The White Dwarfs in AM CVn systems - candidates for SN Ia?

J.-E. Solheim

Institute of Theoretical Astrophysics, University of Oslo, p.o. box 1029-Blindern, N-0315 Oslo, Norway

L. R. Yungelson

Institute of Astronomy of the Russian Academy of Sciences, 48 Pyatnitskaya Street, 119017 Moscow, Russia

Abstract. Thanks to the rapid increase of observations of Supernovae Ia, we may now claim that the Universe is accelerating. SN Ia are believed to be good standard candles, and after correcting the observations by various methods a precise Hubble diagram results. One of the most important problems to solve in astrophysics today is to find the progenitors of SN Ia. Candidates are to be found in close binary systems where one of the components may accumulate Chandrasekhar mass and then explode. We show that the AM CVn systems may contribute to the SNe population, but will not be the dominant contributor.

1. Introduction

One of the most surprising discoveries of the last years is that our Universe is accelerating and is not dominated by matter, but apparently driven apart by a dominating negative pressure, or dark energy. This is the result of observations of distant type Ia supernovae (SN Ia) which are believed to be precise distance indicators. Two independent high-z supernovae searches (Riess et al. 1998; Perlmutter et al. 1999), reach the same conclusion: The SN Ia dim ~0.29 mag at z ~0.5. Complementary results from WMAP (Bennet et al. 2003) and 2dF (Peacock et al. 2001) show evidence for a low matter density ($\Omega_M = 0.3$) and a non-zero cosmological constant ($\Omega_\Lambda = 0.7$), but neither require the presence of dark energy (Strolger et al. 2004).

A SN Ia has no hydrogen or helium in its spectrum. The maximum absolute magnitude (B) varies between -18 and -20. It is possible to correct the light curves of SN Ia with an empirical formulae (parameterisation and stretch of the time-axes) to a final peak magnitude dispersion < 0.2 (Fabbro 2004). The shape of the tails of the light curves of SNe Ia are entirely explained by the nuclear reaction $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$. However, abundance studies show that the amount of $^{56}\text{Ni}$ varies from 0.07 to 0.92, which indicates that the progenitors must have some variety in their composition or nuclear burning rate. The presence of some UV flux, the width of the peak of the early light curve, and the radioactive decay model, all points to a compact progenitor star with radius less than 10 000 km (Hillebrandt & Niemeyer 2000).
In the following we will discuss if AM CVn stars may explode as SN Ia and if they can contribute significantly to the SNe population.

2. The progenitor requirements

The progenitors of SNe Ia are not known for certain. One of the most widely accepted models is that of a carbon/oxygen (CO) white dwarf accreting mass until it reaches \( \sim 1.378 M_\odot \) (Nomoto, Thielemann & Yokoi 1984), close to the Chandrasekhar limit, and then explodes as a SN Ia. In more general terms a SN Ia model must fill the following requirements (Hillebrandt & Niemeyer 2000):

- Agreement of ejecta composition and velocity with the observed spectra and light curves;
- Robustness of the explosion mechanism (no fine tuning needed);
- Intrinsic variability accepted — at least one parameter to explain the variations in maximum energy output;
- Correlation with progenitor systems and their evolution.

The Hubble Higher \( z \) Supernova Search (Strolger et al. 2004) has discovered 42 SNe in the redshift range \( 0.2 < z < 1.6 \) and compared the number counts of SNe in \( \Delta z \) bins with the expected distributions based on the following model parameters: delay time and progenitor distribution or birth rate. Strolger et al. (2004) get the best fit to observations for a narrow Gaussian \((\Delta \tau = 0.2 \tau)\) starbirth model with mean delay times \( \tau \approx 3–4 \) Gyrs.

The challenge is now to find progenitor populations that match the observed redshift distribution.

3. Progenitors for SN Ia

We can visualize in Figure 1, four main close binary channels for creating SN Ia:

- Mergers of double degenerates resulting in the formation of a \( M \gtrsim M_{CH} \) object and central carbon ignition (the CO+CO DD channel);
- Accumulation of Chandrasekhar mass by CO dwarf via stable Roche lobe overflow in semidetached systems with He-white dwarf;
- Accretion of helium from a non-degenerate He-rich companion at a rate of \( \dot{M} \sim 10^{-8} M_\odot \text{yr}^{-1} \), resulting in the accumulation of a He layer of \( \sim (0.10 - 0.15) M_\odot \). The ignition of the carbon in the core is induced by a detonation in the He-layer (Edge Lit Detonation, ELD). If for some reason, e. g., lifting effect of rotation, helium ignition is mild and does not result in disruption of the donor (helium Nova?), the surviving system may become a He-family AM CVn star with a semi-degenerate secondary;
- Mass transfer from a H-rich main-sequence or subgiant star, forming a supersoft X-ray source (SSXRS) which may produce SN Ia via ELD or accumulation of \( M_{CH} \).

