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Carbon-oxygen and oxygen-neon classical novae are Galactic ^{7}Li producers

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Abstract. We report on studies of classical nova (CN) explosions where we follow the evolution of thermonuclear runaways (TNRs) on carbon oxygen (CO) and oxygen-neon (ONe) white dwarfs (WDs). Our simulations are guided by the results of multi-dimensional studies of TNRs in WDs which find that sufficient mixing with WD core material occurs after the TNR is well underway, reaching levels of enrichment that agree with observations of CN ejecta abundances. Our results show large enrichments of ^{7}Be in the ejected gases implying that CNe may be responsible for a significant fraction ($\sim$ 100 $M_{\odot}$) of the ^{7}Li in the galaxy ($\sim$1000 $M_{\odot}$). In addition, the WDs in these simulations are ejecting less material than they accrete. We, therefore, predict that the WDs can grow in mass as a consequence of the TNR and CNe may be an important channel of Supernova Ia progenitors.

Key words. Stars: abundances – Stars: lithium – Stars: Classical novae

1. Introduction

Classical novae occur in close binary systems with a white dwarf (WD) primary and a secondary which is a larger cooler star that fills its Roche Lobe. It is losing material through the inner Lagrangian point which ultimately is accreted by the WD. These binary systems are referred to as cataclysmic variables (CVs). The consequence of the WD accreting sufficient material is a thermonuclear runaway (TNR) in matter that is electron degenerate at the beginning of accretion and thus produces an event that is designated a “nova outburst” (either classical, recurrent, or symbiotic nova; hereafter CN, RN, or SymN). While the observed outburst ejects material into the surrounding circumstellar region, it does not disrupt the WD and continued accretion results in successive TNR and nova events. In some cases, the properties of the WD and accretion result in outbursts repeated on human timescales which are designated RNe. If the orbital separation is large and the secondary is a red giant, then the system is designated a SymN.

The observations of the chemical composition of the gases ejected by a CN explosion, show that they typically are extremely nonsolar (Warner 1995; Gehrz et al. 1998; Bode, Evans 2008; Evans, Gehrz 2012; Starrfield et al. 2012; Downen et al. 2012; Iliadis et al. 2018; Starrfield et al. 2019). Based on both the observationally derived abundances of CNe ejecta and theoretical modeling of the TNR, it is likely that the accreting material has mixed with the outer layers of the WD at some time during the evolution from the beginning of accretion to the observed outburst. Thus, the observed ejected gases consist of a mixture of WD and accreted material that has been processed by hot-hydrogen burning.

Another important motivation driving studies of TNRs on CO WDs is the recent discovery of both ^{7}Li and ^{7}Be in the early high dispersion optical spectra of the ejected material from CN outbursts (Tajitsu et al. 2015, 2016; Izzo et al. 2015, 2018; Molaro et al. 2016; Selvelli et al. 2018; Wagner et al. 2018). These observations have validated earlier predictions (Arnould, Norgaard 1975; Starrfield et al. 1978; Hernanz et al. 1996; José, Hernanz 1998; Yaron et al. 2005) and warrant new theoretical studies to examine the details of this production using improved simulations.

CNe produce ^{7}Li via a process originally described by Cameron, Fowler (1971) for red giants. Starrfield et al. (1978) then applied their mechanism to CN explosions but they assumed that the envelope was already in place. Later Hernanz et al. (1996) and José, Hernanz (1998) followed the accreting material and were able to investigate the formation of ^{7}Be during the TNR. They determined the amount of ^{7}Be carried to the surface by convection and surviving before it could be destroyed by the ^{7}Be(p,γ)^{8}B reaction occurring in the nuclear burning region. If ^{7}Be survives by being transported to cooler regions, it decays via electron-capture to ^{7}Li with an ~ 53 day half-life (Bahcall, Moeller 1969) .

We have now done new studies of TNRs on a wide range of WD masses and compositions and confirm that a TNR on either a CO or ONe nova: (1) overproduces ^{7}Be with respect to solar material and (2) yields amounts that imply that CNe are responsible for significant amounts of galactic ^{7}Li (see below). Hernanz (2015) gives an excellent discussion of the cosmological importance of detecting ^{7}Li in nova explosions.

In addition to studying a wide range of WD masses we have also varied both our initial composition and how we treat the composition. We report on two different methods to treat the accretion of solar material from the companion. First, as in almost all previous studies of accretion onto WDs, we assume that the accreting material mixes with WD matter from the very beginning of the simulation and call this Mixing From Beginning (MFB). The second method is to accrete a solar mixture until the TNR is ongoing and then mix with WD matter. We call the latter method Mixing During the TNR (MDTNR). The benefit of the second method is because the metallicity of the material is smaller during the accretion phase, the simulation can then accrete more material and will reach higher temperatures and densities during the TNR. The properties of the latter simulations more closely resemble the observations.

