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On the formation of neon-enriched donor stars in ultracompact X-ray binaries

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Abstract. We study the formation of neon-enriched donor stars in ultracompact X-ray binaries ($P_{\rm orb} < 80$ min) and show that their progenitors have to be low-mass (0.3–0.4) $M_\odot$ "hybrid" white dwarfs (with CO cores and thick helium mantles). Stable mass transfer is possible if in the initial stages of mass exchange mass is lost from the system, taking away the specific orbital angular momentum of the accretor ("isotropic re-emission"). The excess of neon in the transferred matter is due to chemical fractionation of the white dwarf which has to occur prior to the Roche lobe overflow by the donor. The estimated lower limit of the orbital periods of the systems with neon-enriched donors is close to 10 min. We show that the X-ray pulsar 4U 1626-67, which likely also has a neon-enriched companion, may have been formed via accretion induced collapse of an oxygen-neon white dwarf accretor if the donor was a hybrid white dwarf.

Key words. stars: white dwarfs – stars: mass loss – stars: abundances – binaries: close – X-rays: binaries

1. Introduction

Recently, Juett et al. (2001) reported the discovery of the excess of neon in four low-mass X-ray binaries: 4U 0614+091, 2S 0918-549, 4U 1543-624, and 4U 1850-0857. It is suggested that the Ne is local to these objects. 4U 1850-0857, which belongs to a globular cluster, has a measured orbital period of 20.6 min. From the optical properties of the systems, Juett et al. suggest that all of them are ultracompact: $P_{\rm orb} < 80$ min. A local excess of neon is found also in the ultracompact ($P_{\rm orb} = 41.4$ min) binary pulsar 4U 1626-67 (Angelini et al. 1995; Schulz et al. 2001). Juett et al. propose that in all these binaries the donors are low-mass, neon-rich degenerate dwarfs. Schulz et al. (2001) suggest that the donor in 4U 1626-67 is the core of a carbon-oxygen (CO) or oxygen-neon (ONe) white dwarf which has previously crystallised. However, the evolution of neutron star+white dwarf [henceforth, (wd, ns)] binaries to the Ne-enrichment stage was not studied.

Below, we explore the evolution of white dwarfs which fill their Roche lobes having neutron star companions. We discuss the mechanism of mass exchange and limiting masses of the donors in these binaries in Sect. 2. The process of chemical fractionation that could lead to Ne-enrichment is briefly outlined in Sect. 2.3. The observed systems are discussed in Sect. 3. Some uncertainties of the model and related problems are considered in Sect. 4. Our conclusions follow in Sect. 5.

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2. Evolution of ultracompact binaries

2.1. Formation of ultracompact binaries

After pioneering work of Paczyński (1967) on the ultra-short-period (∼18 min) cataclysmic variable AM CVn, it is commonly accepted that the donors in semi-detached systems with the orbital periods of several tens of minutes may be degenerate dwarfs and that the driving force of the binary evolution is angular momentum loss (AML) due to gravitational wave radiation (GWR).

The basic features of the scenario for the formation of (wd, ns) systems which can evolve into ultracompact X-ray binaries may be summarized as follows (see e.g. Tutukov & Yungelson 1993; Iben et al. 1995, for details). In the Galactic disk stars with masses $>10\,M_\odot$ that are born in binaries evolve into neutron stars, experiencing underway one or two common envelope stages which strongly decrease the orbital separation. Next, their companions

