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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 supernovae (SNe Ia), 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, $M_{\text{crit}}$, needed for explosion. When $M_{\text{crit}}$ is higher than the maximum mass achieved by the WD, the central regions of the WD must spin down before it can explode. This introduces super-Chandrasekhar single-degenerate explosions, and a delay between the completion 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 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-$M_{\text{Ch}}$ WDs in either wide binaries with WD companions or 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 SNe Ia.

Key words: accretion, accretion disks – cosmological parameters – dark energy – supernovae: general – white dwarfs

Online-only material: color figures

1. INTRODUCTION

Type Ia supernovae (SNe Ia) are believed to be the explosions of carbon–oxygen white dwarfs (CO WDs). To explode, a CO WD must reach a critical mass ($M_{\text{crit}}$) generally assumed to be the Chandrasekhar mass ($M_{\text{Ch}} \sim 1.4 M_\odot$). 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 ejected from the progenitor binary. With the exception of signatures by circumstellar material in a small number of SNe Ia (Patat et al. 2007), these strong signatures have not 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 $M > 10^{-7} M_\odot$ 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 $M_{\text{crit}}$ (Anand 1965; Roxburgh 1965; Ostriker & Bodenheimer 1968; Hachisu 1986; Yoon & Langer 2005). We will show that an increase in $M_{\text{crit}}$ 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 four 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 SNe Ia.

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 (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 (Patterson 1980); AE Aqr, 33.06 s (Patterson 1979); V842 Cen, 56.82 s (Woudt et al. 2009); and V455 And, 67.2 s (Araujo-Betancor et al. 2005). These periods are much longer than for NSs, due to the much higher moment of inertia of WDs, but similar to the millisecond pulsars, the surface velocity is only a factor of a 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 2003). 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 SNe Ia 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 though 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 $0.00027 \pm 0.00005$ s yr$^{-1}$ (Mauche 2004), corresponding to a spin-up of $2.7 \times 10^5$ s per solar mass accreted in this system. The WDs which evolve toward SNe Ia 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 $M_{\text{crit}}$, needed for the explosion. This implies that accreting WDs can achieve masses in excess of $M_{\text{Ch}}$ without either exploding or imploding. For a rigid rotator, maximal rotation produces an increase in $M_{\text{crit}}$ 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 $M_{\text{crit}}$ 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 $M_{\text{WD}} > 2 M_\odot$. 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 $M_{\text{crit}}$ 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 $M$ is low or when mass transfer has ceased. The crucial element for explosion is that angular momentum be lost from the central region of the WD. We therefore use the term “spin-down” to refer to the spin-down of the central region, which may not be exactly tracked by the surface spin. Spin-down can be achieved through a combination of angular momentum redistribution (AMR) and angular momentum loss from the WD. As $M$ decreases, AMR may begin; in addition, more angular momentum may be lost per unit time than gained (as is seen in AE Aqr; Meintjes 2002; Ikhsanov et al. 2004). Even isolated WDs can spin down, e.g., through gravitational radiation associated with spin-induced effects (the r-mode instability) (Sedrakian et al. 2006). Spin-down times are uncertain, but almost certainly exhibit a large range, from $<10^8$ years to $>10^9$ years (Lindblom 1999; Yoon & Langer 2005).

4. Explosion occurs when the central spin period has been reduced to a critical value, $P_{\text{crit}}$. As the spin decreases, so does the value of $M_{\text{crit}}$. When the value of $M_{\text{crit}}$ falls below the current mass of the WD, the WD will explode. This requires that the WD has not yet crystallized (in which case the outcome is an accretion-induced collapse (AIC) into a neutron star Nomoto & Kondo 1991). Although AIC is possible, note that the time needed for the WD to cool to low-enough temperatures is several $10^7$ years (Yoon & Langer 2005). Furthermore, continued accretion and the $r$-mode instability act as heat sources; crystallization may therefore be avoided.

3. OBSERVATIONAL SIGNATURES

3.1. Background

Population. Let $f$ denote the fraction of all SNe Ia progenitors in which (a) spin-up produces a significant change in the value of $M_{\text{crit}}$ and (b) the maximum mass achieved by the WD is smaller than $M_{\text{crit}}$, necessitating an interval of spin-down. If the rate of SNe Ia is $R$, then the number, $N_{\text{SD}}$, of spinning-down progenitors in the Galaxy is

$$N_{\text{SD}} = f \times (3 \times 10^4) (\tau / 10^7 \text{ yr}) \times (R / 0.003 \text{ yr}^{-1}),$$

where $\tau$ is the spin-down time, the time between the end of genuine mass gain by the WD and the explosion. A few percent of the spinning-down progenitors could lie within a kiloparsec of Earth. 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 SNe Ia have been occurring in the Galaxy for $10^{10}$ years.

Binary evolution. SD SNe Ia 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 $M$ 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 gains mass and angular momentum until the giant’s envelope is depleted. The final pre-SNe Ia 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. For less evolved subgiant donors and main-sequence (MS) donors the mass ratio, $q$, between the donor and the WD is important. The value of $M$ can be high enough for nuclear burning only when $q > 1$. When the mass ratio reverses, the rate of mass transfer decreases dramatically, and the WD can begin to lose angular momentum. Subgiant donors could become WDs, reproducing the signatures described above for giant donors. For MS donors, the binary will become an accretion-powered cataclysmic variable (CV); long spin-down times would transform the donor into a degenerate object of brown-dwarf mass, with an orbital period as low as $\sim 90$ minutes. Figure 1 shows the evolution of a subgiant donor whose WD companion gains enough mass to slightly exceed $M_{\text{Ch}}$.

