Binary Paths to Type Ia Supernovae Explosions
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The Appearance of Type Ia Supernova Progenitors: If Not SSSs, then What Do They Look Like?

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Abstract. "What do the progenitors of Type Ia supernovae (SNe Ia) look like? How can we hope to find them?" We focus on the epoch during which mass is incident on a white dwarf (WD) at high rates ($>10^{-7} M_\odot$ yr^{-1}). Such epochs are expected in single-degenerate (SD) progenitors, double-degenerate (DD) progenitors, and in a wide range of binaries with WDs that will not achieve the Chandrasekhar mass, M_{Ch}. High-rate accretion onto a WD produces high luminosities through accretion alone; in addition, most calculations show that quasisteady or episodic nuclear burning can occur, increasing the luminosity by more than an order of magnitude. If the photosphere is not much larger than the WD, the emission will have values of $k\,T$ in the range of tens of eV, and the source will appear as a luminous supersoft x-ray source (SSS). Studies of local SSSs that are good candidates for nuclear-burning WDs (NBWDs) suggest that many have low duty cycles of SSS activity. This is consistent with the fact that binary WD models predict about 100 times as many SSSs in external galaxies of all types as are actually detected. Interstellar absorption does not appear to be the problem. Instead, it is likely that the $\sim 10^{37} - 10^{38}$ erg s^{-1} emitted by NBWDs emerges in other wavebands. The challenge we face is to search for highly luminous systems within the Milky Way and nearby galaxies that have unusual properties consistent with NBWDs, and inconsistent with other physical models. Model tests can then be conducted for individual candidates, allowing us to identify large numbers of progenitors years before explosion.

Keywords. stars: white dwarfs, binaries, supernovae — X-rays: binaries — cosmological parameters

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1. Type Ia Progenitors, Nuclear-burning WDs, and SSSs

An ideal way to identify the progenitors of supernovae is to search for changes between images taken before and after the explosion. While successful for core-collapse supernovae, whose progenitors are the brightest of stars, this approach is more challenging for SNe Ia, since the pre-explosion luminosities of even the brightest progenitors are generally too low. During the early 1990's, a hope was sparked that we could discover the progenitors as bright x-ray sources, detectable even in external galaxies.

The origin of this hope was the discovery of supersoft x-ray sources (SSSs), with luminosities greater than 10^{36} erg s^{-1} and values of $k\,T$ in the range of tens of eV. A theoretical argument suggested that these sources could be white dwarfs (WDs) burning accreted matter in a quasisteady manner, possibly even progenitors of accretion-induced collapse (van den Heuvel *et al.* 1992). A link to SNe Ia was established by the first population synthesis of nuclear-burning WDs (NBWDs), which showed that enough CO WDs could be brought to the Chandrasekhar mass, M_{Ch} to make it possible that NBWDs in close binaries could be the dominant contributors to the rate of SNe Ia (Rappaport, Di Stefano, & Smith 1994; Di Stefano *et al.* 1997).

Population synthesis calculations start with a population of binaries and determine which systems pass through a phase in which a WD accretes mass at a high-enough rate to allow mass retention through quasisteady or episodic nuclear burning. The calculations identify those WDs that can achieve M_{Ch} and compute the associated rate of SNe Ia. Thus, the link probed by these calculations is the physical connection between NBWDs and SNe Ia, not the connection between NBWDs and SSSs. To derive the appearance of NBWDs, it will be necessary to study in detail the physical processes that determine the size of the WD's photosphere, the spatial distribution and physical state of gas and dust in the vicinity of the WD, the characteristics of the accretion disk, and the interaction of gas and dust with radiation emanating from the system.

No mathematical theorem shows that NBWDs must have the appearance of SSSs.

