MASSIVE SINGLE AND BINARY STAR MODELS: A COMPARISON

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Abstract We compare the predictions of recent single and binary star models with respect to several observable features. First, we find that rotationally induced mixing and accretion from a close binary component may lead to almost identical surface abundance patterns — with the boron to nitrogen ratio as a marked exception. We then compare the formation of Wolf-Rayet and helium stars in isolation and binary systems and relate them to Type Ib and Type Ic supernovae. We furthermore discuss the influence of a binary companion on the critical initial masses for the white dwarf–neutron star and neutron star–black hole transitions. E.g., assuming an upper initial mass limit for the formation of white dwarfs of $8\,\mathrm{M}_\odot$ in single stars, we argue that this limit may be as high as $16\,\mathrm{M}_\odot$ in binary systems. Finally, we discuss trends for the spins of compact objects emerging from the most recent single star and binary models.

Keywords: Massive stars: surface abundances, remnant masses, remnant spins

1. Introduction

When a distinct feature is observed in a massive star, then it is often not immediately clear whether this feature occurs in this star because it occurs in all stars of the same initial mass and metallicity at a certain point in their evolution. Alternatively, this feature could have its origin in a peculiarity of the observed star, the most frequent one may be that it has, or had, a close binary companion. Examples for such still badly understood observed features are numerous: peculiar surface abundances in main sequence stars (e.g., McErlean et al. 1998, 1999; Smith & Howarth 1998; Herrero et al. 1999; Korn et al. 2000) or evolved stars (e.g., Venn 1999), eruptions as those occurring in Luminous Blue Variables (e.g., Drissen et al. 2001; and references therein), (aspherical) circumstellar shell (Nota et al. 1995), the B[e] supergiant phenomenon (Langer & Heger 1998), the Wolf-Rayet phenomenon (van der Hucht 2001), supernovae of Types Ib and Ic (cf., Podsiadlowski 1996, Langer & Woosley 1996), the rings around Supernova 1987A (Maran et al. 2000), young neutron stars with rapid or slow spins (cf. discussion in Heger et al. 2000), or peculiar supernova remnants, e.g. the Crab nebula (e.g., Fesen et al. 1997).

Even though for some of the mentioned features there are indications that binarity plays a role — e.g., some Wolf-Rayet stars are known to have very close companions; however, how many of the more than 200 Galactic Wolf-Rayet stars (van der Hucht 2001) would, at this time, not be a Wolf-Rayet star had they not had a close companion, is unknown — the contribution of binarity to these features is generally unknown for most of them.

As our group has, in the recent past, computed a large number of evolutionary models for massive single stars and for close binary systems (cf. references below), we present here a comparison of both types of models, i.e. of single star models with those of either close binary primaries (the mass losing, initially more massive components) and secondaries (the possibly accreting, initially less massive components), whatever is adequate. Such a comparison turns out to be helpful in evaluating the relative importance of binary models for an explanation for some of the observational features mentioned above.

A second goal of this comparison is to provide some insight to groups doing population synthesis studies for massive stars and binaries (for which there are several examples presented in these proceedings) into which stellar properties remain unaffected by the presence of a companion star, and which features are affected — may be even to such extent that they do not occur in single stars at all.

Due to the limited space, we consider in the following only the most important form of binary interaction, namely Roche lobe overflow.

2. Main Sequence Stars

When a massive binary starts its first Roche lobe overflow phase, mass is being transfered from the initially more massive star (the primary) to the companion star (the secondary), where the latter is in almost all possible cases a main sequence star. Depending on the initial orbital separation and mass ratio, the secondary star does accrete a large or small fraction of the overflowing matter, with higher accretion efficiencies for initially tighter orbits and mass ratios closer to one (Wellstein 2001).

In this section, we do not discuss the primary stars — those become helium or Wolf-Rayet stars in most cases (cf. Section 3). We will also not discuss those secondary stars which accrete nothing or very little, as those might remain indistinguishable from single stars (except for having a companion star for some time). However, it is generally believed that a significant fraction of all secondaries accretes more than, say, 50% of the overflowing matter. Are any properties of these stars expected to stick out compared to those of single massive main sequence stars?

In principle, there may be three ways to identify those stars. Firstly, they may still have a binary companion, e.g., a helium or Wolf-Rayet star, or a compact object. And if they lost their companion when it exploded as supernova, they may have received an anomalously high space velocity. However, exactly for those cases where the secondary accreted substantially the corresponding effects are smallest: The accretion makes the secondary gain mass and it becomes very luminous, likely outshining the companion. Further, it makes the mass ratio much smaller than one, i.e. the orbital motion of the (bright) secondary will be small. And for the same reason, the explosion of the primary removes only a small fraction of the total mass from the system, and the imposed space velocity will be smaller than in binaries without accretion. Even though there are few cases where accretion onto the secondary has been shown to exist (e.g., in the massive X-ray binary Wray 977, cf. Wellstein & Langer 1999; or the massive Algol system V729 Cygni, cf. Wellstein 2001), those "proven cases" are exceptions.

