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Spin-Up/Spin-Down models for Type Ia Supernovae

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ABSTRACT

In the single degenerate scenario for Type Ia supernova (SNeIa), a white dwarf (WD) must gain a significant amount of matter from a companion star. Because the accreted mass carries angular momentum, the WD is likely to achieve fast spin periods, which can increase the critical mass, M_{crit} , needed for explosion. When M_{crit} is higher than the maximum mass achieved by the WD, the WD must spin down before it can explode. This introduces a delay between the time at which the WD has completed its epoch of mass gain and the time of the explosion. Matter ejected from the binary during mass transfer therefore has a chance to become diffuse, and the explosion occurs in a medium with a density similar to that of typical regions of the interstellar medium. Also, either by the end of the WD's mass increase or else by the time of explosion, the donor may exhaust its stellar envelope and become a WD. This alters, generally diminishing, explosion signatures related to the donor star. Nevertheless, the spin-up/spin-down model is highly predictive. Prior to explosion, progenitors can be super- M_{Ch} WDs in either wide binaries with WD companions, or else in cataclysmic variables. These systems can be discovered and studied through wide-field surveys. Post explosion, the spin-up/spin-down model predicts a population of fast-moving WDs, low-mass stars, and even brown dwarfs. In addition, the spin-up/spin-down model provides a paradigm which may be able to explain both the similarities and the diversity observed among SNeIa.

1. Introduction

Type Ia supernovae (SNeIa) are believed to be the explosions of carbon-oxygen white dwarfs (CO WDs). To explode, a CO WD must reach a critical mass (M_{crit}) generally assumed to be the Chandrasekhar mass ($M_{Ch} \sim 1.4 M_{\odot}$). This can be achieved either through accretion from a companion star (the single-degenerate [SD] scenario) or through the merger of two WDs (the double-degenerate [DD] scenario). Key signatures of the SD scenario include direct detection of progenitors in archival images, direct detection of companions in supernova remnants, and radiation emitted when light and matter from the supernova interact with the companion star or with circumstellar material that had been ejected from the progenitor binary. With the exception of signatures that may be due to absorption by circumstellar material in a small number of SNeIa (Patat et al. 2007), these strong signatures have not yet been definitely detected, calling into question the relevance of SD models.

In SD models, the WD must accrete and retain matter. This requires high mass infall rates, with $\dot{M} > 10^{-7} M_{\odot} \text{yr}^{-1}$ (Iben 1982; Nomoto 1982; Prialnik & Kovetz 1995; Shen & Bildsten 2007). Because infalling matter carries angular momentum, the angular momentum of the WD must increase. Although spin-up seems certain to occur, its effects are difficult to compute from first principles. One effect is an increase in the value of M_{crit} (Anand 1965; Roxburgh 1965; Ostriker & Bodenheimer 1968; Hachisu 1986; Yoon & Langer 2005). We will show that an increase in M_{crit} has a profound effect on the progenitor signatures. Some of the oft-expected donor signatures are diminished, possibly explaining why they have either not been detected, or have been detected only rarely. Nevertheless, the spin-up/spin-down model is testable, because it suggests alternative ways to identify the progenitors and test SD models. In section 2 we discuss the model, using 4 key points to summarize the features relevant to observations of the progenitors and explosions, to which we turn in section 3. In section 4 we discuss how spin-up/spin-down provides a testable paradigm that can explain both the unity and diversity among SNeIa.

2. Spin-Up and Spin-Down

(1) *Infalling matter spins up the WD to near-critical rotation.* Because infalling matter carries angular momentum, the angular momentum of the WD must increase when the infalling matter is retained. Spin-up is a common process in accreting compact objects. Neutron stars (NSs), for example, can be spun up to periods of a few milliseconds (see review by Lorimer 2008). Similarly a number of fast-spinning WDs that must have been spun up by accretion are known, for example WZ Sge, 27.87 s; AE Aqr, 33.06 s; V842 Cen, 56.82 s and V455 And, 67.2 s¹. These periods are much longer than for NSs, due to the much higher moment of inertia of WDs, but similar to the milli-second pulsars, the surface velocity is only a factor of few lower than the escape speed.

