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# Spin-Up/Spin-Down Models

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**Abstract.** Angular momentum transport plays an important role in mass transfer systems, and can significantly spin up an accreting star. When the accretor is a white dwarf (WD) on its way to becoming a Type Ia supernova (SN Ia), the spin up of the WD can have significant consequences for the appearance of the progenitor, the characteristics of the explosion and its aftermath, the geometry of the supernova remnant, and for single-degenerate models, the appearance of the donor star post-explosion. These consequences can be "game changers", altering results that have long been taken for granted. We discuss key features of our spin-up/spin-down models and their implications. We relate our models to work still needed to address the difficult physical issues related to angular momentum transport and its effects on the properties and appearance of Type Ia supernova progenitors.

**Keywords.** stars: white dwarfs, supernovae — accretion, accretion disks

## 1. The Role of Angular Momentum

When a white dwarf (WD) accretes mass, it also gains angular momentum. Detailed calculations of the related effects are difficult because they involve issues that are not yet well understood from first principles, such as the WD's internal viscosity profile and the configuration and effects of magnetic fields. Perhaps because of this, angular momentum considerations have generally not been considered key parts of a possible solution to the Type Ia progenitor puzzle.

During the past year, we have started to consider the role of angular momentum by using basic principles applicable to a wide range of situations and models (Di Stefano *et al.* 2011). By doing this, we have been able to make a set of general predictions. These predictions broaden the reach of single degenerate models, by explaining why a wide range of white-dwarf masses may be expected at the time of explosion. They also challenge many of the now-standard assumptions about the appearance of the donor star at the time of explosion and about the environment in which the explosion occurs. Fortunately, many of these predictions have observable consequences and can therefore be tested. These tests can then be used to develop a better understanding of the fundamental physics that determines how an increase in angular momentum affects massive WDs.

## 2. Spin-Up/Spin-Down: Principles

Our spin-up/spin-down models are based on a small set of simple physical principles.

**(1) It is possible for a WD accreting at high rate to gain angular momentum.** There are only two ways in which this statement could not be true. The first is if angular momentum is not conserved. In the absence of observational evidence, we reject this hypothesis. The second possibility is that the specific angular momentum of any mass ejected from the system is fine tuned so that exiting matter carries with it as much or more angular momentum than the amount incident on the WD. At high rates of accretion, a significant fraction of the incident mass is retained, the WD's magnetic field is likely to be screened (Cumming *et al.* 2001), and the mass flows can be complex. These circumstances make it more likely that angular momentum gained by the WD will not be ejected on short time scales. In fact, the spin up of millisecond pulsars suggests that compact objects can accept angular momentum through accretion; we know of no fundamental reason why WDs cannot gain angular momentum. Indeed, fast-spinning WDs are known, including Mereghetti's "mystery object" (13.2 s; this volume), WZ Sge (27.87 s), AE Aqr (33.06 s), and V842 Cen (56.82 s). (Please see references in Di Stefano *et al.* 2011.) We note in addition that the rotation of the WD's surface may not accurately reflect the internal rotation, so that the amount of "spin up" cannot necessarily be measured by measuring the surface spin rate.

**(2) Spin-up can increase the critical mass of the WD.** Rotation near the WD's center changes the conditions required for explosion, increasing the critical mass. [See Anand 1965; Hachisu 1986; Ostriker & Bodenheimer (1968); Yoon & Langer (2005).] In cases in which the rotation is uniform, the increase may be only about 5%, but differential rotation can push the critical mass to above 2 $M_\odot$. When viscosity dominates, the rotation may be almost uniform (Piro 2008), but otherwise differential rotation can allow for pressure support near the center and higher values of $M_{crit}$.

**(3) It is possible that the donor can provide enough mass at a high rate of accretion to allow the WD to reach $M_{Ch}$, yet not enough to achieve the critical mass before the donor runs out of mass.** A challenge in reproducing the rate of SNe Ia through the SD channel is that the number of binaries in which the donor has enough mass to bring the WD to $M_{Ch}$ may be too small. Raising the required mass by even a few percent ensures that fewer donors can provide enough mass. Thus, the situation in which the WD reaches $M_{Ch}$, but not a significantly higher mass, should be common.

**(4) It is possible for a non-accreting WD, or a WD accreting at low rates, to lose or redistribute angular momentum, and to thereby decrease the critical mass.** Spin-down is inevitable, but the time scale may be long or short, depending on the state of the WD and on the spin-down mechanism. If the donor star can continue to donate mass after the WD has achieved its maximum mass, as is presently occurring in AE Aqr, then mass ejected from the system can carry angular momentum, allowing the WD to spin down over $10^6 - 10^8$ years. Processes such as gravitational radiation may take longer (e.g., Lindblom 1999, Yoon & Langer 2005, Sedrakian *et al.* 2006).