In Table 1 we compare the values in both our MFB and MDTNR studies (for just CO novae) with those in Hernanz et al. (1996), José, Hernanz (1998), and Rukeya et al. (2017). Rukeya et al. (2017) also provide a comparison with José, Hernanz (1998). Although there are differences between the microphysics in SHIVA (José, Hernanz 1998) and NOVA (opacities, equations of state, nuclear reaction rate library), and in the treatment of convection, except for the simulation at 0.6M$_{\odot}$, there is good agreement in our 2 predictions of ^{7}Li ejecta abundances. The agreement is also good comparing our results with Rukeya et al.

Table 1. Comparison of both ^{7}Be ejecta and Ejected Mass results with José and Hernanz (1998) and Rukeya et al. (2017)

WD Mass ($M_{\odot}$):	0.6	0.8	1.0	1.15	1.15	1.15[a]
Core [b]	25	50	50	25	50	50
^{7}Be ejecta abundance by mass						
José, Hernanz (1998)	4.4×10^{-7}	9.6×10^{-7}	3.1×10^{-6}	6.0×10^{-6}	8.1×10^{-6}	3.1×10^{-6}
Rukeya et al. (2017)	5.5×10^{-7}	4.6×10^{-7}	1.6×10^{-6}	4.3×10^{-6}	2.9×10^{-6}	
MFB(This Work)	8.2×10^{-7}	7.0×10^{-7}	1.4×10^{-6}	5.9×10^{-6}	4.4×10^{-6}	
MDTNR(This Work)	3.7×10^{-6}	3.5×10^{-6}	7.1×10^{-6}	1.9×10^{-5}	1.2×10^{-5}	
Ejected Mass ($M_{\odot}$)						
José, Hernanz (1998)	7.0×10^{-5}	6.4×10^{-5}	2.3×10^{-5}	1.5×10^{-5}	1.3×10^{-5}	6.3×10^{-6}
Rukeya et al. (2017)	2.0×10^{-5}	1.3×10^{-5}	8.2×10^{-6}	4.9×10^{-6}	3.6×10^{-6}	
MFB(This Work)	3.7×10^{-7}	4.1×10^{-7}	4.4×10^{-8}	9.8×10^{-8}	1.3×10^{-7}	
MDTNR(This Work)	2.9×10^{-6}	1.1×10^{-4}	6.3×10^{-5}	1.3×10^{-5}	3.4×10^{-5}	

[a]This sequence is reported on in Table 2 of José, Hernanz (1998) and uses the updated opacities of Iglesias, Rogers (1993)
[b]The numbers in this row are the percent of core material in the simulation.

(2017) who used MESA (Paxton et al. 2011, 2013, 2015, 2016, 2018) in their study.

The top row lists the WD mass and the next row gives the specific mixture, either 25% WD matter or 50% WD matter. The next set of rows is the comparison of the ^{7}Be results from each of the studies listed in the left column. The values in the first three rows all assume MFB. The results from José, Hernanz (1998) are higher than those of Rukeya et al. (2017) except for that of 25% WD matter at 0.6 $M_{\odot}$. However, the last column, in which José, Hernanz (1998) redid the same evolutionary sequence, as in the previous column, but with the Iglesias, Rogers (1993) opacities, is nearly identical to that of Rukeya et al. (2017).

Comparing our MFB simulations to those above, however, we find that our ^{7}Be predictions exceed those of Rukeya et al. (2017) except for the simulation with 50% core matter on a 1.0 $M_{\odot}$ WD. In contrast, they fall below those of José, Hernanz (1998) except for the simulations with 25% core matter at 0.6 $M_{\odot}$ and their last simulation with the new opacities. Our MDTNR results are always larger than those reported in both the other studies and our MDTNR value for 50% core matter on a 1.15 $M_{\odot}$ WD is 4 times larger than the value reported in José, Hernanz (1998) using newer opacities.

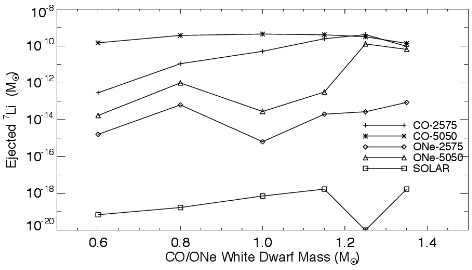

Fig. 1. The predicted ^{7}Li abundance in the ejecta as a function of WD mass in units of solar masses. The TNRs on WDs reach sufficiently high temperatures to deplete the initial ^{7}Li present in the accreted material. The TNR then produces ^{7}Be which is mixed to the surface by strong convection during the TNR and we actually plot that nucleus. ^{7}Be decays ($\sim$ 53 day half-life) after the end of the simulations. The simulations where we mix from the beginning (MFB) eject far less ^{7}Li and are not plotted here. The simulation with solar abundances on a 1.25 $M_{\odot}$ WD did not eject any material.

