at the time of the explosion, it is likely to have normal abundances and kinematics, and to have undergone minimal shock heating and ablation (Mariett et al. 2003; Shappley et al. 2013; Pan et al. 2013).

In addition to these points about the role of multiple systems in compact object mergers, the combined effects of Kozai-Lidov oscillations and tidal friction likely produce many close binaries (Mazeh & Shaham 1979; Eggleton & Kiseleva-Eggleton 2001). Tokovinin et al. (2006) find that the fraction of stellar binaries with tertiary components strongly increases as the inner binary period decreases, suggesting that Kozai-Lidov oscillations drive the system to high enough eccentricity to reach tidal contact, and that subsequent tidal evolution produces the abundance of short-period binaries (Fabrycky & Tremaine 2007). The same mechanism has been invoked to explain the production of hot Jupiters on $\sim 3$ day orbits (Wu & Murray 2003).

Perets & Fabrycky (2009) argued that the same mechanism could produce blue stragglers by causing stellar mergers, leading to stars that otherwise could not exist in the old populations of globular clusters (Leonard & Linnell 1992). Moreover, they noted that since the quadruple fraction is comparable to the triple fraction, there could be double blue straggler binaries, in which mutual Kozai-Lidov oscillations brought both binaries to contact and merger.

Finally, it has also been shown that the quadrupole-order expansion of the three-body Hamiltonian for the secular evolution of triple systems does not capture the dynamics when the mass ratio between the inner two binary components is large, and the eccentricity of the tertiary is non-zero. Katz et al. (2011) and Lithwick & Naoz (2011) showed that the dynamics change qualitatively at octupole-order. In particular, the inner binary can flip from prograde to retrograde, and vice-versa, causing large eccentricity excursions to $1 - e \sim 10^{-4} - 10^{-5}$. Shappee & Thompson (2012) showed that this “eccentric Kozai mechanism” (EKM), which is suppressed in nearly equal mass binaries, can be triggered by mass loss; after the AGB phase of an intermediate-mass star, this could bring a WD to tidal contact with its stellar companion via EKM. They termed this the “Mass-loss Induced Eccentric Kozai mechanism” (MIEK).

Kerzendorf et al. (2012)’s discovery of a metal-poor ([Fe/H] $\approx -1 \pm 0.4$) rotating ($V \sin i \approx 170$ km s$^{-1}$) A-type star (Tycho B) at the center of the Tycho supernova remnant brings these disparate issues into sharp focus.

2 EVOLUTIONARY SEQUENCES & PROBLEMS

The first evolutionary sequence we envision is as follows. A hierarchical quadruple system forms in the thick disk $\sim 10$ Gyr ago with
metallicity $[\text{Fe/Hi}] \simeq -1$, with A/B-A/B ($\simeq 3 - 5 \, M_\odot$) and KG-KG (0.8 - 1 $M_\odot$) components. The initial individual semi-major axes may be $\lesssim 1$ AU, and the semi-major axis of the orbit of the two systems is $\sim 10 - 100$ AU. Our picture is that both systems were brought to tidal contact by either normal Kozai-Lidov oscillations or a combination of EKM and MIEK, or some yet unknown 4-body mechanism. There is also the possibility that the system was simply born with two close binaries. Common envelope and stellar evolution in the more massive system leads to a massive WD-WD binary, which emits gravitational waves and evolves to smaller semi-major axis until it eventually merges, producing SN 1572. Approximately 0.5 - 1 Gyr before the explosion, the less massive binary merges, forming a blue straggler via the mechanism described in Perets & Fabrycky (2009), and producing Tycho B.

The observed rotation velocity of $V\sin \, i \simeq 170$ km s$^{-1}$ is consistent with intermediate-mass low-metallicity A-type blue stragglers (Shara et al. 1997), but it is somewhat higher than is observed in old Galactic open clusters (Mantega et al. 1989). Additionally, a rotation velocity of $170$ km s$^{-1}$ is not exceptional for a field A star (Zorec & Rovej 2012).

The obvious problem with this evolutionary sequence is the kinematics of Tycho B, which are consistent with a cold thin disk population (Kerzendorf et al. 2012; their Table 2). Nevertheless, we see no other way to get a $[\text{Fe/Hi}] \sim -1$ A-type star in the present Milky Way unless it migrated from the outer Galaxy.

The second scenario begins with a thin-disk hierarchical triple system composed of an A/B-A/B binary and an A star tertiary born $\sim 0.5$ Gyr ago. The massive binary evolves in a way similar to the first evolutionary scenario, producing SN 1572, and Tycho B is the surviving tertiary. This scenario has the problem that it would predict $[\text{Fe/Hi}] \sim 0$, unless the system originated in the far outer Galaxy.

Another possibility is that Tycho B is a chance projection. This is only plausible if $[\text{Fe/Hi}]$ is in fact $\sim 0$ since the space density of $[\text{Fe/Hi}] = -1$ A stars is very small. Although Tycho B is within 5$''$ of the geometric X-ray center of the remnant from Chandra, Kerzendorf et al. (2012) argue that the center is not known to within 30$''$ on the basis of radio data. The chance alignment to within $\theta$ at a distance of a few kpc, given a space density of $\sim 3 \times 10^{-4} \, \text{pc}^{-3}$ is $\sim 0.01 (\theta / 5'')^2$. Thus, chance projection is plausible for Tycho B if the metallicity is Solar, or somewhat sub-Solar.