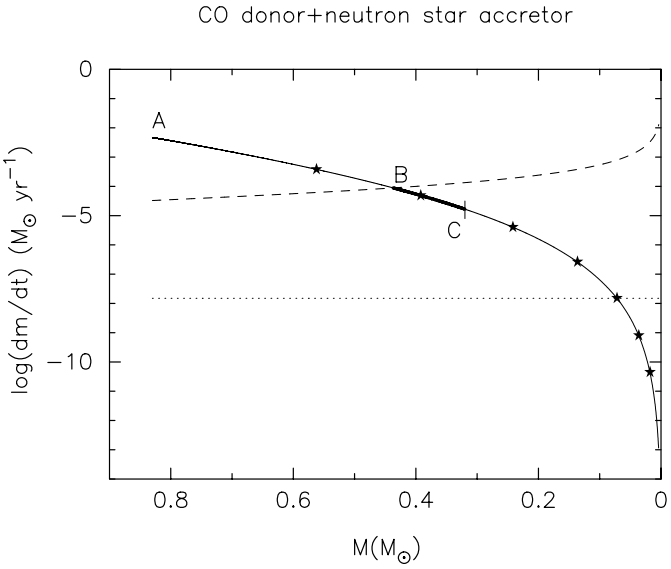

Fig. 1. The solid line shows the mass loss rate from a white dwarf "stabilised" by isotropic re-emission for the case of a system which initially contained a $0.83\,M_\odot$ white dwarf donor and a $1.433\,M_\odot$ neutron star accretor. Dashed line: the upper limit of the mass loss rate from the system by the isotropic re-emission (for $r_{\rm ns} = 10\,$km). Dotted line: $\dot{M}_{\rm Edd}$ for a neutron star. Asterisks mark the parameters of the system at $\log t({\rm yr}) = 3, 4, 5, 6, 7, 8, 9$. Systems with different initial $M_{\rm d}$ follow curves which are indistinguishable on the scale of the figure. To the left of the beginning of the mass-loss curve (A) the Roche-lobe filling white dwarfs are dynamically unstable. Between A and B isotropic re-emission is not efficient enough for ejection of all matter lost by white dwarf. "Hybrid" white dwarfs which are able to transfer matter stably have initial masses corresponding to the thick part of the mass-loss line BC.

experience dynamically unstable mass loss and become white dwarfs. If the resulting systems have orbital separation $\sim R_\odot$, AML via GWR may bring the white dwarf to Roche-lobe overflow (RLOF) within the lifetime of the Galactic disk and under certain conditions (see below) stable mass exchange leading to exposure of the Ne-enriched core may ensue.

In globular clusters neutron stars most probably acquire their companions via exchange interactions with primordial binaries (e.g. Rasio et al. 2000). The subsequent evolution is similar to that of the disk binaries.

2.2. Mass transfer in ultracompact binaries: The nature of the donors and the limits of their initial mass

In systems with degenerate donors, at the onset of Roche-lobe overflow the mass transfer rate $\dot{M}$ may be several orders of magnitude higher than the Eddington limiting accretion rate ($\dot{M}_{\rm Edd}$) for a white dwarf or neutron star accretor (Vila 1971; Tutukov & Yungelson 1979), (see Fig. 1). Formation of a common envelope engulfing the whole system and merger of components or collapse of the neutron star into a black hole may be avoided if the excess of the matter which cannot be accreted leaves the system taking away the specific orbital angular momentum of the accreting component ("isotropic re-emission" Soberman et al. 1997). This role may be accomplished by radiatively driven outflows (King & Begelman 1999; Tauris & Savonije 1999). The equation for the mass loss rate by a white dwarf in the presence of AML by GWR and "isotropic re-emission" used in this study may be found in Yungelson et al. (1996).

Figure 1 shows this mass loss rate for a (wd, ns) system with initial masses of donor and accretor $M_{\rm d} = 0.83\,M_\odot$ and $M_{\rm a} = 1.433\,M_\odot$, respectively[1]. Since all white dwarfs approach zero-temperature radii after cooling for several 100 Myr (Panei et al. 2000) and since most systems will be very much older than this when their orbits have decayed sufficiently to start mass transfer, we use in our computations the mass – radius ($M - R$) relation for cold spheres derived by Zapolsky & Salpeter (1969) in the form given by Rappaport et al. (1987), assuming equal mass fractions of carbon and oxygen. For this $M - R$ relation, if the mass retention efficiency of the accretor is close to zero, (wd, ns) systems with $M_{\rm d} \gtrsim 0.83\,M_\odot$ are dynamically unstable.