2. Luminous Supersoft X-Ray Sources (SSSs)

The Galaxy and Magellanic Clouds. Of the ∼18 known "local" SSSs, roughly half are in binaries in which quasisteady nuclear-burning could be occurring. Of these, several are known to experience x-ray "off" states, during which the optical flux increases. The transitions may be caused by changes in the accretion rate. Since we are more likely to have discovered NBWDs that are "on" as SSSs a larger fraction of the time, it is certainly possible that many NBWDs have low SSS duty cycles. A low duty cycle is supported by the failure to find evidence of large ionization nebulae surrounding the NBWD candidates observed as SSSs. Chiang & Rappaport (1996) demonstrated that such nebulae are expected unless the duty cycle of SSS activity is very small. Only CAL 83 was found to be surrounded by the predicted "supersoft nebula".

Other Galaxies. SSSs with values of kT in the range $75 - 100$ eV, and with L close to 10^{38} erg s^{-1} are very likely to be detected (Di Stefano 2010a). This range of temperatures and luminosities is expected for NBWDs that have WD masses $> 1.0\ M_{\odot}$, and which emit as SSSs. A large fraction of sub-Chandrasekhar NBWDs would be detectable if they emitted as SSSs, including DD progenitors during their symbiotic phase.

We therefore searched for SSSs in external galaxies in hope of finding the most massive NBWDs, assured that we could take an almost complete census, if these intriguing objects appear as SSSs. Instead of finding hundreds or thousands, we found numbers smaller by about two orders of magnitude. The true discrepancy between the numbers of SSSs and the numbers of SNe Ia progenitors expected may be far worse, however, because some of the SSSs are too luminous to be WDs, and are more likely to be black holes. In addition, many of the SSSs correspond to classical novae and are not likely to achieve M_{Ch}. For a description of the results and their implications see Di Stefano 2007; also Di Stefano, Kong, & Primini 2006, 2010; Di Stefano *et al.* 2009, 2010; Di Stefano 2010a, 2010b.

Because there is no fundamental reason for NBWDs to appear as SSSs, and because those SSSs that are candidate NBWDs are known to "turn off", possibly with low long-term duty cycles, the lack of bright SSSs in external galaxies cannot be taken as evidence for a lack of NBWDs.

3. Nuclear-Burning White Dwarfs (NBWDs)

NBWDs form a natural extension of the class of cataclysmic variables (CVs). CVs are accreting WDs that have low-mass donor stars, small $\dot{M}$, and luminosities typically smaller than 10^{32} erg s^{-1}. NBWDs have donors that are typically of higher mass and which may also be more evolved. Values of $\dot{M}$ may be large enough to allow incoming matter to be burned and retained. Thus, NBWDs are the high-$\dot{M}$ extension of the population of CVs. There is also a deeper connection, because NBWDs with donors that are not too evolved, will become CVs after the donor's mass has fallen below that of the WD. The NBWD phase may be viewed as an epoch during which some WDs evolve toward CV-hood. This picture is supported by the fact that the masses of the WDs in CVs tends to be larger than the masses of isolated WDs and also larger than the WDs in so-called "pre-CVs", binaries which will evolve to become CVs (Zorotovic *et al.* 2011). With a spatial density of $\sim 10^{-5}$ pc^{-1}, there are a few million CVs in the Galaxy. If only 10% of all CVs started mass transfer when the donor was more massive than the accretor, and if the NBWD phase lasts for only 1% of the duration of the active CV phase, then there are a few thousand Galactic NBWDs on their way to becoming CVs. Even if no accreting WD ever reaches M_{Ch}, there would be a significant number of NBWDs with masses near or above $0.8\,M_\odot$, and these would be very bright, and potentially very hot as well, if the photosphere is comparable in size to that of the WD. This is consistent with theoretical results derived through population synthesis (e.g., Rappaport *et al.* 1994).

Symbiotics can be NBWDs. The difference between symbiotics and CVs is that the donor stars in symbiotics are generally giants. They donate mass through winds and/or through Roche-lobe filling. The rate at which mass falls toward the WD is typically much higher than in CVs; in many systems, the rate is in the range expected for either recurrent novae or else for quasisteady nuclear burning. Thus, some symbiotics are expected to appear as SSSs, and indeed SSS emission from a small number of symbiotics has been detected. The number of symbiotics in the Milky Way has been estimated to be as high as 10^5. Until recently, only a few hundred symbiotics were known, and the number is slowly increasing through new surveys and concerted follow-up efforts (e.g., Corradi *et al.* 2010). If $0.1\% - 1\%$ of symbiotics are in an SSS phase at any given time, then there should be hundreds to thousands of symbiotic NBWDs in our Galaxy, and in external galaxies, such as M101 and M31 as well.

