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Magnetic Torques Imply Fewer Double Detonations

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Abstract

Binary systems composed of one helium-rich non-degenerate star and one carbon-oxygen white dwarf (He+CO) have long been considered a promising progenitor candidate for a number of astrophysical transients like archetypical supernovae of the type Ia, Iax, and a number of less luminous phenomena, such as He-novae and AM CVn stars. Among the proposed mechanisms capable of initiating a detonation of the degenerate core of the WD, the sub-Chandrasekhar mass double detonation has received increased attention in recent years. We present the results of a number of numerical simulations on the evolution of helium accreting CO WDs with an emphasis on the effects of differential rotation and magnetic fields in the context of the Spruit-Tayler (ST) dynamo. We present findings of two papers: Neunteufel et al. (2017) and (forthcoming) Neunteufel et al. (2018)

1 Astrophysical Context

The, as of yet unresolved, production mechanism of supernovae (SNe) of the type Ia and related transients, like SNe Iax, is an intensely debated subject in current astrophysics. A better understanding of this subject is seen as necessary due to the importance of SNe Ia as standard candles in cosmological distance measurements (Perlmutter et al., 1999; Riess et al., 1998; Schmidt et al., 1998). Among the proposed progenitors of these transients, binary systems composed of one low mass, non-degenerate helium-rich star (He-star) and one carbon oxygen white dwarf (CO WD), in conjunction with the double detonation (DDet) ignition mechanism, i.e., a detonation in an accreted helium shell on a CO WD igniting a secondary detonation of the CO core, (Taam, 1980a,b; Nomoto, 1980, 1982a,b), has been seen as one of the most promising models.

It has been shown previously that, neglecting rotation, that the DDet scenario can be achieved by steady accretion of less than $\sim 0.3\ \mathrm{M_\odot}$ of helium (Woosley & Kasen, 2011, e.g.) at mass transfer rates $\leq 10^{-7}\ \mathrm{M_\odot/yr}$. It was also shown, however, by Yoon & Langer (2004a) and Yoon & Langer (2004b) that the introduction of rotational effects (though neglecting the effects of the Tayler-Spruit mechanism) will lead to helium ignition at reduced helium shell masses $\leq 0.01\ \mathrm{M_\odot}$. This effect was traced back to increased viscous heating in the upper layers of the accreted envelope. However, viscous heating-induced ignition was found to occur at densities that were found to be too low (Woosley & Weaver, 1994, $< 10^6\ \mathrm{g/cm^3}$, as proposed by) to allow for the formation of a shock subsequent to helium ignition and, consequently, inhibiting the DDet scenario.

Neunteufel et al. (2017) presented a number of WD accretion calculations, including the rotational effects discussed by Yoon & Langer (2004b) as well as the Tayler-Spruit dynamo. The most significant effect of the inclusion of these magnetic mechanisms was shown to be the enforcement of quasi-solid body (hereafter also: quasi-rigid) rotation on the accreting WD. Quasi-rigid rotation has the effect of stabilizing the accreted helium layer against premature ignition of the helium through compressional and viscous heating. Consequently, only systems accreting faster than $3 \cdot 10{-}8\ \mathrm{M_\odot/yr}$ are able to ignite helium through heating. Systems accreting slower than $3 \cdot 10^{-8}\ \mathrm{M_\odot/yr}$ depend on helium ignition being triggered by the density of the helium substrate.

This proceeding reiterates results obtained by Neunteufel et al. (2017) and discusses preliminary results on binary evolution calculations, assuming a full set of rotational effects, including the Tayler-Spruit dynamo.

2 Methods

The Binary Evolution Code (BEC) is a well established computational framework capable of performing detailed one-dimensional numerical experiments of single or binary star systems (Langer et al., 2000; Yoon & Langer, 2004a).

For the purposes of this study, the BEC has been modified to allow for the inclusion time-dependent accretion rates in single star models. These rates may be chosen arbitrarily or resemble rates expected in a naturally occurring binary system.

We make use of the full treatment of rotational insta-

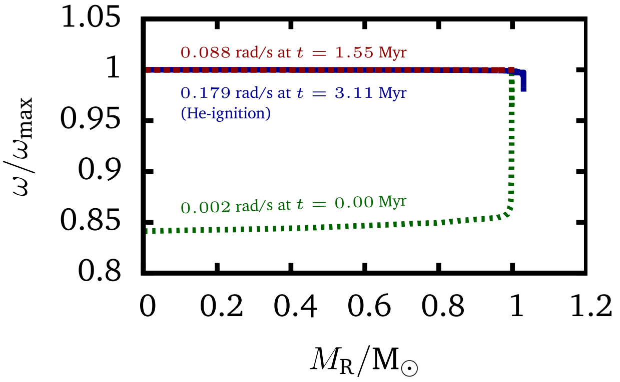

Figure 1: Rotational velocity (normalized) with respect to total mass of an accreting CO WD at three different stages of evolution: At the start of helium accretion ($t = 0.00$ Myr), the midpoint between the start of accretion and helium ignition ($t = 1.55$ Myr) and shortly after helium ignition ($t = 3.11$ Myr). (Figure adapted from Neunteufel et al., 2017)