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 allow circumbinary material to dissipate. Furthermore, the donors are likely to be either compact objects at the time of explosion or low-mass stars. Signatures of interaction with the supernova would therefore be diminished relative to the case in which spin is unimportant. In addition, the donors tend to be dim, making them difficult to detect. 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.

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Note 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 SNe Ia take place in multiple systems, stars not directly involved in the explosion may produce detectable signatures.
Nuclear burning should take place, however, while the WD gains mass.

Tests of the models. Systematic searches of data from wide-field surveys, including SDSS, Pan-STARRS, and LSST, can 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). To test spin-up/spin-down models, we want to measure the mass function of the spinning-down WDs. The maximum mass will tell whether differential rotation occurs. Even if no super-M$_{\text{Ch}}$ WDs were found, the mass distribution would provide hitherto unavailable information on the mass gain during binary evolution.

Wide double WDs. Binaries containing a super-M$_{\text{Ch}}$ in wide orbit with a compact companion are distinctive: they exhibit the spectra of two hot WDs (Figure 2). The lower the mass of the secondary, the cooler it will be, and the larger the spectral contrast will be. 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 SNe Ia 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 SNe Ia progenitors. The key difference is that the WD’s mass, while larger than typical of WDs, is smaller than M$_{\text{Ch}}$ (see, e.g., Meintjes 2002).

3.3. Detecting the Remnants of the Donors

The SNe Ia release the donor from orbit. Hansen (2003) and Justham et al. (2009) considered donors that had not yet finished evolving 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 SNe Ia 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 our model is that, if the donor started as an MS star and if $r$ 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, $v \sim 570$ 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

Cosmology. If explosions at different cosmic times have different amounts of local absorption, this would introduce a systematic uncertainty into measurements of the universe’s acceleration. When the WD must spin down before explosion, circumstellar material will disperse and play a smaller role.

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5 Nuclear burning should take place, however, while the WD gains mass. The lack of SSS-like emission may be due to an extended photosphere or absorption by circumstellar matter that dissipates prior to explosion (Di Stefano 2010a, 2010b).
regardless of redshift. If, therefore, spin-up/spin-down is common, the systematic uncertainty is less significant.

**Prompt explosions.** Some SNe Ia occur within a few $10^5$ years after star formation (see, e.g., Maoz & Badenes 2010). If spin-up occurs in these “prompt” systems, then their spin-down times must be well under $10^9$ years.

**Variety.** Our model predicts variety in the mass of the exploding WD and in the spin-down times. While some of the standard signatures may be detected in some cases, the trend in spin-up/spin-down predictions is toward diversity among the explosions, with fewer systems exhibiting post-explosion interaction with the donor or circumbinary material. The distribution of explosion properties can provide indirect tests. Direct model tests may be provided by discovering the distinctive pre-explosion (super-$M_{\text{Ch}}$ WDs) or post-explosion (high-speed brown dwarfs and WDs) systems in our Galaxy.

### 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, the effects we predict will persist. 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 SNe Ia 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 $M_{\text{Ch}}$. 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 $M_{\text{Ch}}-1.05 M_{\text{Ch}}$. 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 $M_{\text{Ch}}$; thus, typical pre-explosion WDs should have masses close to $M_{\text{Ch}}$. By measuring the distribution of primary WD masses, we will therefore learn about the binaries whose evolutions produce SNe Ia.

All other things being equal, each value of $M$ would correspond to a specific value of $P_{\text{cm}}$, 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 $\tau$. Furthermore, if there is residual low-level accretion, this also affects the spin-down time. Thus, the value of $P_{\text{cm}}$ may be viewed as a second parameter which influences the explosion characteristics.

Finally, the variety of conditions expected at the time when high-$M$ 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. 2010), an SN 2002cx-type explosion, showing an unusual light curve and pattern of spectral evolution. The chemical composition, pre-explosion Hubble Space Telescope 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 SNe Ia. 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 SNe Ia. Key elements can be tested through observations. While not all SNe Ia progenitors may be SD, and

![Figure 2. Logarithm of luminosity vs. 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 $10^6$, $10^7$, $10^8$, and $10^9$ 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 $0.2 M_\odot$ 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). The 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.](image-url)
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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Figure 3. Top panel: logarithm of the angular separation (in mas) between the pre-explosion super-MS WD and its WD companion, as a function of the companion’s mass. Top curve: the distance, $D$, to the binary is 100 pc; bottom curve: $D = 1$ kpc. To compute the orbital separation we assumed that the donor is either a subgiant or giant that fills its Roche lobe until its envelope is exhausted. Bottom panel: the logarithm of the companion’s vs. its mass. Bottom 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. donor’s the core mass. Upper curve is computed assuming that the donor has a total mass of $3M_\odot$ at the time its WD companion explodes. The dot-dash line represents the speed of brown dwarfs released from close orbits by the explosion. These fast brown dwarfs are new predictions of our model.
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