We can measure the spins in these specific systems because the WDs are intermediate polars (IPs) where the accretion is channeled along the field lines of the WD (Warner 1995). This is possible only for relatively modest accretion rates; higher rates will increase the infalling matter density and probably quench the magnetic fields. The binaries most likely to be progenitors of SNeIa have rates of mass transfer that are hundreds or thousands of times greater than those inferred for IPs. The retention of mass should make it possible to spin mass-gaining WDs to even shorter periods than measured for IPs, even if measurements are difficult.

GK Per, which experienced a classical nova in 1901, has a spin period of 351 s, and is spinning up at a rate measured to be $0.00027 \pm .00005 \text{s yr}^{-1}$ (Mauche 2004), corresponding to a spin-up of 2.7×10^5 s per solar mass accreted in this system. The WDs which evolve towards SNeIa must accrete *at least* $0.2 M_{\odot}$. Although the specific angular momentum carried by infalling matter will vary among binary systems [see, e.g., Popham & Narayan (1991)], the spin-up of GK Per suggests that WDs can gain enough angular momentum to reach critical rotation.

(2) *The rotation increases the critical mass M_{crit} , needed for the explosion.* This implies

¹see the catalogue of intermediate polars at <http://asd.gsfc.nasa.gov/Koji.Mukai/iphone/iphone.html>

that accreting WDs can achieve masses in excess of M_{Ch} without either exploding or imploding. For a rigid rotator, maximal rotation produces an increase in M_{crit} of roughly 5% (Anand 1965; Roxburgh 1965). For more complex radial distributions of the internal angular momentum, Ostriker & Bodenheimer (1968) showed that the critical mass could become very high; they constructed models with M_{crit} as high as $4 M_{\odot}$, noting, however, that not all of the configurations they considered were likely to be realized in nature. Hachisu (1986) also found stable equilibrium configurations with $M_{WD} > 2 M_{\odot}$. Yoon & Langer (2005) considered spin-up due to accretion and derived comparably high masses. Piro (2008) included viscous effects and found that, under certain input assumptions, the WD should be able to achieve a state close to uniform rotation during much of the accretion phase, but that differential rotation could be important during a short-lived ($\sim 10^3$ years) “simmering” phase just prior to explosion. The bottom line is that the values of M_{crit} are difficult to compute from first principles, and that the rigid-rotation limit can be taken to give a lower bound.

(3) *Spin-down can occur when \dot{M} is low or when mass transfer has ceased.* As \dot{M} decreases, more angular momentum may be lost per unit time than gained (as is seen in AE Aqr Meintjes 2002; Ikhsanov et al. 2004). Gravitational radiation associated with spin-induced effects can produce spin-down in even isolated WDs. (Sedrakian et al. 2006). Spin-down times are uncertain, but almost certainly exhibit a large range, from $< 10^6$ years to $> 10^9$ years (Lindblom 1999; Yoon & Langer 2005).

(4) *Explosion occurs when the spin period has been reduced to a critical value, P_{crit} .* As the spin of the super-Chandrasekhar WD decreases, so does the value of M_{crit} . When the value of M_{crit} falls below the current mass of the WD, the WD will explode or, if it has crystallized, it may collapse (Nomoto & Kondo 1991). The nature of the event and its appearance depend on the state of the WD when mass gain stops and on the details of the subsequent evolution. For example, does mass transfer continue at a low level? what is the time required for spin down?

3. Observational Signatures

3.1. Background

Population: Let f denote the fraction of all SNeIa progenitors in which (a) spin up produces a significant change in the value of M_{crit} , and (b) the maximum mass achieved by the WD is smaller than M_{crit} , necessitating an interval of spin down. If the rate of SNeIa is R , then the number of spinning-down progenitors in the Galaxy is $f \times (3 \times 10^5) (\tau/10^8 \text{yrs}) \times (R/0.003 \text{yr}^{-1})$, with up to a few thousand lying within a kpc of Earth. τ is the spin-down time: the time between the end of genuine mass gain by the WD and the explosion. There could be an even larger number of Galactic post-explosion systems: $f \times (3 \times 10^7) \times (R/0.003 \text{yr}^{-1})$, if SNeIa have been occurring in the Galaxy for 10^{10} years.