All matter in excess of $\dot{M}_{\rm Edd}$ can be lost from the system only if the liberated accretion energy of the matter falling from the Roche lobe radius of the neutron star to the neutron star surface is sufficient to expel the matter from the Roche-lobe surface around the neutron star, i.e. $\dot{M} < \dot{M}_{\rm max} = \dot{M}_{\rm Edd}\,(r_{\rm L,ns}/r_{\rm ns})$, where $r_{\rm ns}$ is the radius of the neutron star (King & Begelman 1999; Tauris et al. 2000). The dependence of $\dot{M}_{\rm max}$ on the mass of the donor is also plotted in Fig. 1. Since the mass-loss line in Fig. 1 holds as well for initial $M_{\rm d} < 0.83\,M_\odot$, within our assumptions "isotropic re-emission" from a neutron star is actually possible for donors with initial $M_{\rm d} \lesssim 0.44\,M_\odot$. Unless there is an even more efficient way to stabilise the mass transfer than by "re-emission", this excludes ONe white dwarfs as donors as these have $M \gtrsim 1.1\,M_\odot$ (Gil-Pons & García-Berro 2001). Similarly also massive CO dwarfs are excluded as donors.

The overabundance (relative to solar) of Ne suggests, that the progenitors of the donors in the X-ray systems under consideration have experienced core helium burning including the $^{14}{\rm N}(\alpha,\gamma)^{18}{\rm F}(\alpha,\gamma)^{22}{\rm Ne}$ reactions chain. Thus the donors cannot be low-mass helium white dwarfs.

This leaves as the last option the so called "hybrid" white dwarfs which have CO cores and thick He mantles. They are formed from components of close binaries with initial masses in the range from 2.5 to $5\,M_\odot$ which experience RLOF prior to core He ignition, become He-burning stars and, after completion of core He burning, evolve directly into white dwarfs. Their mass is $\simeq(0.3{-}0.7)\,M_\odot$ (Iben & Tutukov 1985; Han et al. 2000).

[1] We neglect the effects of an X-ray irradiation induced stellar wind which may enhance mass loss by the donor (Tavani & London 1993).

In a calculation of the model of the population of compact stars in the Galaxy (Nelemans et al. 2001) the birthrate of such (wd, ns) systems with $M_{\rm wd} \leq 0.4\,M_\odot$ is $2.7 \times 10^{-6}\,{\rm yr}^{-1}$. For comparison, the birthrate of progenitors of X-ray binaries with hydrogen-rich donors in the same model is $1.3 \times 10^{-5}\,{\rm yr}^{-1}$.

2.3. Neon-enrichment

Even after core helium exhaustion the abundance of Ne in the cores of hybrid white dwarfs is low, so to observe the strong Ne enrichment, the cores have to be crystallised and fractionated. In the models of white dwarfs these processes take several Gyr, depending on the mass of the dwarf, transparency of the outer layers, total amount of ^{22}Ne and uncertainties in phase diagrams (Hernanz et al. 1994; Montgomery et al. 1999). Figure 2 shows that the orbital periods of (wd, ns) pairs enter the observed range of ∼10 min in less than 10 Myr. (The meaning of the lines and asterisks in Fig. 2 is the same as in Fig. 1.) Hence, the enrichment of the white dwarf core by Ne, must have happened before RLOF.

For an initial metallicity $Z = 0.02$, after completion of He-burning, the mass abundance of ^{22}Ne in the core of the star cannot be larger than $X_{^{22}{\rm Ne}} = 0.02$. During crystallisation of *binary* mixtures of (C/Ne) and (O/Ne), Ne settles in the center and forms a Ne-enriched nucleus which contains all ^{22}Ne formed in the dwarf and has the so called azeotropic abundance $X^{\rm a}_{^{22}{\rm Ne}}$ of Ne (Isern et al. 1991).

