

Research Paper

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Stars, Companions, and their Interactions: A Memorial to Robert H. Koch



Cataclysmic Variables as Supernova Ia Progenitors

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Although the identification of the progenitors of type Ia supernovae (SNeIa) remains controversial, it is generally accepted that they originate from binary star systems in which at least one component is a carbon-oxygen white dwarf (WD); those systems are grouped under the wide umbrella of cataclysmic variables. Current theories for SNeIa progenitors hold that, either via Roche lobe overflow of the companion or via a wind, the WD accumulates hydrogen or helium rich material which is then burned to C and O onto the WD's surface. However, the specifics of this scenario are far from being understood or defined, allowing for a wealth of theories fighting for attention and a dearth of observations to support them. I discuss the latest attempts to identify and study those controversial SNeIa progenitors. I also introduce the most promising progenitor in hand and I present observational diagnostics that can reveal more members of the category.

Keywords: type Ia supernova progenitors, cataclysmic variables, circumstellar material

1. INTRODUCTION

In October 2011, the Nobel prize committee awarded the Noble prize in physics to three astronomers “for the discovery of the accelerating expansion of the universe through observations of distant supernovae.” This award essentially recognized the significance of type Ia supernovae (SNeIa) as essential astrophysical tools for the study and exploration of fundamental properties in the cosmos, which was already well-known within the astronomical community. The astronomical community also knows that it is critical to identify and explore the properties of these tools and understand their progenitors confirming that they are the same for all observed events, at all distances in the universe.

The efforts to identify SNeIa progenitors have started more than a decade ago, however no single event has been securely connected to a progenitor system. This is because the explosion destroys every signature of its parent system, leaving us little to work with. In this report, I would like to discuss briefly some theoretical and observational advances in the field, along with some recent discoveries that provide

diagnostics of the elusive SNeIa progenitors, arming us with the necessary tools to identify and study them in our galaxy.

2. SETTING THE STAGE

Generally speaking, SNeIa progenitors are binaries with a carbon-oxygen white dwarf (WD) accreting material from its companion with mass accretion rates of $\sim 10^{-8} M_{\text{sun}}/\text{yr}$ and higher. As the WD approaches the Chandrasekhar mass limit of $1.4 M_{\text{sun}}$, its core reaches the ignition temperature for carbon fusion, which initiates a thermonuclear runaway leading to a complete destruction of the WD and in a spectacular explosion, the SNeIa. The result of this explosion can outshine the host galaxy and can be seen in both nearby galaxies and in those at higher redshifts. This is one property of SNeIa that makes them popular observationally, and facilitates their study. Furthermore, SNeIa have been observed in all stellar populations, in both elliptical and spiral galaxies, therefore they are not closely tied to star forming regions or metal-poor stars. Most importantly, because the explosion results from the destruction of a WD

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at a certain mass, all light curves and spectra of SNeIa look the same, everywhere in the universe.

The latter is their key property making them ideal distance yardsticks in the universe: the absolute magnitude of all events at the peak of the explosion is the same ($M_B \sim M_V \sim -19.3 \pm 0.3$) therefore, knowing their standard magnitude (and applying corrections for reddening) we can use the distance modulus equation to derive the distance to the supernova and to its host galaxy. Furthermore, taking one step further and measuring the redshift of the supernova host galaxy, we can derive cosmological properties of the universe, and is the only known way of constraining the dark energy equation of state.

Much more can be said about the use of SNeIa in astrophysics, however little is known about their progenitors. For example, it is known that these progenitors are binaries with at least one WD component. Generally speaking, there are 2 possible companions to this white dwarf, providing two different scenarios which lead to SNeIa. The companion to the WD can be another white dwarf; this is known as the double degenerate scenario. In this case, the binary is losing angular momentum via gravitational radiation, and the two stellar components eventually merge. Most of the times though, a neutron star emerges from this scenario (Nomoto & Kondo 1991). The alternative is for the companion to the WD to be a main sequence star or a more evolved star; this belongs in the category of cataclysmic variables (CVs).

