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A progenitor binary and an ejected mass donor remnant of faint type Ia supernovae

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ABSTRACT

Type Ia supernovae (SN Ia) are the most important standard candles for measuring the expansion history of the universe. The thermonuclear explosion of a white dwarf can explain their observed properties, but neither the progenitor systems nor any stellar remnants have been conclusively identified. Underluminous SN Ia have been proposed to originate from a so-called double-detonation of a white dwarf. After a critical amount of helium is deposited on the surface through accretion from a close companion, the helium is ignited causing a detonation wave that triggers the explosion of the white dwarf itself. We have discovered both shallow transits and eclipses in the tight binary system CD−30°11223 composed of a carbon/oxygen white dwarf and a hot helium star, allowing us to determine its component masses and fundamental parameters. In the future the system will transfer mass from the helium star to the white dwarf. Modelling this process we find that the detonation in the accreted helium layer is sufficiently strong to trigger the explosion of the core. The helium star will then be ejected at such a velocity that it will escape the Galaxy. The predicted properties of this remnant are an excellent match to the so-called hypervelocity star US 708, a hot, helium-rich star moving at more than 750 km s⁻¹, sufficient to leave the Galaxy. The identification of both progenitor and remnant provides a consistent picture of the formation and evolution of underluminous type Ia supernovae.

Key words. binaries: spectroscopic – subdwarfs – supernovae

1. Introduction

The search for the progenitors of SN Ia is ongoing, but the observational evidence remains inconclusive. In the standard single-degenerate scenarios mass is transferred in a stable way by either a main sequence star or a red giant to a white dwarf (WD) companion. In the double-degenerate scenario a close binary consisting of two white dwarfs shrinks due to angular momentum lost by the emission of gravitational waves and eventually merges. Possible progenitor systems have been proposed for both channels, but not conclusively identified yet. Although most SN Ia form a homogeneous class, about one third of them differ significantly in their luminosities and other observational properties and their proper classification is crucial when using such events as standard candles for cosmology (Wang & Han 2012).

Underluminous SN Ia have been proposed to originate from a so-called double-detonation of a white dwarf. After a critical amount of helium is deposited on the surface through accretion from a close companion, the helium is ignited causing a detonation wave that triggers the explosion of the white dwarf itself even if its mass is significantly lower than the Chandrasekhar limit (Nomoto1982; Woosley et al. 1986). Hydrodynamic simulations predict the explosion of a CO-WD with a minimum mass

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of only $\sim 0.8 \, M_\odot$ as underluminous SN Ia triggered by the ignition of an He-shell of $\sim 0.1 \, M_\odot$ (Fink et al. 2010) in this so-called double-detonation scenario. He-stars have already been proposed as possible donors for the single-degenerate scenario (Yoon & Langer 2003, Wang et al. 2009a, 2009b) conveniently explaining the lack of hydrogen in the spectra of SN Ia. Recent studies indicate that this scenario might also be consistent with the lack of helium in standard SN Ia spectra as long as the accreted He-layer is thin (Sim et al. 2010, Kromer et al. 2010).

In the course of the MUCHFUSS project (Geier et al. 2011), which aims at finding hot subdwarf binary systems with massive companions, we have discovered a possible progenitor for such a supernova consisting of a hot subdwarf B star (sdB) and a white dwarf in an extremely compact binary (Heber et al. 2013, Geier et al. 2012). This system, CD$-$30$^\circ$11223, was also independently discovered by Vennes et al. (2012).

Hot subdwarf stars are evolved, core-helium-burning objects. About half of the sdB stars reside in close binaries with periods ranging from $\sim 0.1 \, \text{d}$ to $\sim 30 \, \text{d}$ (Maxted et al. 2001, Napiwotzki et al. 2004a). The sdB is the core of a former red giant star that has been stripped off almost all of its hydrogen envelope through interaction with a companion star. The mass of the emerging sdB star is constrained to about half a solar mass in order to allow central helium burning. After the helium-burning phase the sdB star will turn into a white dwarf.