Binary Evolution: SD SNeIa progenitors must have donor stars whose state of evolution, mass, and orbital separation enable them to contribute mass at high rates. Giant donors can do this if the orbital separation is favorable. Once \dot{M} from a giant donor is high enough to promote nuclear burning by the WD, it is likely to stay high. The binary will be a symbiotic in which the WD can gain mass and angular momentum until the giant’s

envelope is depleted. The final pre-SNeIa state is a wide-orbit double WD.

The same evolutionary path can be followed when the donor starts mass transfer as a subgiant if its core is evolved enough. Less evolved subgiant donors and main-sequence (MS) donors follow an alternative channel in which the mass ratio, q , between donor and WD plays an important role. The value of \dot{M} can be high enough to promote nuclear burning only when $q > 1$. When the mass ratio reverses, the rate of mass transfer decreases dramatically. The WD can begin to spin down. The donor may lose a significant fraction of its remaining mass. Subgiant donors could become WDs, reproducing the signatures described above for giant donors. For MS donors, the binary will become an accretion-powered CV; long spin-down times would transform the donor into a degenerate object of brown-dwarf mass, with orbital period as low as ~ 90 minutes. Figure 1 shows the evolution of a subgiant donor whose WD companion gains enough mass to slightly exceed M_{Ch} .

3.2. Progenitor signatures

Missing Signatures: Signatures thought to be integral parts of SD models are diminished. For example, even a spin-down time of 10^5 years provides enough time for circumbinary material to dissipate. Furthermore, the donors are likely to be either compact objects at the time of explosion or else low-mass stars. Signatures of interaction with the supernova would therefore tend to be diminished relative to the case in which spin doesn't play a role.² In addition, the donors tend to be dim, making them difficult to detect, especially in external galaxies. Nor are the WDs likely to be burning nuclear fuel just prior to explosion. This is consistent with the small numbers of supersoft x-ray sources found in external galaxies (Di Stefano et al. 2006; Di Stefano 2010b,a; Di Stefano et al. 2010, 2004, 2003).³

Tests of the models: Systematic searches of data from wide-field surveys, including SDSS, Pan-STARRS, and LSST, should be able to identify those Galactic progenitors nearest to us. [See, e.g., Kleinman et al. (2007); Szkody et al. (2006) for SDSS-based identification of WDs, and CVs, respectively.] To test spin-up/spin-down models, we want to measure the mass function of the spinning-down WDs. The maximum mass will tell us the maximum value of M_{crit} , testing whether differential rotation occurs. Even should no super- M_{Ch} WDs be found, the mass distribution would provide hitherto unavailable information on the mass gain during binary evolution.

Wide double WDs: Binaries containing a super- M_{Ch} in a wide orbit with a compact companion are distinctive, in that they exhibit the spectra of two hot WDs (Figure 2).

²Note that signatures related to circumbinary material and/or interactions with a companion can be ambiguous. For example, a DD may take place inside a common envelope if the envelope ejection efficiency is low. Or, if some SNeIa (either SD or DD) take place in high-order multiple systems, stars not directly involved in the explosion may produce detectable signatures.

³Nuclear burning should take place, however, while the WD gains mass. The lack of SSS-like emission, may be due to an extended photosphere or to absorption by circumstellar matter that then dissipates prior to explosion Di Stefano (2010b,a).

The lower the mass of the secondary, the cooler it will be, and the larger will be the spectral contrast. Studies which have identified WD/M-dwarf pairs in data from e.g., SPY (Maxted et al. 2007) demonstrate that it will be possible to either identify or place limits on the existence of the wide double-WD progenitors we predict. The double-WD SNeIa progenitors with the smallest spectral contrast would be those in which the secondaries are the most massive. These would, however, be distinctive in another way: the separation between the two components could be resolvable (the top panel of Figure 3). When the spectrum indicates that the secondary mass is also high, follow-up observations to determine if the WDs can be resolved would also be useful.