Generally speaking, CVs are binaries with a WD accreting material from its companion, which can be a low main-sequence star, an evolved star (giant or subgiant) or another white dwarf. Accretion is usually taking place when the companion fills its Roche lobe, via the inner Lagrangian point of the binary. In the cases of giant's donor stars, mass transfer onto the WD can also occur via the wind of the giant star. The main property of the system is that the WD is accreting mass, with mass growth rate approximately equal to the mass transfer rate from its companion, which is of the order of 10^{-10} to $10^{-7} M_{\text{sun}}/\text{yr}$ (single degenerate scenario) At the same time, CVs are known for frequent "cataclysmic" events (such as nova explosions), which result to mass loss from the white dwarf, making it hard to reach the desirable Chandrasekhar mass limit and to an explosion. Even in systems in which such explosive events are rare, the high mass transfer rate leads to an expansion of the white dwarf's photosphere, the formation of a common envelope which removes angular momentum from the system leading to the merging of the two stars and the formation of a neutron star.

3. OBSERVATIONAL CLUES

Observational efforts have been mostly directed towards identifying possible observational signatures of the progenitor binary. To that direction, recent supernova spectra are examined and historical supernova Ia remnants are under close inspection. Some of the relevant research highlights are:

1) Hydrogen detection: although SNeIa, by definition, do not have hydrogen lines in their spectra, if the progenitor is a single degenerate system then hydrogen could be present in the post-explosion data as a remaining of the accretion process onto the white dwarf, or ejected as a wind from the atmosphere of a main sequence donor star. So far, most relevant searches have been proven fruitless. The only positive detection so far, was discovered in the echelle spectrum of SN 2007le, where a "spatially unresolved component" of the redshifted H-alpha line, coinciding with the location of the supernova, and could not be attributed to emission from the supernova host galaxy (Simon et al. 2009). This emission was considered an indication that the progenitor was a single degenerate binary

2) Detection of the donor star-companion to the white dwarf: in the single degenerate scenario, the WD increases mass upon accreting from a main sequence or giant star until it reaches the Chandrasekhar mass limit. The subsequent supernova explosion disrupts the binary giving a "kick" velocity to the companion, however it is not affecting the rest of its stellar properties. Therefore, if the SNeIa progenitor is a single degenerate binary, the donor star will still be present in the vicinity of the explosion, and will have different proper motion properties than the rest of the stars in its neighborhood. Research efforts to this direction, are focused on nearby supernova Ia remnants, in which the ejecta are dissolved and transparent to allow for a study of the kinematic properties of the stars in the field. At the same time, outcomes of such work is controversial, as it is challenging to study the kinematics of distant faint stars (e.g. SN 1572--Tycho SN--Ruiz-Lapuente et al. 2004, Kerzendorf et al. 2009)

3) Variable NaID lines: recent studies have revealed the presence of variable NaID absorption lines several days after the peak explosion of SN 2006X (Patat et al. 2007), which were attributed to ionization and recombination of circumbinary NaID from the supernova. UV radiation from the SNeIa explosion ionized this material, which slowly recombined post-SNeIa to produce the observed variable

NaID absorption. This scenario requires that circumbinary NaID is present in the progenitor system, which is possible only in the case of a single degenerate binary. Similar variable NaID emission has now been detected in a group of SNeIa (e.g., SN 1999cl, Blondin et al. 2009, SN Ia 2007le, Simon et al. 2009) and it is pointing to the single degenerate scenario (C-O WD + giant donor star) for a SNeIa progenitor.