The mass of this Ne-rich nucleus is

$$M_{\rm Ne-r} = (X_{^{22}{\rm Ne}}/X^{\rm a}_{^{22}{\rm Ne}})\,M_{\rm wd}. \quad (1)$$

If, following Bravo et al. (1992), one assumes $X^{\rm a}_{^{22}{\rm Ne}} = 0.07$ – an intermediate value of $X^{\rm a}_{^{22}{\rm Ne}}$ for O/Ne and C/Ne mixtures – and takes for $M_{\rm wd}$ the maximum mass of the convective core of a $0.378\,M_\odot$ "hybrid" dwarf – $0.2\,M_\odot$ (Iben & Tutukov 1985), then the mass $M_{\rm Ne-r}$ of the Ne-enriched core is $\simeq 0.06\,M_\odot$.

If the white dwarf didn't have enough time to crystallise, the mass loss uncovers material of the convective core of the progenitor of the dwarf. Then the mass fraction of Ne may be down to the initial ∼0.001.

3. Comparison with the observed Ne-rich X-ray binaries

3.1. 4U 0614+091, 2S 0918-549, 4U 1543-624, and 4U 1850-0857

Figure 2 shows the evolution of a semidetached system which initially contained a "hybrid" white dwarf and a neutron star, in orbital period – mass loss rate coordinates. Taking the mass of the Ne-enriched core of $0.06\,M_\odot$ estimated in Sect. 2.3 as typical, one obtains a rough lower limit of the orbital periods of binaries with the Ne-rich white dwarf donors of about 10 min. The white dwarf

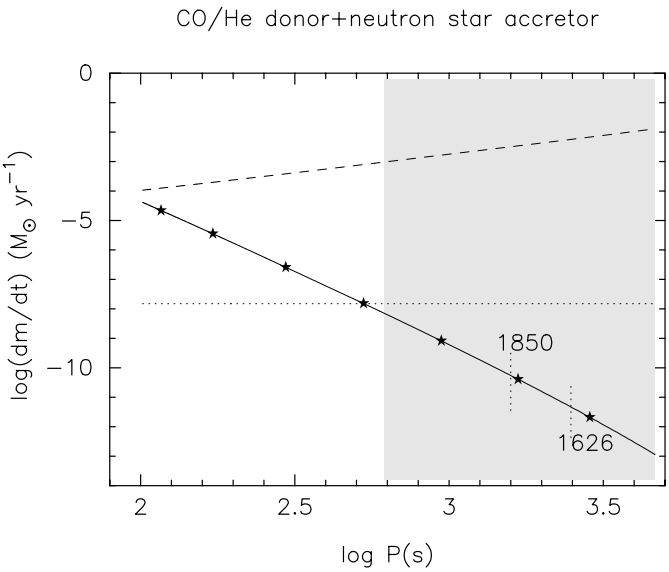

Fig. 2. Orbital period – mass loss rate relation for a system which initially contained a $0.38\,M_\odot$ "hybrid" white dwarf donor and a $1.433\,M_\odot$ neutron star accretor. The meaning of the lines and symbols is as in Fig. 1. The vertical dashed lines mark the orbital periods of 4U 1850-0857 and 4U 1626-67. Within the period range corresponding to the shaded area the donors may transfer neon-enriched matter.

enters the range of periods (or masses) for which Ne-enrichment is possible in several Myr following the onset of RLOF (Fig. 2).

Our calculations of the mass loss rate also give the mass of the donor as a function of the orbital period. We thus infer the donor masses for 4U 1850-0857 and 4U 1626-67 to be 0.027 and $0.01\,M_\odot$, respectively (see more detailed discussion of the latter system in Sect. 3.2).