Because the components’ separation in these systems is much less than the size of the subdwarf progenitor in its red-giant phase, these systems must have experienced a common-envelope (CE) and spiral-in phase (Han et al. 2002, 2003 and references therein). In this scenario, a star evolving to become a red giant and the more compact companion spiral towards each other in a common envelope. The orbital energy lost during this process is deposited in the envelope until it is eventually ejected leaving a close binary system as remnant.

Although most of the close companions to sdB stars are low-mass main sequence stars, brown dwarfs or low-mass WDs ($\sim 0.5 \, M_\odot$), more massive compact companions like WDs, neutron stars or black holes have been either observed or predicted by theory (Geier et al. 2007, 2010). The short-period sdB+WD binary KPD 1930+2752 is regarded as progenitor candidate for an SN Ia (Maxted et al. 2000, Geier et al. 2007).

Here we report the discovery of both shallow transits and eclipses in the tight binary system CD$-$30$^\circ$11223 composed of a carbon/oxygen white dwarf and a hot helium star, allowing us to determine its component masses and fundamental parameters. This system turns out to be an excellent progenitor candidate for the double-detonation SN Ia scenario and can be linked to the hypervelocity subdwarf US 708, the likely donor remnant of such an event.

2. Observations

CD$-$30$^\circ$11223 ($\alpha_{2000} = 14^{h}11^{m}16^{s}2, \delta_{2000} = -30^\circ53'03'', m_V = 12.3 \, \text{mag}$) was selected as UV-excess object and spectroscopically identified to be an sdB star (Vennes et al. 2011, Németh et al. 2012). We selected this star as a bright backup target for our MUCHFUSS follow-up campaign. Due to unfavourable observing conditions, which prevented us from observing our main targets, two medium resolution spectra ($R \sim 2200, \lambda = 4450 \sim 5110 \, \text{Å}$) were taken consecutively with the EFOSC2 spectrograph mounted at the ESO NTT on June 10, 2012. The radial velocity shift between those two spectra turned out to be as high as $600 \, \text{km s}^{-1}$.

First spectroscopic follow-up data was obtained with the grating spectrograph mounted on the SAAO-1.9m telescope on July 2, 2012. The RV-curve derived from 18 single spectra confirmed the short orbital period of 0.0498 d and a high RV-semiamplitude ($K = 370 \pm 14 \, \text{km s}^{-1}$). In order to improve the orbital solution and minimize the effect of orbital smear-
Fig. 2. Fit of synthetic LTE models to the hydrogen Balmer lines of a coadded ISIS spectrum. The normalized fluxes of the single lines are shifted for better visualisation.

Fig. 3. Fit of synthetic LTE models to the helium lines (see Fig 2).

Fig. 4. $T_{\text{eff}} - \log g$ diagram. Evolutionary tracks (solar metallicity) of core helium-burning star with masses of 0.45 $M_\odot$ (dotted lines), 0.50 $M_\odot$ (short-dashed lines) and 0.55 $M_\odot$ (long-dashed lines) are plotted for different hydrogen envelope masses (0.000 $M_\odot$, 0.001 $M_\odot$, 0.005 $M_\odot$ from the lower left to the upper right). The diamond marks CD−30°11223.
The derived orbital parameters from the ISIS data set are treated separately to investigate systematic errors. Details about the analysis method and error estimation are given in (Geier et al. 2011). The derived orbital parameters from the ISIS dataset ($K = 378.6 \pm 1.0 \text{ km s}^{-1}, \gamma = 17.6 \pm 0.7 \text{ km s}^{-1}$, see Fig. 1 lower panel) and the Goodman dataset ($K = 374.5 \pm 1.1 \text{ km s}^{-1}, \gamma = 21.3 \pm 0.8 \text{ km s}^{-1}$, see Fig. 1 upper panel) are consistent taking into account that systematic uncertainties are usually somewhat higher than the statistical 1σ errors given here. The deviation in system velocity is most likely caused by a slight systematic zero-point shift between the two instruments. For further analysis we used the average values. Those values are in reasonable agreement with the results ($K = 386.9 \pm 1.9 \text{ km s}^{-1}, \gamma = 31.5 \pm 1.3 \text{ km s}^{-1}$) of Vennes et al. (2012), although somewhat discrepant.