4. CVs AS SNeIa PROGENITORS: THE V Sge-TYPE CATEGORY

From the previous discussion, it seems that nature points towards cataclysmic binaries (single degenerate scenario) for the most likely progenitors of most of the observed events. Within the different categories of such systems, V Sge-type objects appear to be more promising. The members of this group consist of a WD and a giant or subgiant donor star, in an orbital period of less than a day, and accrete in a high mass transfer rate of $10^{-7} M_{\text{sun}}/\text{yr}$. Their light curves have very characteristic shape of alternating bright and faint phase. The manner with which the WD increases in mass, is described by the accretion wind evolution scenario, coined by Hachisu & Kato (2003). In short, during the bright phase, mass is transferred onto the WD from resulting to an increase of the disk size on dynamical timescales and to a slow expansion of the white dwarf's atmosphere. When the photospheric mass reaches $0.07 M_{\text{sun}}$, a massive wind phase is also initiated, reaching velocities of 1,000 km/sec. While this wind collides with the donor star, removes its surface layers. The result is for mass transfer from the donor star to be suppressed and subsequently stop. The white dwarf's atmosphere is then contracting to its initial value and the brightness of the system gradually decreases to the faint optical state. The presence of the wind is essential to prevent the photosphere of the WD to expand significantly and create a common envelope about the binary and the subsequent collision of the two components of the binary. The cycle is repeated when mass transfer starts again. This cyclical behavior also represents the manner with which the white dwarfs in those systems accumulate mass, eventually reaching the Chandrasekhar mass limit. The V Sge stars is essentially a phase in the evolution of the system, that should last about 10^5 years. Hachisu & Kato (2003) predict that about 100 such objects should be present in our galaxy alone at all times; we now know of six candidate sources (including the prototype), and I will now discuss the properties of the latest addition to the category, QU Carinae (QU Car), which also provides new diagnostics for the identification and study of systems in this category.

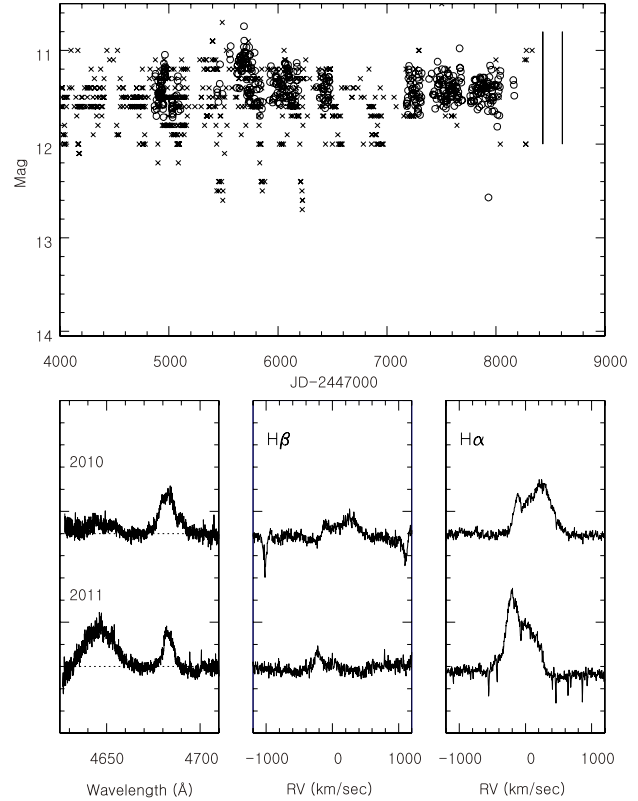


Fig. 1. Top: long-term American Association of Variable Star Observers visual (crosses) and All Sky Automated Survey V magnitude (open circles) light curve of QU Carinae. It demonstrates that over time, the system exhibits V Sge-type bright and faint states, albeit the latter are shorter-lived than those of the prototype. The times of our 2010 - 2011 spectroscopic observations are also marked in the figure. Bottom: snapshot observations of the main spectral features of QU Car at the two epochs of our observations. From left to right, we present the Bowen blend (CIII/NIII/OII) at 4,630 - 4,660 Å, and the HeII 4,686 Å (left panel) the H β emission (central panel) and the H α emission components (right panel). Relevant discussion is in the text.

QU Car was first introduced as a blue variable star, possible twin to the low-mass X-ray binary Sco X-1 (Stephenson et al. 1968). The optical spectrum of the binary displayed pronounced Balmer emission lines and HeII emission at 4686. The latter was used to derive a spectroscopic period of 10.9 h for the binary (Gilliland & Phillips 1982). The optical spectrum also displays a strong Bowen blend (CIII/NIII/OII at 4630 - 4660 Å) and pronounced CIV 5801 - 5812 Å emission (Gilliland & Phillips 1982, Drew et al. 2003). No absorption lines from the donor star are present.