Secondly, accretion stars may be recognised by their extremely rapid rotation: The accretion of matter is connected with the accretion of large quantities of angular momentum, which can quickly spin the accretion star up to critical rotation (Packet 1981). Indeed, one interpretation of the Be/X-ray binaries is that the Be star is spun up by accreting matter from the progenitor of the compact companion which now produces the X-ray emission (Pols et al. 1991). The problem to identify X-ray quiet binaries with spun-up accretion stars is that massive stars are rapid rotators in general, and as the inclination angle of the rotation axis is

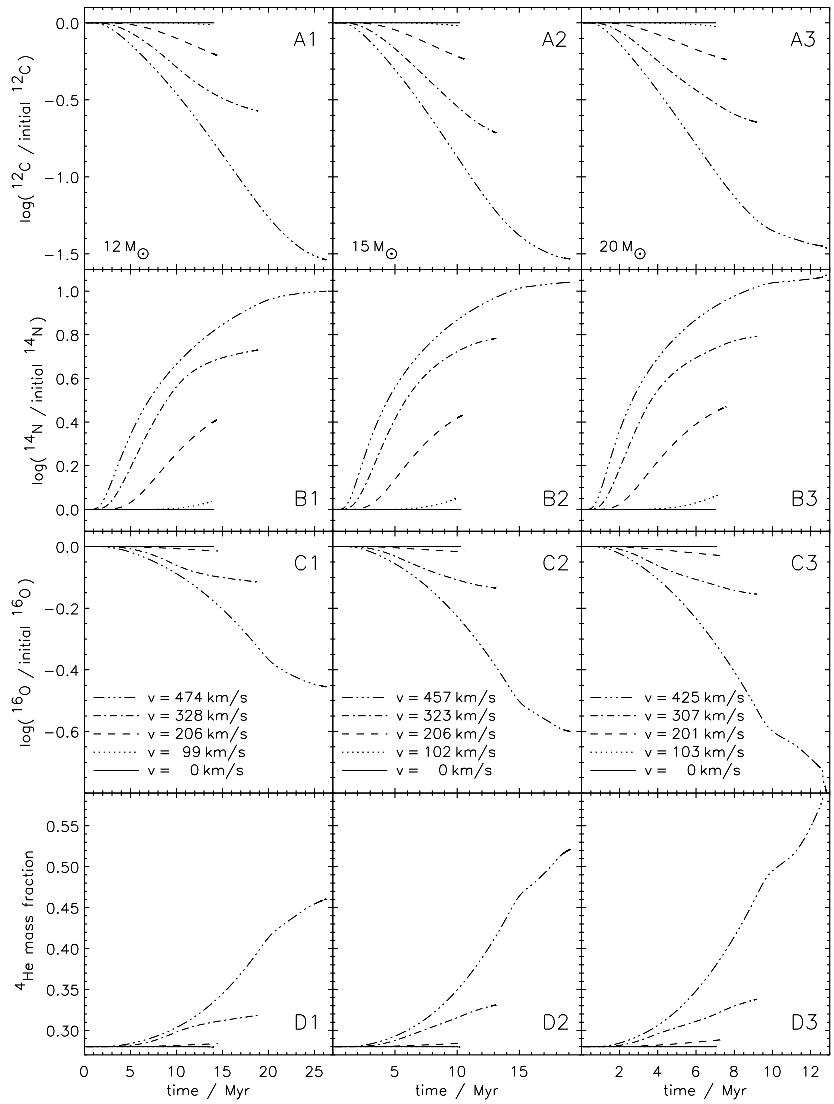

Figure 1. Evolution of the surface abundances during core hydrogen burning, for stars of $12\,M_\odot$ (right column), $15\,M_\odot$ (middle column) and $20\,M_\odot$ (left column), for various initial rotation rates, as indicated (cf. Heger & Langer 2000).

mostly unknown it is hard to pick extreme cases. Furthermore, stars above 15...20 $M_\odot$ have sufficient angular momentum loss due to their radiation driven winds to quickly lose any extreme rotation, even if they were spun-up to critical rotation in the past (cf. Langer 1998, and Langer & Heger 1998).

Table 1. Surface mass fractions, or enhancements for the surface abundances relative to the initial abundances, for secondary stars after the major mass transfer phase, for various Case A and Case B systems. Systems No. 1 to 74 do not include rotational physics (spin up due to accretion and rotationally induced mixing) and are described in more detail in Wellstein et al. (2001). Sequence R1 does include rotational physics (see Wellstein 2001); here, the abundances are given before (bA) and after the Case A mass transfer.