CVs and other mass-transfer binaries: Wide-field surveys, combined with x-ray-source catalogs, can identify CVs and other mass transfer binaries. It is interesting to note that AE Aqr appears to have had an evolution that mirrors what is expected for SNeIa progenitors. The key difference is that the WD’s mass, while larger than typical of WDs, is smaller than M_{Ch} (see, e.g., Meintjes 2002).

3.3. Detecting the Remnants of the Donors

The SNeIa releases the donor from orbit. Hansen (2003) and Justham et al. (2009) considered cases in which the donor has generally not yet finished its evolution at the time of explosion. In the spin-up/spin-down scenario, many donors will have lost their envelopes prior to explosion; the binary will therefore be lighter and have a lower orbital velocity (bottom panel of Figure 3). With the current observational sample (Oppenheimer et al. 2001; Justham et al. 2009) it is not possible to verify that high-speed WDs and isolated low-mass WDs are remnants of SNeIa explosions, or to distinguish among models. New surveys, particularly those that allow high-proper-motion remnants to be identified, will provide more data.

A unique feature of the spin-up/spin-down model is that, if the donor started as a MS star and if τ is large, the donor will be a degenerate brown-dwarf-mass object at the time of explosion. Its speed will be high: for a two-hour period around a $1.6 M_{\odot}$ WD, $v \sim 570 \text{ km s}^{-1}$. Although they constitute a small fraction of Galactic brown dwarfs (at most $10^{-4} - 10^{-3}$), some of these objects could be discovered through their action as lenses, if complementary data allow radiation from the brown dwarf to be detected Di Stefano (2008)

3.4. Other Connections with SNeIa observations and calculations

SNeIa are used as cosmological probes. If explosions occurring at different cosmic times have different amounts of local absorption, this would introduce a systematic uncertainty into measurements of the acceleration of the Universe. When the progenitor is a super- M_{Ch} WD that must spin down before explosion, circumstellar material will play less of a role regardless of redshift. If, therefore, f is large, the systematic uncertainty becomes less significant.

It is important to note, however, that both SD and DD models predict that SNe explosions can occur in a wide range of systems (footnote 2), so that absorption could play

a role in some. Even when spin up occurs, if the mass gain outstrips the increase in M_{crit} , the explosion could take place during the epoch of high \dot{M} .

There is evidence that some SNeIa occur “promptly”, within a few $\times 10^8$ years after star formation, [see e.g., Maoz & Badenes (2010)]. This places limits on the spin-down time for exploding WDs with high-mass donors.

4. Spin-Up/Spin-Down: A new paradigm

Conservation of angular momentum plays an important role in astrophysics. It allows NSs and black holes to be spun up to near maximal rotation. It seems almost certain that WDs can be similarly spun up. Indeed, given the variety of donors and accretion geometries exhibited in nature, spin-up can fail only if there is a fundamental physical principle that disallows it. As long as spin-up to near-maximal rotation occurs, some of the effects we discussed will occur. Although theoretical uncertainties make predictions difficult, we have shown that spin-up/spin-down has testable consequences. The measurements we propose can therefore provide input for theoretical work.

The spin-up/spin-down model appears capable of explaining the full range of SNeIa properties. The mass, M , of the WD at the time of explosion is the first parameter that determines the observable characteristics. Without spin up, SD explosions should occur soon after the WDs reach a critical mass that is very close in value to M_{Ch} . With spin-up, the value of M is influenced by the properties of the initial binary. For a rigid rotator, the WD masses should lie in the range $M_{Ch} - 1.05 M_{Ch}$. In other models, the mass can be higher. By identifying the maximum WD mass, we will learn about the angular momentum profile of the pre-explosion WDs. Of course, only a small fraction of donors can provide enough mass to allow the WD to significantly exceed M_{Ch} ; thus, the largest number of pre-explosion WDs should have masses very close to M_{Ch} . By measuring the distribution of primary WD masses, we will therefore learn about the binaries whose evolutions produce SNeIa.