bilities currently available in BEC, namely the Solberg-Hoiland instability, the secular shear instability, dynamical shear instability and Eddington-Sweet circulation, we further include magnetic effects in the form of the Tayler-Spruit instability (Spruit, 2002), implemented as described in Neunteufel et al. (2017).

We present results obtained in model sequences of binary systems covering initial WD masses of 1.10 $M_\odot$ and 1.00 $M_\odot$ with initial orbital periods of 0.035 d $\leq P_{\text{init}} \leq 0.07$ d and initial donor star masses 0.4 $M_\odot \leq M_{\text{d,i}} \leq 1.00$ $M_\odot$.

We employ an external criterion in order to distinguish between an ignition leading to a subsonic burn (also: deflagration) from one leading to a supersonic burn. In this, we follow the criterion laid out by Woosley & Weaver (1994), with supersonic shocks developing if the density at the point of unstable helium ignition (here defined as the point where the helium burning timescale becomes comparable to the star's dynamic timescale) is $\rho_{\text{ign}} > 10^6$ g/cm^3.

3 Effects of the Tayler-Spruit Mechanism

Fig. 1 shows representative rotational profiles of accreting WDs from the start of mass transfer onto a slowly rotating accretor to the point of helium ignition. A quasi-rigid rotational profile is established early during mass transfer and continues until a point shortly before the onset of unstable helium ignition. Unstable helium ignition is preceded by a period (≈ 100 yr) of gradually increasing helium fusion, leading to a noticeable inflation of the outermost helium shell region of the WD. This, owing to conservation of angular momentum, leads to the decrease in angular velocity in the outer shell structure in the final model depicted in fig. 1.

The imposition of quasi-rigid rotation on the accretor leads, as detailed by Neunteufel et al. (2017), to a significantly increased helium demand in order to attain unstable helium ignition.

4 Results

The outcome of a He+CO system, influenced by the ST dynamo, strongly depends on the initial WD mass ($M_{\text{WD,i}}$) initial orbital period (P_{init}) and the initial donor star mass ($M_{\text{d,i}}$). Fig. 2 gives an overview of the attainable outcomes in He-star+CO WD systems. These can, broadly, be divided into four distinct categories:

- He detonation. This outcome is reached if the mass transfer rates reached during interaction are low enough to preclude premature helium ignition through compressional heating. This is generally the case if Roche lobe overflow (RLOF) occurs during the donor star's core helium burning phase (case BA mass transfer) if $M_{\text{d,i}} < 0.85$ $M_\odot$. Further, the donor star must be able to provide sufficient helium to initiate helium ignition (see Neunteufel et al., 2017, for a more detailed discussion). This outcome is indicated if $\rho_{\text{ign}} > 10^6$ g/cm^3.
- He flash. This outcome is expected if the mass transfer rates during RLOF are high enough to cause helium ignition mainly through compressional heating. Ignition under conditions of high mass transfer rates is associated with ignition densities below $\rho_{\text{ign}} > 10^6$ g/cm^3, leading to a subsonic flash instead of a supersonic detonation. The required high mass transfer rates are caused in most cases by RLOF being initiated after helium core burning has concluded in the donor star (case BB mass transfer). High mass transfer rates can also be reached in case BA systems if the donor star is exceptionally massive $M_{\text{d,i}} > 0.85$ $M_\odot$. A special case are systems where mass transfer starts as case BA, then stops, due to the evolution of the donor star, and then restarts as case BB (unsteady accretion). Some of these systems undergo deflagrations exhibiting helium shell masses much higher than steadily accreting systems with similarly low ignition densities.
- Delayed merger I. This case is reached in systems undergoing case BB mass transfer with mass transfer sufficiently high to quench helium shell burning in the donor, but too low to cause an immediate helium ignition. The end state of this kind of system are two CO WDs with extensive helium envelopes.
- Delayed merger II. This outcome is precipitated by the same evolutionary condition as the detona-