The atmospheric parameters effective temperature $T_{\text{eff}}$, surface gravity log $g$, helium abundance and projected rotational velocity were determined by fitting simultaneously the observed hydrogen and helium lines of the single spectra with metal-line-blanketed LTE model spectra (Heber et al. 2000) as described in Geier et al. (2007). No significant variations of the parameters with orbital phase have been detected. Average values and standard deviations have been calculated for the ISIS dataset ($T_{\text{eff}} = 28800 \pm 200 \text{ K}, \log g = 5.67 \pm 0.03, \log y = -1.50 \pm 0.07, v_{\text{rot}} \sin i = 180 \pm 8 \text{ km s}^{-1}$) and Goodman datasets ($T_{\text{eff}} = 29600 \pm 300 \text{ K}, \log g = 5.65 \pm 0.05, \log y = -1.46 \pm 0.14, v_{\text{rot}} \sin i = 174 \pm 12 \text{ km s}^{-1}$), separately. We adopt the average values from both datasets for further analysis. The final helium abundance is taken from the ISIS data, because of the higher number of He-lines in the spectral range.

The atmospheric parameters are consistent with literature values within the uncertainties (Vennes et al. 2011; Németh et al. 2012). More detailed information about the systematic errors of this method can be found in Geier et al. (2007, 2011). Table 1 shows the orbital and atmospheric parameters, Fig. 4 the position of CD–30°11223 in the $T_{\text{eff}}$–log $g$ diagram.
0.963 by comparing the slightly different line profiles calculated under both assumptions (Claret & Bloemen 2011). This correction was applied to the \( v_{\text{rot}} \sin i \) before deriving the binary parameters. The best fit is achieved for an sdB mass of 0.47 \( \pm 0.03 \) \( M_\odot \) and a WD mass of 0.74 \( \pm 0.02 \) \( M_\odot \). However, we found that the radius of the WD is about 10% smaller than predicted by the zero-temperature mass-radius relation for WDs, which provides a lower limit for the WD radius (see Fig. 4 second panel from above, Verbunt & Rappaport 1988).

In order to explore the influence of this discrepancy, we imposed the restriction that the white dwarf is within 2% of the \( M-R \)-relation and allowed for deviations from corotation (solution 2). We determined an estimate for the temperature of the WD from our light curve analysis. Since we see a significant feature when the sdB occults the WD, we can derive a black-body temperature of 24700 \( \pm 1200 \) K for the WD, which leads to a radius about 5% higher than expected from the zero-temperature relation. We adopt this more realistic value for our analysis. In this case the derived masses are somewhat higher (\( M_{\text{sdB}} = 0.54 \pm 0.02 \) \( M_\odot \), \( M_{\text{WD}} = 0.79 \pm 0.01 \) \( M_\odot \)).

Although both solutions are consistent within their uncertainties we refrain from favouring one over the other. In order to calculate the kinematics and the further evolution of the system, we adopt the average values for the component masses (\( M_{\text{sdB}} = 0.51 \) \( M_\odot \), \( M_{\text{WD}} = 0.76 \) \( M_\odot \), see Fig. 5).

Comparing the derived sdB masses with evolutionary tracks for core helium-burning objects (Fig. 3), it can be seen that the appropriate tracks are consistent with the position of \( CD-30^\circ 11223 \) in the \( T_{\text{eff}}-\log g \) diagram. Furthermore, the effective temperature and surface gravity of the star tell us that the sdB has just recently been formed and started the core-helium-burning phase, which typically lasts for about 100 Myr.

5. Gravitational wave radiation

Because of its short orbital period, \( CD-30^\circ 11223 \) is expected to be a strong source of gravitational waves. We therefore calculated the current gravitational wave emission of \( CD-30^\circ 11223 \). The gravitational wave strain amplitude \( h \) scales with the masses of both binary components, the binary inclination, the orbital period and the distance of the system.