AE Aqr is a remarkable system, providing an example of a binary that appears to have undergone the type of evolutionary pathway we suggest will be relevant for some SNe Ia progenitors. The WD appears to have gained mass during a phase of high $\dot{M}$. The present-day spin suggests that spin-up occurred during the high-$\dot{M}$ phase. Today, the system is spinning down as matter that falls toward the white dwarf at low rates, is ejected through a propeller mechanism. (For more on AE Aqr and for additional references please see Patterson 1979, Meintjes 2002, and Ikhsanov *et al.* 2004.)

This simple set of assumptions allows for a great deal of diversity, largely because of the diversity in binary models. Given this diversity, there are likely to be some cases in which the spin up of the WD plays little role in determining the timing of the explosion, the characteristics of the progenitor pre-explosion, and the detectability of the donor star post-explosion. But in other cases, spin-up and the need for spin-down before explosion, can significantly alter our expectations.

In cases in which spin-up/spin-down is important, its effects tend to make the donor less massive and dimmer, both before and after explosion. Unless the donor is a giant, accretion may occur at only a low rate just prior to explosion, if at all, making the total system luminosity small. Interaction of the supernova with the small, low-mass donor will be minimal, and may not produce effects that we can detect at present. Discovering the donor in the remnant in the years after explosion will be more difficult.

On the other hand, spin-up/spin-down predicts the existence of massive, spinning WDs in the Galaxy, each with a low-mass companion. These systems should be detectable. Furthermore, the post-explosion observational signatures of the donor stars "widowed" by the explosion are different.

## 3. Spin-Up/Spin-Down: Predictions

**Range of WD masses at explosion.** Because most donors will not be massive enough and/or evolved enough to bring the WD to masses much above $M_{Ch}$, most exploding WDs will have masses close in value to $M_{Ch}$. Nevertheless, a small fraction, determined by the distribution of binary and WD properties, may be significantly super-Chandrasekhar at the time of explosion. This suggests that super-Chandrasekhar WDs are possible in both SD and DD models.

**Range of donor properties at the time of explosion.** In particular, if spin-up/spin-down has played an important role, the donor may be a WD or a very low-mass object by the time of explosion. This changes the interaction of the supernova with the donor, so that it is less likely that hydrogen and/or helium from the donor will be detectable post-explosion; this element, for the specific case of giant donors has been discussed by Justham (2011). In addition, the probability of a "flash" being generated by the interaction of the supernova with the donor is also reduced. Finally, searches for the widowed donor, even in nearby galaxies such as the LMC (see, e.g., Pagnotta & Schaefer, this volume), must reach deeper in order to place limits on single-degenerate progenitors.

**High-rate accretion may have ceased long before explosion.** In the epoch just prior to explosion, the binary may be very dim. The primary would be a spinning WD with mass larger than $M_{Ch}$. The secondary would be one of three types of star: (1) a CO WD; (2) a He WD; (3) the low-mass component of a cataclysmic variable (CV). In case (3), mass transfer would be continuing at a low rate, right up until the time of explosion. The implication is that, in all cases, the binary would be dim prior to explosion. This would make it difficult or impossible to detect in external galaxies.†

**Range of circumbinary environments at the time of explosion.** During the spin-down phase, mass transfer will have ceased or else may be proceeding at a low rate. Thus, if gas ejected during an epoch of high $\dot{M}$ had formed a relatively dense circumbinary environment, this gas may have time to dissipate, depending on the length of the interval required for spin-down. This means that a range of circumbinary gas and dust densities post-explosion are consistent with SD models, and also with DD models.

† The dim state of the progenitor just prior to explosion does not represent the luminosity during the epoch when (1) for a SD binary, the WD was gaining mass, making it a bright nuclear burning WD, or (2) for a DD binary, the last common envelope was about to occur and winds were incident on the WD at a high rate.

## 4. Examples

The concepts of spin-up/spin-down are valid for all progenitor models. Soker (this volume) has applied them to DDs. Below, we give examples of the progenitor, just prior to explosion in two specific SD models.

### 4.1. *Double White Dwarfs*

Pre-explosion, the progenitor binary can consist of two WDs. One of these will have a mass lying between $M_{Ch}$ and the WD's critical mass. The second WD could be either a carbon-oxygen or helium WD. The two WDs would have started cooling at the same time, and would have different temperatures, corresponding to their different masses. The value of the orbital period would satisfy the period-core-mass relationship, where the "core mass" is the mass of the less massive WD.

### 4.2. *Cataclysmic Variables*

Pre-explosion, the progenitor binary can consist of a spinning WD that may be slightly or, in rare cases, significantly over the Chandrasekhar limit, in orbit with a vary low-mass star donating mass at the low rates typical of cataclysmic variables (CVs). The longer the spin-down time, the lower the mass of the secondary. The donor may even be a degenerate object with a mass in the range typical of brown dwarfs. This system will be a dim x-ray and optical source pre-explosion, with a bolometric luminosity likely to be under $10^{32}$ erg s$^{-1}$. The system AE Aqr is an analog, which is not a progenitor because the WD did not gain enough mass to achieve $M_{Ch}$, although its mass could be as high as $0.9\,M_{\odot}$.

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