Nr.	$M_{1,i}$ $M_\odot$	$M_{2,i}$	$\dot{M}$	$M_{2,f}$ $M_\odot$	He $[\frac{X}{X_i}]$	Li	Be $[\log\frac{X}{X_i}]$	B	C $[\frac{X}{X_i}]$	N $[\frac{X}{X_i}]$	O $[\frac{X}{X_i}]$	Na $[\frac{X}{X_i}]$
1	12	11.5	A	21.5	1.23	-8.0	-22	-13	0.56	3.9	0.85	1.7
3	12	11	B	20.4	1.14	-8.8	-11	-10	0.61	3.4	0.88	n.b.
27	12	8	B	17.5	1.12	-10	-22	-17	0.45	3.7	0.89	n.b.
31	12	7.5	A	17.8	1.26	-10	-29	-27	0.23	5.4	0.81	2.0
34	16	15.7	A	27.8	1.20	-9.8	-22	-11	0.16	5.4	0.85	1.7
35	16	15.7	B	27.5	1.19	-9.2	-18	-8.3	0.58	3.8	0.84	1.8
51	16	13	B	24.8	1.13	-9.8	-19	-11	0.28	4.6	0.88	1.6
60	16	11	A	23.8	1.26	-10	-22	-25	0.10	6.0	0.81	2.0
65	25	24	A	40.6	1.28	-5.0	-13	-14	0.21	5.5	0.80	1.8
68	25	24	B	39.2	1.12	-9.4	-22	-8.7	0.49	3.7	0.88	1.5
74	25	16	A	33.3	1.28	-10	-19	-23	0.04	6.5	0.79	1.9
R1	16	15	bA	15.8	1.00	-2.9	-1.5	-0.3	0.97	1.1	1.00	1.0
R1	16	15	A	23.8	1.12	-8.6	-13	-4.5	0.47	3.7	0.92	1.5

Then, thirdly, one may try to identify accretion stars by enrichments of the surface in hydrogen burning products, which they might have acquired from their companion star. Indeed, the models of Wellstein et al. (2001), which were computed assuming maximum accretion efficiency, show that the N/C-ratio may increase by a factor of 10...100, and the N/O-ratio by a factor 3...10 (see Table. 1). Enrichments of this kind have in fact been observed in several OB stars (e.g., Schönberner et al. 1988). However, their interpretation remains ambiguous in most cases since such enrichments are also predicted by the most recent single star models for massive stars (cf. Fig. 1), where they are caused by rotationally induced internal mixing processes. Even an observed correlation of the surface enrichment with the stellar rotation rate does not break this degeneracy, as it is naturally predicted by both, the single star and the binary models.

The perhaps clearest way to distinguish both evolutionary channels has been proposed by Fliegner et al. (1996): a simultaneous determination of nitrogen and *boron* surface abundances. As boron is predicted to be destroyed in massive rotating stars very early (cf. Heger & Langer 2000), a boron depletion combined with a normal nitrogen abundance clearly points towards the action of rotational mixing and can not be reproduced by binary mass transfer (cf. Table 1). However, a boron depletion combined with a nitrogen enhancement — which seems to be the more frequent case; cf. Fliegner et al. (1996), Venn et al. (1996) — can be due to either rotation or binarity. This behaviour is confirmed by the most recent binary models of Wellstein (2001), which include rotation for both components of the binary models. Unfortunately, we do not yet know the boron abundances for a large sample of OB stars, as its determination requires high-resolution UV spectroscopy. Accordingly, we do not yet know which fraction of the enriched OB stars are accretion stars.

3. To form and explode Wolf-Rayet stars

Current single star evolutionary models predict that stars with initial masses above 20...30 $M_\odot$ can lose all of their hydrogen due to stellar winds and become Wolf-Rayet stars — the uncertainty in the limiting mass coming mostly from poorly known red supergiant mass loss rates (cf. Vanbeveren et al. 1998). In case of very rapid rotation, this mass limit may be lower (Fliegner & Langer 1994, Meynet 2000, Heger et al. 2000).

A mass limit above $\sim 20\,M_\odot$ implies that Wolf-Rayet stars formed by single stars have masses of $M_{\rm WR} \gtrsim 5\,M_\odot$ (Schaller et al. 1992, Woosley et al. 1993, Heger et al. 2000, Maeder & Meynet 2000). In a close binary, however, there is no such mass limit. Primary components of any initial mass lose their hydrogen envelopes completely in case of a Roche lobe overflow evolution. Therefore, one expects from binary models that hydrogen-free stars of all masses are formed. Those hydrogen-free stars which start out with a low mass show pure helium (plus trace elements) at their surface throughout their evolution, and never develop high carbon or oxygen surface abundances, since the helium star winds become weaker for lower masses (cf. Langer 1989, Woosley et al. 1995).