The abundance of Ne relative to solar found in the observed Ne-rich X-ray binaries ranges from 1.9 ± 0.3 to 2.87 ± 0.16. For oxygen an underabundance is reported: 0.37 ± 0.06 to 0.52 ± 0.04. Taken at face value, these relative abundances translate into a local Ne/O ratio of 0.63–0.77. If true, these values are considerably higher than one would expect for the above used abundance of Ne in the nucleus of the dwarf $X^{\rm a}_{^{22}{\rm Ne}} = 0.07$. But Isern et al. (1991) notice, that $X^{\rm a}_{^{22}{\rm Ne}}$ may be well underestimated by a factor ∼3. If this is true, the Ne/O ratio comes into better agreement with observed values. The mass of the Ne-enriched core then becomes slightly higher than $0.02\,M_\odot$, still comparable with our estimates of the masses of the white dwarfs in 4U 1850-0857 and 4U 1626-67.

The problem of a low predicted Ne/O ratio would also hold for initially more massive donors, if stable mass loss would be possible for them. In the core of a $1.1\,M_\odot$ ONe dwarf the Ne/O ratio is ∼0.4 (Gil-Pons & García-Berro 2001). For a "standard" $0.6\,M_\odot$ CO white dwarf with an initially equimolar distribution of C/O and traces of Ne, a final Ne/O ratio ∼0.25 is expected in the core (Segretain et al. 1994).

All four Ne-enriched X-ray binaries contain, presumably, weakly magnetised neutron stars. This may be a result of the decay of the magnetic field by accretion (Taam & van de Heuvel 1986).

3.2. 4U 1626-67: An accretion induced collapse?

4U 1626-67 differs from the binaries discussed above by the presence of a 7.7 s X-ray pulsar with a strong magnetic field estimated from cyclotron emission: $(3.2\pm0.1)(1+z)\times 10^{12}$ G, where z is gravitational redshift (Orlandini et al. 1998). Applying a polytropic $M-R$ relation, Verbunt et al. (1990) estimated its donor mass as $\sim 0.02\,M_\odot$. A similar estimate of $M_{\rm d}$ was obtained by Schulz et al. (2001) under the *assumption* that velocities of the lines in the Ne/O complex and their Doppler shifts reflect Keplerian motions in the accretion disk. Thus, existing estimates of $M_{\rm d}$ are consistent with Ne-enrichment of the donors. A very low value of $M_{\rm d}$ in 4U 1626-67 is also favoured by the probability of detection considerations (Verbunt et al. 1990).

The high magnetic field strength suggests that the neutron star is young and accretion was negligible. The absence of enhanced abundances of O-group elements in the spectrum of 4U 1626-67 argues against the origin of the neutron star in a SN II event (Angelini et al. 1995). Taam & van de Heuvel (1986) suggested that this X-ray pulsar was formed recently – $(2-10)\times 10^7$ yrs ago – by an accretion induced collapse (AIC) of a white dwarf. Verbunt et al. (1990) rejected the AIC model, based on the argument that the time between AIC and resumption of mass transfer is $\sim 10^8$ yr, longer than then assumed e-folding decay time ($\sim 10^7$ yr) for the magnetic fields of neutron stars. Later, the analysis of magnetic fields of isolated radio pulsars have shown that the magnetic field decay scale is probably $\gtrsim 10^8$ yr (Bhattacharya et al. 1992). This, along with the discovery of Ne-enrichment in the system, suggests that one should reconsider the formation of 4U 1626-67 via AIC, especially, since the details of pre-collapse evolution were never studied before.

In the model for the population of compact stars in the Galaxy (Nelemans et al. 2001) the birthrate of ONe white dwarfs with $M \geq 1.2\,M_\odot$ accompanied by "hybrid" white dwarfs with $0.35 \leq M \leq 0.5\,M_\odot$ which get into contact within 10 Gyr is 1.25×10^{-6} yr^{-1}. This rate is within the limits for occurrence of AIC's in the Galaxy set by nucleosynthesis considerations (Fryer et al. 1999).