We calculate it as described in Roelofs et al. (2007) to be as high as \( h = -21.5 \pm 0.3 \). \( CD-30^\circ 11223 \) should therefore be one of the strongest gravitational wave sources detectable with missions like NGO/eLISA (Kilic et al. 2012; Nelemans 2009). It sticks out even further, because due to the presence of eclipses its binary parameters are determined to very high accuracy. Therefore this system can be used as verification source for upcoming space missions.

No period change due to the orbital shrinkage caused by the emission of gravitational wave radiation has been detected in the SWASP data (\( P = 1.01 \times 10^{-12} \pm 3.38 \times 10^{-12} \) \( \text{s}^{-1} \)). This non-detection is consistent with the theoretically expected value of \( P \sim 6 \times 10^{-13} \) \( \text{s}^{-1} \). However, within only a few more years the orbital shrinkage should become detectable.

6. Binary evolution calculations

More interesting than the present state of this system is its future evolution, which can now be studied in detail using theoretical models. Employing Eggleton’s stellar evolution code (Eggleton 1971, 1972, 1973), we calculate the evolution of the sdB star and its WD companion. The code has been updated with the latest input physics over the past four decades (Han et al. 1994). Pols et al. [1995, 1998].

7. Hypervelocity sdO as donor remnant

Theoretical predictions about whether or not a progenitor candidate will explode as SN Ia are useful, but in general difficult to
test. Usually the theoretically predicted SN rates are compared to the observed ones, but these comparisons are often hampered by selection effects. A more direct proof would be the identification of the remnant objects. We therefore follow the future evolution of CD−30°11223. At the end of the He-accretion phase and just before the SN event, the orbital period of the binary is predicted to have shrunk to 0.019 d due to the further loss of orbital energy through the emission of gravitational waves. The sdB primary lost a fair amount of mass (∼ 0.1 M☉), which was transferred to the WD companion. The orbital velocity of the sdB will be about 600 km s⁻¹ and therefore close to the Galactic escape velocity. As soon as the WD is disrupted, the sdB will be ejected. Depending on the ejection direction of such an object relative to its trajectory around the Galactic centre, the Galactic rest frame velocity could be even higher by up to 240 km s⁻¹. In this case the remnant star will leave the Galaxy.

Such so-called hypervelocity stars have indeed been discovered (Brown et al. 2005; Hirsch et al. 2005; Edelmann et al. 2005). However, all but one of the known 22 objects are intermediate-mass main-sequence stars. This enigmatic star (US 708) has been classified as helium-rich hot subdwarf travelling at a Galactic rest frame velocity of at least 750 km s⁻¹ (Hirsch et al. 2005), which matches the predicted ejection velocity of CD−30°11223 very well. It was proposed that this star might be the ejected He-donor after the WD companion exploded as SN Ia (Justham et al. 2009; Wang & Han 2009).

In this scenario, the compact binary CD−30°11223 and the hypervelocity star US 708 represent two different stages of an evolutionary sequence linked by a SN Ia explosion. The existence of objects like US 708 thus provides evidence that binaries like CD−30°11223 are viable SN Ia progenitor candidates.

8. Age of the binary system

The analysis of our data also allows us to constrain the initial component masses and the age of the binary. Furthermore we can constrain both its past and future trajectory.
8.1. Kinematic analysis

Using a standard Galactic gravitational potential with a Sun-Galactic centre distance of 8.4 kpc and a local standard of rest circular motion of 242 km s⁻¹ (see Model I in Irrgang et al. 2013), we computed the past and future trajectory of CD–30°11223 (see Fig. 8). The orbit shows the typical characteristics of the local thin disc population, i.e., almost circular motion around the Galactic centre and small oscillations in direction perpendicular to the Galactic disc. The heliocentric distance to the star increases during the next 42 Myr until the supernova is predicted to explode from its current value of 364 ± 0.003 pc.