All other things being equal, each value of M would correspond to a specific value of P_{crit} , the spin at which the value of the critical mass would become equal to M . In fact, however, the angular momentum and internal states will differ at the time mass accretion halts, introducing a difference in the values of τ . Furthermore, if there is residual low-level accretion, this also affects the spin down time. Thus, the value of P_{crit} may be viewed as a second parameter which influences the explosion characteristics.

Finally, the variety of conditions expected at the time when high- \dot{M} mass infall ceases, combined with a wide range of possible spin-down evolutions can yield very different pre-explosion conditions. These can in turn produce some truly unusual light curve and spectral evolutions. While we cannot determine whether spin-up effects explain the characteristics of any specific explosion, it is instructive to consider SN 2008ge (Foley et al. 2008), an SN 2002cx-type explosion, showing an unusual light curve and pattern of spectral evolution. The chemical composition, pre-explosion HST images, and lack of star formation in the host galaxy make it almost certain that SN 2008ge was the explosion of a WD. Yet, the explosion itself may have been different from most SNeIa. A complete deflagration or else incomplete burning have been invoked as possible explanations.

Spin-up/spin-down produces a new paradigm for the progenitors of SNeIa. Key elements can be tested through observations. While not all SNeIa progenitors may be SD, and not all SDs may be significantly affected by spin up, it seems inevitable that angular momentum plays a role in some of the progenitors.

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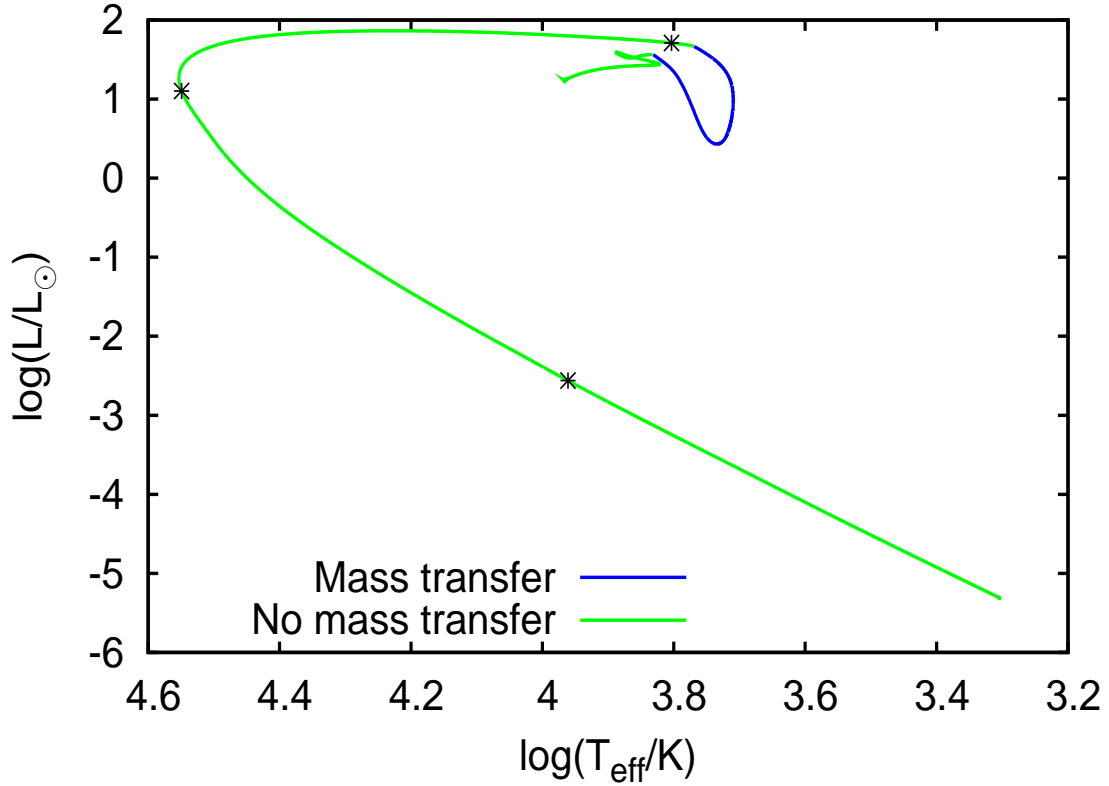