The initial binary may contain e.g. a $0.38\,M_\odot$ "hybrid" white dwarf (for which we know the internal structure from Iben & Tutukov 1985) and a $1.2\,M_\odot$ oxygen-neon one (Fig. 3). At the beginning of the RLOF $P_{\rm orb} = 2$ min. The outer $0.12\,M_\odot$ of the donor consist of He. The maximum rate of stable He-burning at the surface of a massive white dwarf is about $10^{-5}\,M_\odot\,{\rm yr}^{-1}$ (Kato & Hachisu 1999), lower than the mass loss rate by the donor in the initial stages of mass transfer. Mass exchange in this case may be also stabilised by isotropic re-emission of optically thick wind from accretor, generated by He-burning (Hachisu et al. 1996). Therefore stable helium burning is likely to set in on the surface of the $1.2\,M_\odot$ accreting white dwarf.

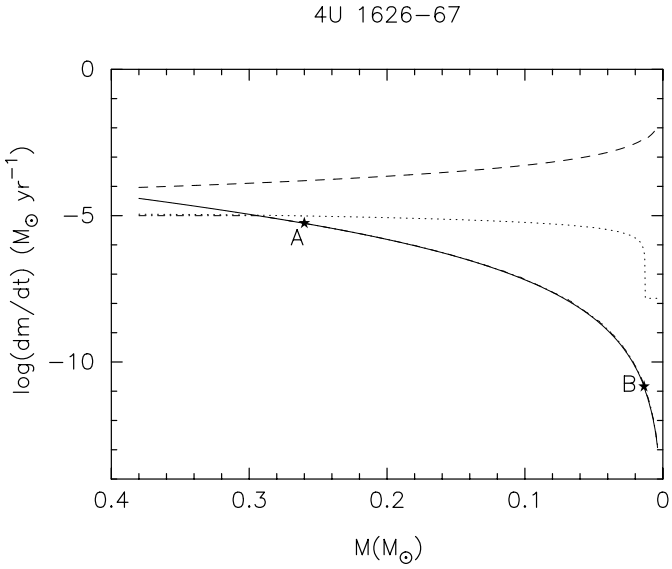

Fig. 3. Solid line – mass exchange rate in a system which initially consisted of a $0.38\,M_\odot$ "hybrid" donor and a $1.2\,M_\odot$ ONe white dwarf accretor. The dashed line is the upper limit of the "isotropic re-emission" rate for an accreting white dwarf. The dot-dashed line – accretion rate. The dashed line – $\dot{M}_{\rm Edd}$, first for a white dwarf, then for a neutron star. At point A the He mantle of the donor is exhausted, at point B the white dwarf collapses into a neutron star.

Like Verbunt et al. (1990), we assume that the white dwarf collapses into a $1.26\,M_\odot$ neutron star after the increase in mass to $1.44\,M_\odot$. This happens after 240 Myrs of accretion, when $P_{\rm orb} \approx 2000$ s. The mass of the donor is at that moment $0.0132\,M_\odot$. The Ne/O ratio in the core for azeotropic abundance of Ne (0.1 to 0.3, see Sect. 2.3) doesn't contradict the measured Ne/O ratio in 4U 1626-67 (Schulz et al. 2001): 0.22 ± 0.15.

The collapse interrupts mass transfer for $\sim 1.56\times 10^8$ yr due to the loss of binding energy of the dwarf (see for details Verbunt et al. 1990). This time span may not be sufficient for the decay of the magnetic field of the pulsar. When after resumption of the contact the period of the system has increased to 41.4 min, the mass of the donor is $0.0101\,M_\odot$.

Until this moment the neutron star in our model system has lived after the AIC for about 350 Myr. If magnetic fields do not decay on long time scale its field will not have decayed sufficiently. The accretion of $0.003\,M_\odot$ onto a neutron star is most probably insufficient for destruction of its magnetic field (if the frozen field and incompressible fluid approximations (Cheng & Zhang 1998) are assumed). Assuming solid body rotation and conservation of angular momentum, one gets $\simeq 1.3$ ms for the initial spin period of the neutron star. The present spin period of the neutron

star in 4U 1626-67 is 7.7 s, close to the "death-line" of radio pulsars for $B = 3\times10^{12}$ G (Bhattacharya 1996). Thus, it is conceivable that 4U 1626-67 harbours a neutron star which ceased to be a radio pulsar, but didn't experience recycling.