CD–30°11223 is the closest sdB binary known so far and the mass of its WD companion is higher than the average mass of CO WDs (~ 0.6 M⊙). In order to explore the formation of this exceptional system, we performed a binary population synthesis study in a similar way as described by Han et al. (2002, 2003). For given WD masses ranging from 0.6 M⊙ to 1.4 M⊙, an initial set of 10⁶ WD+MS binaries was generated. For the main-sequence stars the initial mass function of Salpeter was used. The orbital period distribution was assumed to be flat in log a. The binaries have been evolved through the common envelope phase for different values of the CE-efficiency parameters α_CE, which is the fraction of the available orbital energy used to eject the envelope, and α_AB, the contributed fraction of internal energy.

8.2. Binary formation scenario

CD–30°11223 is by far the closest known SN Ia progenitor with respect to Earth. The explosion will take place in a direction of the sky close to the current positions of the constellations Ara and Norma. Adopting an absolute visual magnitude of up to ~19 mag for the SN Ia, the apparent magnitude seen from Earth might be as high as ~7.6 mag or about as bright as SN 1006, the brightest stellar event in recorded history so far (Winkler et al. 2003).
Fig. 7. Results of binary evolution calculations with initial masses of the two components and the orbital period similar to the sdB+WD binary system. Left panel: The evolutionary track of the He star is shown as solid curve and the evolution of the orbital period as dash-dotted curve. Right panel: The solid and dash-dotted curves show the mass-transfer rate and the mass of the WD envelope (He shell) varying with time after the He star fills its Roche lobe, respectively. Dotted vertical lines in both panels indicate the position where the double-detonation may happen (the mass of the He shell increases to \( \sim 0.1 M_\odot \)). The initial binary parameters and the parameters at the moment of the SN explosion are also given in the two panels.

Fig. 8. Three-dimensional trajectory of CD\( -30^\circ 11223 \) in a Cartesian Galactic coordinate system with the z-axis pointing to the North Galactic pole. Current positions of CD\( -30^\circ 11223 \) (blue +), Sun (black \( \odot \)), and Galactic centre (black +) are marked. The approximate point in time of the supernova explosion is symbolized by the red asterisk, while the arrow marks the position of the Sun at that time. Solid lines indicate the future 42 Myr, dashed lines the past 150 Myr. CD\( -30^\circ 11223 \)’s kinematic properties are obviously those of the local thin disc population.

Following CE. Thus, the orbital shrinkage during CE evolution is not significant and the produced sdB+WD system generally has an orbital period much longer than that of CD\( -30^\circ 11223 \).

Only for a very small value of \( \alpha_{\text{CE}} = 0.3 \), which is very unlikely, some binaries reach the margin of 0.05 \( \, M_\odot \). Indeed, the median period of the observed sdB binaries is as high as \( \sim 0.6 \, M_\odot \) (Geier et al. 2011).

However, an sdB+WD binary can also be formed when the main-sequence progenitor of the subdwarf has an initial mass larger than 2 \( \, M_\odot \) and fills its Roche lobe during the Hertzsprung Gap or at the base of the FGB. In this case, the envelope is more tightly bound and the orbital shrinkage required to eject the CE becomes higher. In Fig. 9 (lower panel) the orbital period distribution is shown for this scenario when \( \alpha_{\text{CE}} = \alpha_{\text{th}} = 0.75 \), similar to the best fitting model of Han et al. (2003). As seen in the figure, short orbital periods just as in the case of CD\( -30^\circ 11223 \) are expected.

Additional to the orbital period distribution, we also investigated the distribution of sdB masses formed via this channel. While the standard CE-scenario predicts a mass distribution with a sharp peak at \( 0.47 \, M_\odot \), the sdB masses from more massive main-sequence stars (i.e. \( > 2 \, M_\odot \)) show a significant scatter for higher values of \( \alpha_{\text{CE}} \) and even more so, if we allow for a contribution of thermal energy in the CE-process by increasing the parameter \( \alpha_{\text{th}} \). The sdB mass for this channel largely depends on the mass of the progenitor and can range from 0.3 to 1.0 \( \, M_\odot \) (see Fig. 10). This is consistent with the sdB mass of up to 0.54 \( \, M_\odot \) determined in the case of CD\( -30^\circ 11223 \).