QU Car has also been extensively observed and studied in UV wavelengths, both by the IUE satellite and by STIS/HST (Drew et al. 2003). The UV spectrum displays a rich suite of interstellar absorption lines, indicating that QU Car is a distant object. Indeed, Drew et al. (2003) derived a distance of ~ 2 kpc for the system, placing it towards the Carina arm of

our galaxy. Based on the spectral energy distribution of the optical and UV spectrum, luminosity of the system is ~ 1037 ergs/sec and the mass transfer rate 10^{-7} - $10^{-6} M_{\text{sun}}/\text{yr}$.

The long-term light curves of the system from ASAS¹ and AAVSO² indicate that the system has bright and faint states, similar to those of the prototype of the class, V Sge (top panel of Fig. 1 and Kafka et al. 2008). The high resolution data presented here were taken at a time where there was no contemporaneous photometry, therefore the optical state of the system is derived based on the appearance and properties of the spectral features of the star³. Our snapshot high resolution ($R \sim 30,000$) data were obtained using the echelle spectrograph on the Du Pont telescope of the Las Campanas observatories⁴, during 5 observing nights in 2010 and 2011. Examples of the two epochs of spectra are presented in Fig. 1 (bottom), and are centered around the H α and H β lines and the Bowen blend (from right to left). Both Balmer lines presented here have similar structure to those in V Sge, with components reaching velocities of ± 550 km/sec. At the same time, both Balmer lines seem to be significantly attenuated in 2010 indicating that, at that time, the binary may be transiting to a faint state. Lack of an ephemeris doesn't allow decomposition of the different line components and their correlation with different parts of the binary.

In the 4610 - 4720 Å region, the HeII 4686 Å line faithfully follows the variations of the Balmer lines. In the 2010 spectra, the Bowen blend appears significantly attenuated, reaching the spectrum noise level at times, echoing the behavior of the Balmer lines. At the same time, the CIV 5801, 5812 Å lines are not present in the system. If the dominant species for QU Car's Bowen blend is CIII from the donor star, then this variation should not be present. An alternative origin for CIII is a CO-rich white dwarf. If we accept the latter explanation then the faint state corresponds to a significant depression of the WD's photosphere, which is expanded during the wind phase. Therefore, we can interpret the attenuated Bowen blend in the faint state of QU Car as being the binary's WD's photospheric emission and conclude that QU Car was indeed in a faint state during the 2010 spectroscopic observations.

Perhaps the most interesting behavior of spectral features in QU Car, though, are the NaID lines which are in absorption in all our spectra. Their radial velocities are stationary at each epoch of observations, changing very slowly between epochs in the radial velocity space, from

-6 km/sec in 2010, to -13.5 km/sec in 2011. The lines are not kinematically associated with any other emission or absorption component of the system. A lack of any night-to-night variation is consistent with them being rather circumbinary in nature, indicating the presence of slowly expanding material similar to the one predicted in hydrodynamic models around high mass-transfer rate CVs. This can be ejected from a wind and expand slowly from the system, similar to circumbinary material found after nova explosions from Williams et al. (2008) and in the debris from a number of supernova Ia in relevant studies. This circumbinary material can be the missing link, connecting the supernova Ia explosions to their progenitors, making QU Car a very likely SNeIa candidate.

5. FINAL REMARKS

It is very possible than more than one channels lead to the observed events. Nature has already provided us with a number of events that can't simply be explained by thermonuclear runaway of white dwarfs in CVs. However, the accretion wind evolution scenario provides a very plausible framework leading to SNeIa explosions from single degenerate systems. The recent work on QU Car also provides new diagnostics that can be used to observationally identify V Sge-type systems and improve our understanding on the elusive SNeIa progenitors.

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¹All Sky Automated Survey. <http://www.astrouw.edu.pl/asas/>

²American Association of Variable Star Observers. <http://www.aavso.org/>

³More details can be found at Kafka & Honeycutt (2012)

⁴<http://www.lco.cl>

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