Double-degenerate binaries pass through a symbiotic phase. Binaries evolving toward SNe Ia through double-degenerate (DD) channels must pass through a phase in which a WD has mass incident at high rates. Prior to the common envelope that brings the two WDs into a close orbit, the first-formed WD is in orbit with a more massive giant star that will eventually come to fill its Roche lobe, sparking mass transfer that will be unstable on a dynamical time scale and producing a common envelope. The giant must have a well-evolved core. In fact, if the merger will be between two CO WDs, the core will have mass larger than $0.5\,M_\odot$ at the time when the giant fills its Roche lobe. It will therefore be losing mass to winds, long before it fills its Roche lobe. In addition, the gravitational influence of the WD will focus the winds. Thus, the WD will have mass incident at a high-enough rate to promote quasisteady or episodic nuclear burning. These systems will appear as symbiotics (Di Stefano 2010b).

4. Implications

If no WD were ever to explode, the number of NBWDs would still have to be as high as a few thousand in galaxies like our own. A genuine lack of NBWDs, at a level of ~100 times fewer than expected if SDs supply the majority of SNe Ia, would limit the SD channel, and would also constrain the size of the contribution from the DD channel. More important, it would mean that our understanding of binary evolution, WD accretion, symbiotic populations, and the mass distribution of accreting WDs is significantly flawed.

If Not SSSs, Then What? If the energy doesn't emerge at x-ray wavelengths, then it must be emitted in other wavebands. There are two possibilities. One is that the photosphere of the NBWD is large enough that the bulk of the radiation emerges in the ultraviolet (UV). Indeed, there are indications that when the local SSSs enter x-ray "off" states, the energy is shifted in a manner consistent with the expansion of the photosphere and the irradiation of the disk by an EUV emitter (Greiner & Di Stefano 2002). The size of the photosphere may change in time, possibly with the accretion rate, so that NBWDs may exhibit a range of SSS duty cycles.

The contribution of Lepo *et al.* in this volume explores the possibility that more NBWDs can be found through their emission in the UV, particularly in cases in which the mass accretion rate is so high that not all of the incident matter can be burned. This scenario has also been considered by van den Heuvel *et al.* (1992). We note however, that photospheric expansion can occur even when the value of $\dot{M}$ permits quasisteady nuclear burning to occur.

How can we discover NBWDs, with $\dot{M}$ either in or above the quasisteady burning region? NBWDs which emit the bulk of their energy in the UV may have some signatures of young stars. Clues to their true nature may be provided by the presence of unusual binary companions, and orbital periods that are linked to the UV luminosity. Furthermore, these systems can inhabit regions of their galaxies in which stars of intermediate age or older form the dominant stellar population.

The second possibility is that heavy winds absorb radiation emitted by the WD, reemiting it in the infrared (IR). The contributions by Kato and Nielsen in this volume explicitly consider the observational consequences of self-obscuration by winds. Heavy winds likely absorb the soft X-ray and UV radiation emitted by NBWDs in symbiotics. Note, however, that even when the donor is a main-sequence star, winds are expected, especially at the high accretion rates most likely to eventually produce SNe Ia. Thus, a significant amount of the energy released by nuclear burning could be emitted in the IR.

In fact, we expect that in some systems, a hot-UV-emitting WD could be accompanied by heavy winds that obscure the UV emission in some directions at some times, but not in all directions at all times. Thus, we expect signatures of a hot and cool component. These signatures can be similar to but not necessarily identical to those that define symbiotics.

The key to discovering NBWDs is that they are luminous, and they also are numerous enough that some should be located within a kpc of Earth. If we search for systems that are luminous in some combination of the UV and IR, with a range of distinctive properties, we will discover nearby NBWDs. We will inevitably find among them some that will eventually explode as SNe Ia, through either the DD or SD channel, thereby finding important clues to the solution of the Type Ia progenitor puzzle.

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