We therefore conclude that CD\( -30^\circ 11223 \) was most likely formed via CE-ejection of a main sequence star with a mass larger than 2 \( \, M_\odot \), which means that it originated from a young stellar population.

8.3. White dwarf cooling age and progenitor masses

We derived a mass of 0.76 \( \, M_\odot \) for the WD companion based on observations. Using an initial-to-final mass relation for isolated WDs the mass of the progenitor should have ranged from 3 to 4 \( \, M_\odot \) (see Fig. 7 in Kovetz et al. 2009 and references therein). Binary evolution is expected to lower the mass of the final WD and this progenitor mass estimate therefore has to be considered as lower limit.
Assuming a lifetime on the main sequence $\tau_{\text{MS}} = 10^{10} \text{yr} \times (M/M_\odot)^{-2.5}$, the progenitor lived for a maximum of 640 Myr. We constrain the temperature of the WD in our light curve analysis to be $\sim 25000$ K. Therefore its cooling age is $\sim 30 - 40$ Myr. The lifetime of the sdB on the extreme horizontal branch is of the same order as the one of the WD and we therefore derive a similar progenitor mass of more than $3 M_\odot$ consistent with the disc kinematics and the constraints from binary formation scenarios.


### 9. Conclusions

Systems like CD–30°11223 are young, which is consistent with the non-detection of objects with such high RV-shifts in the course of the MUCHFUSS project so far (Geier et al. 2011, 2011). Most targets of this survey are faint subdwarfs located in the old halo population. The sdB-donor double-detonation channel is therefore predicted to occur in young stellar populations and contribute to the SN Ia population with short delay time (Ruiter et al. 2009).

Given that systems like CD–30°11223 are progenitors of some thermonuclear SN, a rough estimate can be made about the rate of such events. CD–30°11223 is one out of $\sim 100$ solved sdB binaries (Geier et al. 2011). About 50% of the known sdB stars are in close binary systems. So we can estimate the number fraction of systems like CD–30°11223 to be about 0.5% of the whole population of sdB stars. According to binary evolution calculations, the birthrate of such stars in our Galaxy is $\sim 5 \times 10^{-2} \text{yr}^{-1}$ (Han et al. 2003). We therefore estimate the number of progenitor systems and the resulting SN Ia rate to be $\sim 2.5 \times 10^{-3} \text{yr}^{-1}$. This is consistent with the theoretical birthrate predicted for the WD+He star channel ($\sim 3 \times 10^{-4} \text{yr}^{-1}$, Wang et al. 2010). But more importantly, it is smaller than the SN Ia birthrate of $\sim 3 \times 10^{-3} \text{yr}^{-1}$ and therefore consistent with observations (Capellanaro & Turato 1997).

Although sub-Chandrasekhar scenarios in general have no well defined explosion mass, the parameter space for the sdB binary progenitors turns out to be quite narrow. According to hydrodynamic simulations the minimum mass of the WD should be $\sim 0.8 M_\odot$, because carbon burning is not triggered for objects of much lower mass (Sim et al. 2012). On the other hand, the WD must consist of carbon and oxygen to be able to explode as SN Ia. This limits the mass to values lower than $\sim 1.1 M_\odot$, because even more massive WDs consist of oxygen, neon and magnesium and would rather collapse than explode. This mass range is further narrowed down by binary evolution calculations. Very close sdB+WD systems with companion masses around $0.8 M_\odot$ are predicted to be formed in much higher numbers than binaries with more massive companions. Another important constraint is
that the timespan from the binary formation after the CE to the SN1a explosion must be shorter than the core helium-burning lifetime (~ 100 Myr). Otherwise the sdB will turn into a WD before helium can be transferred. This restricts the orbital periods of possible sdB+WD progenitors to less than ~ 0.07 d.

The double-detonation scenario with hot subdwarf donor is the only proposed SN1a scenario where both progenitors and remnants have been identified. Analysing a larger sample of those objects will allow us to put tight constraints on their properties and evolution.

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