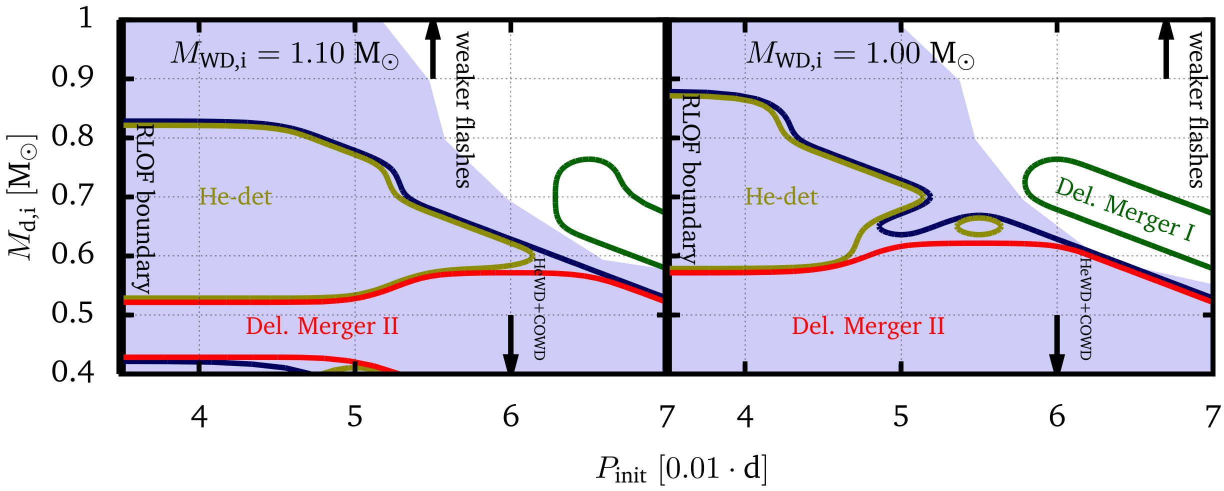

Figure 2: Results of 274 detailed stellar evolution models Neunteufel et al. (2018). The models are continued up to the point of either the first occurrence of unstable helium ignition ($\tau_{\rm nuc,He} \approx \tau_{\rm dyn}$) or the end of mass transfer. Lines represent borders between regimes with different outcomes. Helium detonations were previously predicted in the blue shaded region Wang et al. (2013)

tion (i.e., case BA mass transfer) but with a donor star insufficiently massive to provide the required helium to set off helium ignition on the accretor. Core helium burning is quenched by the donor becoming less massive than $\simeq 0.3\ {\rm M}_\odot$ (depending on its current CO content). Systems of this kind will usually end up as a double degenerate, one of which (the former accretor) will be rapidly rotating. The former donor will be a HeCO WD with a strongly mixed core containing He, C and O, while the former accretor will be a CO WD with a relatively massive He shell.

Helium detonation was previously predicted to occur in the shaded regions in Fig. 2 by Wang et al. (2013). The reduction of the parameter space demanded by this study leads to a reduction in the expected occurrence rates by a factor of 10 to 20.

Fig. 3 shows the correlation of ignition density and final surface rotational velocity in all simulated systems experiencing helium ignition. All systems contained within the parallelogram experience unsteady accretion. Systems not undergoing unsteady accretion show a strong correlation between final surface rotational velocity and ignition density with a noticeable gap between systems experiencing detonation and systems experiencing deflagration. This gap is adequately explained by the mechanism detailed by Neunteufel et al. (2017). However, the separate grouping of systems undergoing unsteady accretion suggests that the only way for deflagrating systems to attain high rotational velocities is unsteady accretion. Since the window for unsteady accretion is very small for any $M_{\rm WD,i} - M_{\rm d,i}$ combination, these systems are a relative minority.

In case of a helium ignition leading to a detonation, then leading to a double detonation, then to the destruction of the WD, it is expected that the former donor star would survive the ensuing supernova and be flung away from the location of the former binary with a rest frame velocity equal to its former orbital velocity. The relation of the former donor's runaway velocity to its mass is shown in fig. 4. The structure of the data points suggests a correlation between remnant mass

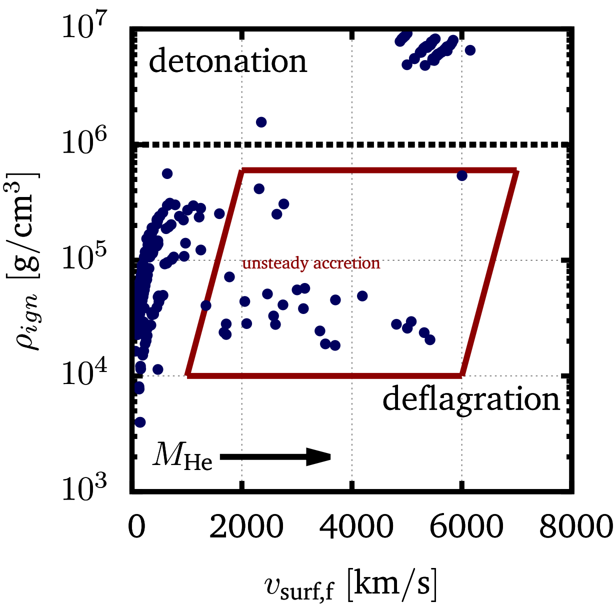

Figure 3: Ignition density over surface rotational velocity at the point of helium ignition for helium accreting WDs with initial masses $M_{\rm WD,init} = 0.82...1.10\ {\rm M}_\odot$. The surface rotational velocity correlates with the mass of accreted helium (Neunteufel et al., 2017). Models inside the red parallelogram experience unsteady accretion.