Fig. 1.— Hertzsprung-Russell diagram of the donor star in initial binary system of an $0.7 M_{\odot}$ WD and a $2 M_{\odot}$ MS star (final: $M_{WD} \sim 1.5 M_{\odot}$, $M_{companion} \sim 0.3 M_{\odot}$). Red indicates the phase of mass transfer to the WD. Crosses indicate different times after mass transfer has ceased ($10^6, 10^7, 10^9$ years). Mass transfer starts when the donor is in the Hertzsprung gap and continuous during the GB. After mass transfer the donor star evolves into a He WD. After 10^6 years: the donor will appear as low-mass He-star. After 10^7 years as a hot He-WD, after 10^9 years as a cooler He-WD.

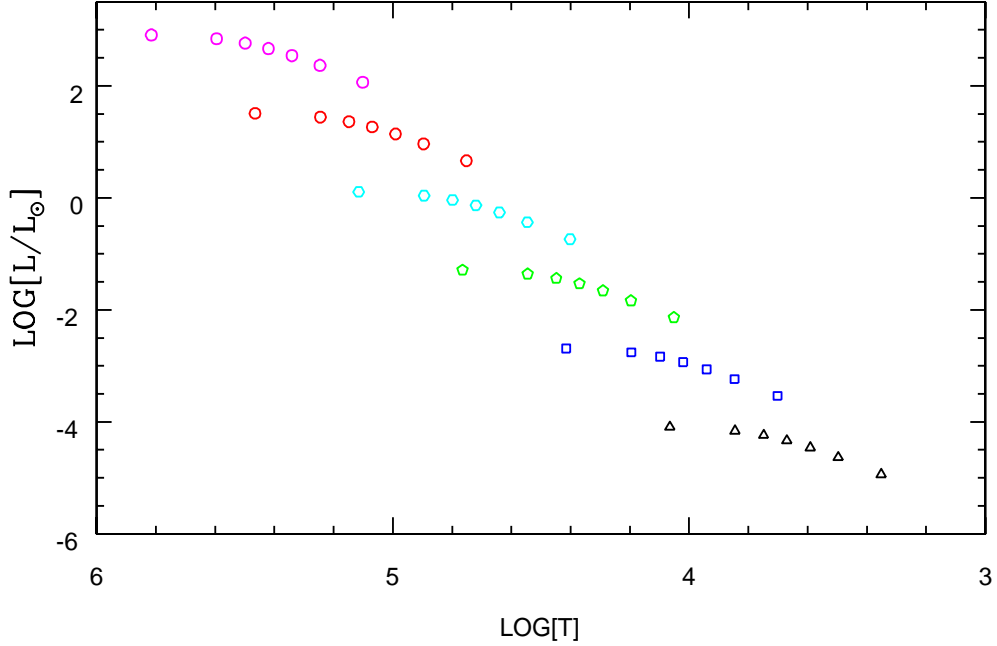


Fig. 2.— Logarithm of luminosity versus the logarithm of temperature for cooling WDs in wide double-WD binaries. Each sequence of single-color points with a fixed number of sides corresponds to a given time after the end of mass transfer. The top row (magenta points) corresponds to 10^5 years, and red, cyan, green blue, and black points correspond to 10^6 , 10^7 , 10^8 , 10^9 , 10^{10} years, respectively. The hottest and brightest system in each sequence corresponds to a Chandrasekhar-mass WD. The super-Chandrasekhar-mass primaries we consider may be somewhat hotter and brighter. Each subsequent point in the same-age sequence corresponds to a WD with a mass $0.2M_{\odot}$ lower than the previous point of the sequence. The minimum mass shown is $0.2 M_{\odot}$. We used the realization of Mestel’s cooling law suggested by Kawaler (1998). Although this model does not exactly mirror the physical systems we want to study, this figure illustrates the important feature that the massive WD is likely to be brighter and hotter than its lower-mass companion, and that both WDs are bright and hot compared with the majority of Galactic WDs, which are older.