At the stage when our model system resembles 4U 1626-67, the mass exchange rate is $\simeq 4 \times 10^{-12}\,M_\odot\,\mathrm{yr}^{-1}$. As already noticed before (Chakrabarty 1998; Schulz et al. 2001), all model $\dot{M}$ for 4U 1626-67 based on $M-R$ relations are considerably lower than the estimates of $\dot{M}$ based on the observed spin-up rate and simple angular momentum conservation considerations. It is plausible that the secular $\dot{M}$ is consistent with model expectations, while mass transfer rate $\dot{M}$ inferred from the observed spin-up of the pulsar (if correct) reflects the accretion rate from an unstable accretion disk (Schulz et al. 2001). The latter experiences thermal ionization instability if $\dot{M}_\mathrm{a} \lesssim 7.4 \times 10^{-10}$ and $\lesssim 2.5 \times 10^{-9}\,M_\odot\,\mathrm{yr}^{-1}$, for a pure C or O disk, respectively (Menou et al. 2002).

4. Discussion

White dwarfs may be considered as a *ternary* C/O/Ne ionic mixture. For such mixtures Ogata et al. (1993) predict the formation of an almost pure Ne core upon solidification for *any* C:O ratio. If this core ultimately contains all ^{22}Ne generated in the white dwarf its mass is only $\sim 0.004\,M_\odot$, much less than given by Eq. (1) and this would require much larger P_orb for X-ray binaries showing Ne enrichment.

On the other hand, according to Segretain (1996), if a $0.6\,M_\odot$ white dwarf is considered as a ternary mixture with $X_\mathrm{C} = X_\mathrm{O} = 0.495, X_{^{22}\mathrm{Ne}} = 0.01$, almost all Ne concentrates in a thin layer around $M_\mathrm{r}/M_\mathrm{wd} \approx 0.7$. Then spilling of Ne-enriched matter over the neutron star would require extremely fine tuning of the model.

Another intriguing problem concerns X-ray bursts. They were reported for 4U 0614+091, 2S 0918-549, and 4U 1850-0857. None of the bursts have shown atypical behaviour (Juett et al. 2001). Carbon flashes at $\dot{M} < 0.1\,\dot{M}_\mathrm{Edd}$ were never studied. Extrapolation of the calculations of Cumming & Bildsten (2001) over 2 orders of magnitude may be not very relevant. However, it shows that for $X_\mathrm{C} \sim 0.2$, characteristic for "hybrid" dwarfs and $\dot{M} \sim 10^{-11}\,M_\odot\,\mathrm{yr}^{-1}$, accreted carbon possibly burns stably. Thus, the origin of the bursts in systems with *any* low-mass C-rich donors deserves further attention.

5. Conclusion

We have shown that within the framework of the white dwarfs cooling model developed by Isern et al. (1991), Bravo et al. (1992), Segretain et al. (1994), Hernanz et al. (1994) it is possible to explain the formation of the Ne-enriched donors in X-ray binaries if their progenitors were low-mass CO white dwarfs with thick He mantles. A necessary condition is that the white dwarfs had enough time to be substantially chemically fractionated. This means that the mass transfer had to start several Gyr after the formation of the white dwarfs. We estimate that the masses of Ne-rich donors in these systems are $\lesssim 0.06\,M_\odot$ and their orbital periods have to be $\gtrsim 10$ min. The expected Ne/O ratios are $\sim(0.1-0.4)$.

Finally we conclude that the X-ray pulsar 4U 1626-67 could follow an evolutionary path similar to the other Ne-rich systems, with the only difference that it used to have a massive ONe white dwarf component that collapsed into a neutron star relatively recently. We estimate the current mass of the donor in this system as $0.01\,M_\odot$.

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