We also show in this table the comparison of the amount of ejected mass. For these cases, the sequences listed for José, Hernanz

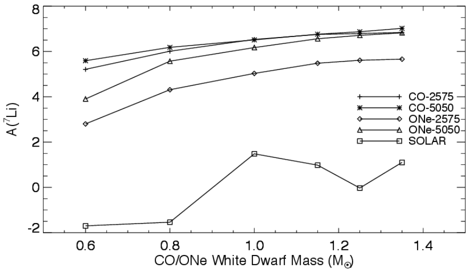

Fig. 2. The predicted ^{7}Li abundance in the ejecta as a function of WD mass but in units of A(^{7}Li). A(^{7}Li) is the unit commonly used in studies of ^{7}Li in the galaxy (A(^{7}Li) = log N(^{7}Li)/N(H) +12.00: Boesgaard et al. (2019) and references therein).

(1998) all eject more mass than either Rukeya et al. (2017) or our MFB set of calculations. Once José, Hernanz (1998) switch to an updated opacity table, however, their ejected mass drops by a factor of two and is more in line with Rukeya et al. (2017). However, comparing our MDTNR values, they are larger than José, Hernanz (1998) for the 3 simulations with 50% core material but smaller for the 0.6 $M_\odot$ (25% core matter) and the $1.15_\odot$ (25% core matter). Finally, except for the simulation with 25% WD matter at 0.6 $M_\odot$, they are all larger than the equivalent simulations by Rukeya et al. (2017).

The amount of ^{7}Li (actually produced as ^{7}Be) in the ejected material in solar masses is shown in Figure 1 as a function of CO or ONe WD mass. Figure 2 shows the same data but in terms of the A(^{7}Li) value (Boesgaard et al. 2019) so as to be consistent with most of the studies of the stellar abundances of ^{7}Li in the galaxy. All our MDTNR sequences eject material enriched in ^{7}Be. This is because these sequences reach higher temperatures and densities than the MFB sequences which results in larger convective velocities. Thus, more ^{7}Be is brought to the surface during the TNR and remains there as the top of the convective region moves inward as the TNR declines back to quiescence.

The amount of enrichment is an increasing function of CO WD mass but varies for ONe WD mass. It was realized by (Hernanz et al. 1996; José, Hernanz 1998) that CO classical novae produced more ^{7}Li than ONe novae and the rationale can be found in their paper. We note that all the initial ^{7}Li (or ^{6}Li) in the accreting material is destroyed by the TNR.

Our simulations show that for CO WD mass ≥ 1.15 $M_\odot$ the mass fraction of ^{7}Li (^{7}Be) ejected is either 2×10^{-5} (25% WD matter and 75% solar matter) or 10^{-5} (50% WD matter plus 50% solar matter). The amount of ejected mass for the same WD range is $\sim 10^{-5} M_\odot$ for the 25% WD matter and 75% solar matter simulations and $\sim 2 \times 10^{-5}$ for the 50% WD matter plus 50% solar matter. Interestingly, these values imply an ejected ^{7}Li mass of $\sim 2 \times 10^{-10}$ $M_\odot$ for either composition. If we take a value for the CN rate of 50 yr^{-1} (Shafter 2017), a lifetime for the galaxy of 10^{10}yr, and our production values we arrive at a predicted abundance of $\sim$100$M_\odot$ for the ^{7}Li produced by CNe in the galaxy.

We also address the question: *what is the total amount of ^{7}Li in the galaxy?* The number usually quoted is $\sim$150$M_\odot$ (Hernanz et al. 1996; Molaro et al. 2016). However, we arrive at a different value. Lodders et al. (2009) give a value of 2.0×10^{-9} for the solar system abundance of ^{7}Li/H by number. We convert to mass fraction by multiplying by 7 and obtain 1.4×10^{-8} for X(^{7}Li)/X(H). We assume that the baryonic mass of the galaxy is $\sim 10^{11}$ $M_\odot$ and the mass fraction of hydrogen is 0.71 (Lodders, Palme 2009; Lodders et al. 2009). Therefore, the total mass of ^{7}Li in the galaxy should be $0.71 \times 10^{11} \times 1.4 \times 10^{-8}$ or $\sim$1000$M_\odot$. Finally, the primordial ^{7}Li abundance in the galaxy is $\sim$80$M_\odot$ requiring a galactic source of ^{7}Li (Fields 2011). ^{6}Li is produced by spallation and not by nuclear reactions in stars, however, so that there should not be a correlation in the abundances of these two isotopes in stellar sources.

2. Conclusions

Our results confirm that CO and ONe novae are overproducing ^{7}Be, which decays to ^{7}Li. Moreover, the observations of ^{7}Be and ^{7}Li found in the early high dispersion optical spectra of the ejected material from CN outbursts (both CO and ONe) (Tajitsu et al. 2015, 2016; Izzo et al. 2015, 2018; Molaro et al. 2016; Selvelli et al. 2018; Wagner et al. 2018) report much higher values than we predict. In fact, at least 10 times higher than previously predicted (Starrfield et al. 1978; Hernanz et al. 1996; José, Hernanz 1998). The amount of ^{7}Li produced by CNe, in combination with the observations, allow us to assert that CNe are responsible for a significant fraction of the ^{7}Li in the galaxy.

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