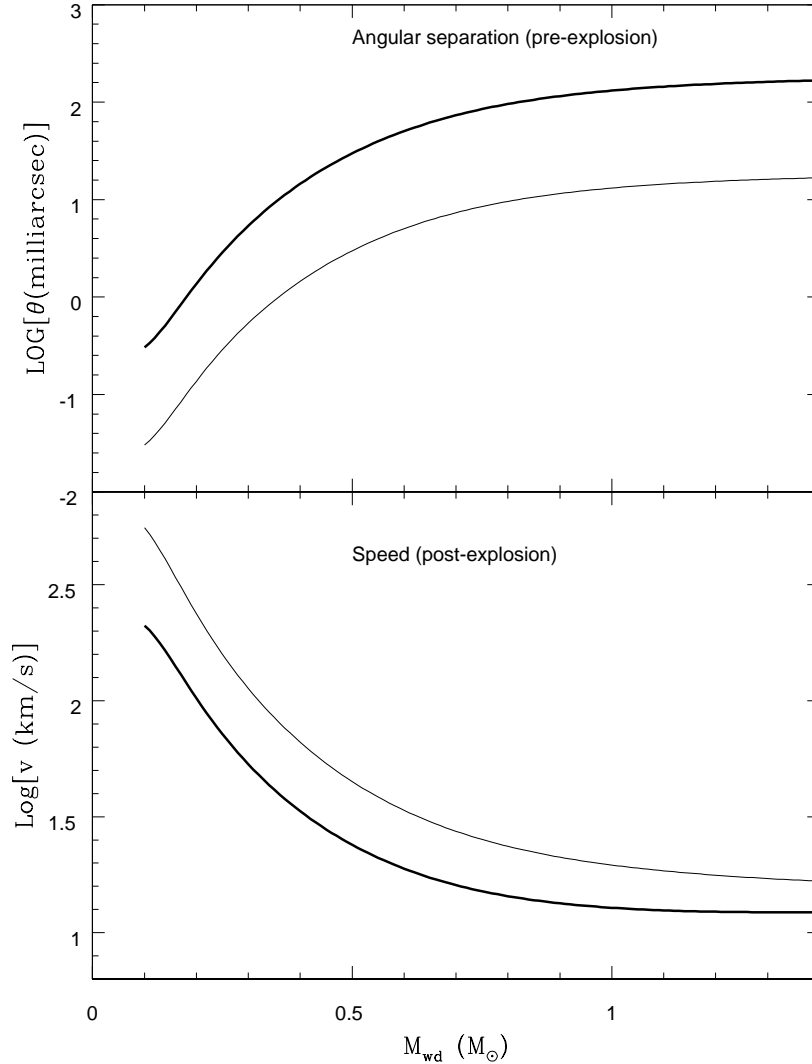


Fig. 3.— **Top panel:** Logarithm of the angular separation (in mas) between the pre-explosion super- M_{Ch} WD and its less massive WD or pre-WD companion, as a function of the companion’s mass. Top, dark curve: the distance to the binary is 100 pc; bottom, lighter curve: the distance to the binary is 1 kpc. To compute the orbital separation we assumed that the donor star is either a subgiant or giant that fills its Roche lobe until its envelope is exhausted. **Bottom panel:** The logarithm of the speed of the companion is plotted as a function of the companion mass. Bottom, dark curve: results for the spin-up/spin-down model, in which the donor has lost its envelope prior to the explosion. Plotted is the orbital speed (presumably close to the ejection speed) vs the core mass of the donor. Upper, lighter curve is computed assuming that the donor star has a total mass of $3 M_{\odot}$ at the time its WD companion explodes.