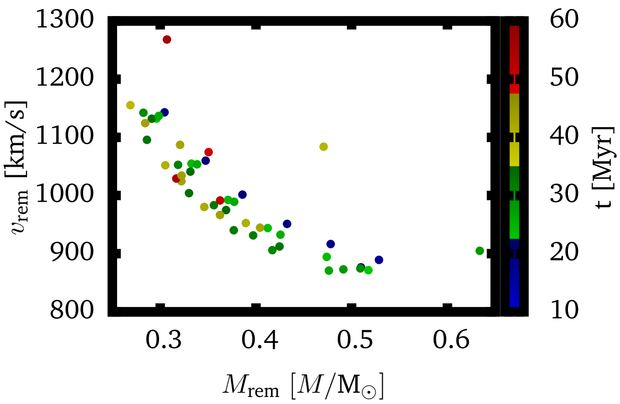

Figure 4: Final orbital velocities v_{rem} of our donor star models versus their mass M_{rem} for systems where the donor is released by detonation of the white dwarf. Remnants of masses less than ≈ 0.26 M$_\odot$ are expected to be in the process of WDs at the point of ejection.

and velocity with expected velocities ranging between 850 km/s $< v_{rem} < 1280$ km/s, at least within the confines of our parameter space. It should be noted that the upper limit of this range lies just below the expected ejection velocity of the observed hypervelocity hot subdwarf US 708 (Geier et al., 2015).

5 Conclusions

We summarize our findings as follows:

- Inclusion of the Tayler-Spruit mechanism favors quasi-rigid body rotation in accreting WDs.
- Quasi-rigidity during accretion leads to significantly increased helium shell masses at the point of both helium detonation and helium deflagration.
- The increased helium demand leads to a subclass of "failed" detonations, creating close hybrid HeCO-CO double degenerate systems.
- The expected occurrence rates of helium detonation-driven supernovae are reduced compared to previous predictions.
- Helium detonations are largely expected to occur on rapidly rotating WDs. Helium deflagrations favor slow rotation with exceptions only in cases of unsteady accretion.
- Inclusion of the Tayler-Spruit mechanism can plausibly explain the existence of hypervelocity hot subdwarfs as surviving donor star of helium-driven supernovae.

Further research will include the following:

- Double detonations of rapidly rotating CO WDs currently lack reliable predictive synthetic spectra. The same is true for deflagrations in thick helium shells. Computation of such spectra would provide an important link to observation.
- A better characterization of ejected donor stars could aid in the interpretation of astrometric survey data and provide an experimental check of our calculations.
- It has been shown that time variability in the mass transfer rates in binaries has a significant impact on the outcome of an affected system. A more detailed study of these effects could aid in the conduct of future theoretical calculations.

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References

Geier S., et al., 2015, Science, 347, 1126

Langer N., Deutschmann A., Wellstein S., Höflich P., 2000, A&A, 362, 1046

Neunteufel P., Yoon S.-C., Langer N., 2017, A&A, 602, A55

Neunteufel P., Yoon S.-C., Langer N., 2018, forthcoming

Nomoto K., 1980, in Wheeler J. C., ed., Texas Workshop on Type I Supernovae. pp 164–181

Nomoto K., 1982a, ApJ, 253, 798

Nomoto K., 1982b, ApJ, 257, 780

Perlmutter S., et al., 1999, ApJ, 517, 565

Riess A. G., et al., 1998, AJ, 116, 1009

Schmidt B. P., et al., 1998, ApJ, 507, 46

Spruit H. C., 2002, A&A, 381, 923

Taam R. E., 1980a, ApJ, 237, 142

Taam R. E., 1980b, ApJ, 242, 749

Wang B., Justham S., Han Z., 2013, A&A, 559, A94

Woosley S. E., Kasen D., 2011, ApJ, 734, 38

Woosley S. E., Weaver T. A., 1994, ApJ, 423, 371

Yoon S.-C., Langer N., 2004a, A&A, 419, 623

Yoon S.-C., Langer N., 2004b, A&A, 419, 645