3 QUADRUPOLE SYSTEMS WITH CLOSE BINARIES

There are a number of quadruple systems known that may consist of two close binaries, and which may thus be prototypes for the system we envision in the first scenario for SN1572+Tycho-B. These include CzeV343 (Cagaš & Pejcha 2012), V994 Her (Lee et al. 2008), OGLE J051343.14-691837.1 (Oid 2008), Rivinius et al. (2011), BD-22 5866 (Shkolnik et al. 2008), VW LMi (Pribulla et al. 2008), KIC 4247791 (Lehmann et al. 2012), and others (e.g., Pilecki & Szczygieł 2007).

V994 Her is a B8+A0 + A2+A4 quadruple system with individual periods of $\sim 2$ and $\sim 1.4$ days, and with an estimated mutual period of a few thousand years (Lee et al. 2008). BD-22 5866 is a K7+K7 + M1+M2 quadruple system with individual periods of $\sim 2.2$ and $\lesssim 62$ days, and with an estimated semi-major axis of $\sim 5.3$ AU (Shkolnik et al. 2008). VW LMi has a contact eclipsing binary with period $\sim 0.48$ days with a non-eclipsing detached binary with a period of $\sim 7.9$ days, $\text{on a mutual orbit}$ with period $\sim 355$ days and eccentricity $\sim 0.1$ (Pribulla et al. 2008).

Although none of these systems is precisely analogous to that required to explain SN 1572+Tycho-B, we consider the existence of such objects to essentially prove that the quadruple scenario we propose is possible. Perets & Fabrycky (2009) make the similar point that binary blue straggler systems should exist since mutual Kozai could produce quadruple systems with close binaries that subsequently merge. Here, we simply appeal to the existence of higher mass binaries that might then produce WD-WD binaries capable of leading to Ia supernovae.

4 RATES & FRACTIONS

Approximately 2% of all stars born in the mass range $\sim 2.5 - 8 M_\odot$ become Ia supernovae (Horiuchi & Beacom 2010). If sub-Chandrasekhar mass binaries produce Ia supernovae, the fraction is smaller.

Triples — About $\sim 10\%$ of systems are triple (Raghavan et al. 2010), but the uncertainty in this statement increases as a function of mass, particularly for systems which might have large mass ratios. In general, we can say that multiplicity is a strong function of mass since over 70% of B- and A-type stars have companions (Shatsky & Tokovinin 2002; Kouwenhoven et al. 2007). For these reasons, Thompson (2011) argues that in principle all Ia supernovae could occur in triple systems, particularly since systems comprised of, e.g., A/B-A/B + G/WD would be very difficult to find.

Quadruples — The fraction of all intermediate-mass stars in quadruple systems consisting of two close binaries is more uncertain. For KIC 4247791, the a priori probability for eclipses of both quadruple systems consisting of two close binaries is about $0.17 \times 0.1$ if both orbital planes are randomly oriented on the sky. This implies that such systems are $\sim 60$ times more common than observed. Since just one system has been found among the $\sim 10^3$ intermediate-mass systems monitored by Kepler (Pinsonneault et al. 2012), we conclude that $\sim 6 \times 10^{-3}$ or $0.6\%$ of intermediate-mass systems are hierarchical quadruples consisting of two close binaries. Poisson statistics on a single such system suggest that the upper and lower limits on the fraction of such systems is $\sim 3$ and $\sim 10$ times higher and lower, respectively, than our nominal estimate at 95% confidence.

This fraction is consistent with the expectation from multiplicity studies. The quadruple fraction ($f_{\text{quad}}$) is smaller than the triple fraction by $\sim 1/3$ (Raghavan et al. 2010). If we suppose that $\sim 0.1$ of these systems are either born close ($f_{\text{close}}$), or could be strongly affected by Kozai-Lidov oscillations, then one expects $f_{\text{quad}} \times f_{\text{close}} \sim 0.03 \times 0.1 \sim 3 \times 10^{-3}$ or $\sim 0.3\%$ of all systems to be quadruples composed of two close binaries. Unfortunately, little
is known for massive A/B-A/B binaries in quadruple systems with K/G-K/G binaries, as such systems would be exceedingly difficult to discover and characterize.

One theoretical argument made by Shappee & Thompson (2012) is that intermediate-mass star binaries in triple systems (or, presumably, quads) will in general be more susceptible to MIEK since the ratio of their ZAMS mass to their WD mass is large, implying that there will be a phase after the primary evolves when the mass ratio of the two components of the more massive binary is large, leading to the EKM. For this reason, it may be more likely to produce the type of close binary that will lead to Ia supernovae in quads with A/B-A/B components, and thus the factor $f_{\text{close}}$ could be larger than $\sim 0.1$ in the above estimate.

Summary—Within the very considerable uncertainties, the fraction of intermediate-mass triple systems and quadruple systems composed of two close binaries is consistent with the fraction of intermediate-mass stars that become Ia supernovae.

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