In Figure 1, we also show a wide binary channel, with a white dwarf that may accumulate \( M_{CH} \) in a symbiotic system via wind accretion. However, it is estimated that it gives only a minor contribution to the total rate of SN Ia.
Figure 1. Evolutionary scenarios for potential progenitors of SN Ia. The lower left branch shows the double degenerate (DD) option where a pair of CO white dwarfs merges. The lower right branch (CO+He) represents the double-degenerate family of AM CVn stars. The Helium-star family of AM CVn stars is formed in the branch of objects with nondegenerate helium cores.

4. Can AM CVn objects contribute to the SN I population?

In Figure 1 we find AM CVn stars in two channels. The main characteristics of AM CVn systems are that they are ultra-compact binaries, with orbital periods 10-65 min, showing no hydrogen in their spectra. A dozen such systems are known (Solheim 2003; Nelemans 2004). They may have degenerate (DD-family)
Figure 2. Rates of potential SNe Ia after an instantaneous star formation burst. Solid line — merger of CO+CO pairs with total mass $> M_{Ch}$. Long dashes — the rate of accumulation of $M_{Ch}$ in AM CVn systems of DD-family when mass loss during helium flashes is taken into account. Dots — the same in binaries with He-star donors. Dash-dot-dot-dot line — ELDs in binaries with He-star donors. Dash-dots — accumulation of $M_{Ch}$ in AM CVn systems of DD-family if 100% efficient accumulation of accreted He is assumed. The scaling corresponds to formation of one binary with mass of the primary component $> 0.8 M_\odot$ per year, a flat distribution over initial separation of components, and a flat distribution of the mass ratios of the components.

or semi-degenerate (He-star family) donors. In both families their progenitors evolve with the orbital period shortened by loss of angular momentum by gravitational wave radiation, to a certain minimum period. In the course of further evolution the orbital period increases, while the mass transfer rate is decreasing (see, e.g., Nelemans et al. 2001). In both channels the accretor may grow as mass is transferred, and when reaching the Chandrasekhar limit explode or collapse. In the case of an explosion, it will be a SNIa. In the case of collapse, the formation of a neutron star is expected, but observational manifestation of such an event is unclear. In the DD-family, the population mainly depends on the efficiency of the tidal coupling between the accretors spin and orbital motion. For the He-star family the population depends on the chances for an ELD to occur before the Chandrasekhar mass is reached (Nelemans et al. 2001).

Using an updated version of the Tutukov & Yungelson (1996) code for population of stars with helium donors, we have computed the occurrence rate of SNIa appearing from various channels. Figure 2 shows the rates after an instantaneous star formation burst. For AM CVn stars we apply two options: efficiency of He accumulation as determined by Iben & Tutukov (1996) and a 100% efficiency that provides us the upper limit for occurrence rate. We find
that even in the most optimistic case for production of SNe from AM CVns, the CO+CO channel dominates, but it does not follow the distribution observed in the Hubble Higher z Supernova Search (Strolger et al. 2004).

In Figure 3 we present the population of known AM CVn systems in a $\dot{M}$ vs. period diagram, where also the evolutionary tracks for the objects of DD- and He-star families are shown. For only 4 objects we have reliable $\dot{M}$ determinations (Nasser et al. 2001; El-Khoury & Wickramasinghe 2000), the others have uncertain values based on periods, mass ratios and luminosities. The figure suggests that most of the currently observed AM CVns are likely to belong to the He-star family, and this may mean that progenitors of this population are not decimated by ELDs, in agreement with conclusions by Yoon & Langer (2004), who find that the effects of rotation reduce the violence of helium flashes. We may speculate that helium Novae are produced instead of ELDs. On the other hand, we may also speculate about a sink for the DD-family, either by inefficient coupling between spin and orbital motion (Nelemans et al. 2001), or by mergers in common envelopes associated with shell He explosions at relatively
high $\dot{M}$ or expansion when the accretion rate is $\dot{M}_{\text{Edd}} > \dot{M}_{\text{acc}} > \dot{M}_{\text{crit}}$, where $M_{\text{crit}}$ is the upper limit for the rate of stable He burning.

5. Conclusion

The AM CVn systems we know today are helium transferring objects, which can explode as SN Ia. However, with accreter masses of the order $1.0\,M_\odot$, donor masses $< 0.1\,M_\odot$ (Solheim 2003) and a low mass transfer rate, the majority of currently observed AM CVns will not reach the $M_{\text{Ch}}$ limit in a Hubble time.

The apparent lack of AM CVns of the DD-type, suggests that either the efficiency of formation of AM CVns in this family is lower than current calculations suggest, or a fraction of this population has not been observed because of yet unrecognized selection effects. In any case at present the AM CVn stars can contribute at most $\sim 1$ per cent to the SN Ia occurrence rate, and they do not follow the number density pattern determined by the Hubble Higher $z$ Supernova Search.

However, the study of AM CVns may give us valuable information about their progenitors and conditions for SN Ia explosions, which are needed to explain the existence of standard candles and the need for a dark energy in our Universe.

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