The cores of helium stars which are born with a mass above $\sim 2\,M_\odot$ collapse to neutron stars at the end of their lives and explode as supernovae (Woosley et al. 1995). The same holds for most of the more massive Wolf-Rayet stars formed from single or binary stars — whether or not the most massive Wolf-Rayet stars form black holes rather than supernovae is currently still debated (Wellstein & Langer 1999; Brown et al. 2001; see also Section 4).

Clearly, supernovae originating from initially massive stars which end their lives without hydrogen envelope correspond to observed supernovae of Type Ib and Type Ic (Nomoto et al. 1996), of which the Ibs show

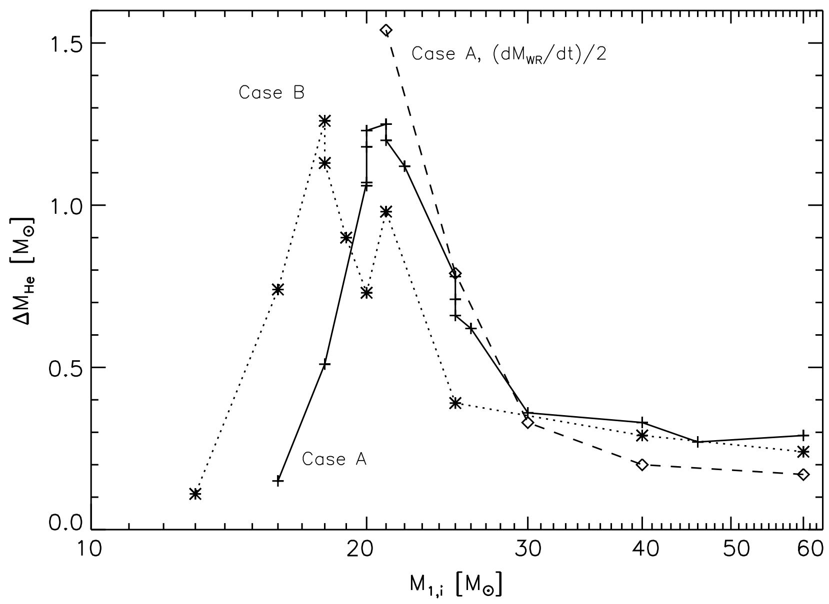

Figure 2. The amount of helium present in the primary components at their immediate pre-supernova stage, as function of their initial mass, for Case A (solid line) and Case B (dotted line) models. The dashed line corresponds to Case A systems computed with a WR wind mass loss rate reduced by 50 % (cf. Wellstein & Langer 1999.)

helium lines in their spectra, and the Ics don't. As the observed rate of Type Ib/c supernovae seems to be higher than what is expected from single stars only (Capellaro et al. 1999), it seems clear that the Wolf-Rayet and helium stars formed due to binary mass transfer make up for a major fraction of them.

Wellstein & Langer (1999) have investigated the amount of helium left in the envelopes of helium and Wolf-Rayet star models which formed in binaries, at the time of their supernova explosion (cf. Fig. 2). They found two initial mass ranges with less than a few tenths of a solar mass of helium remaining: One is 12...15 $M_\odot$ (note that less massive primaries evolve into white dwarfs; cf. Section 4), and the other comprises of initial masses above $\sim 30\,M_\odot$ (which overlaps with WR stars from single stars which end up with little helium). Attributing the latter to Type Ic supernovae, Type Ib supernovae would be produced by primaries of massive close binaries in the intermediate mass range.

4. Mass limits for the formation of compact objects

The evolution of stars, and more specifically their fate, is determined by their masses. Unfortunately, the *initial* mass of a star is *not* always sufficient to predict its evolution and fate, because the star may lose mass on their way. In particular, mass loss alters the evolution of the core when the core is not surrounded by a nuclear shell source. E.g., any mass loss during the core hydrogen burning phase of evolution may affect the fate of the star — which causes the predictions for the end of the most massive stars ($M_{\rm initial} \gtrsim 30\,{\rm M}_{\odot}$) to be a function of their metallicity and initial rotation rate (Schaller et al. 1992, Maeder & Meynet 2000, Heger et al. 2000).

One implication is that for the primary components of binaries, the initial mass limits for the formation of compact objects (white dwarf, neutron star, or black hole) are significantly increased for most binary evolution channels. This is evident if mass transfer (i.e. heavy mass loss from the primary) commences already during the primary's core hydrogen burning phase (so called Case A mass transfer). However, it remains true for systems which start their mass transfer due to the expansion of the primary star towards the red supergiant stage (Case B mass transfer). Only if the mass transfer starts after the primary has gone through most of its core helium burning would the mass limits not be affected by the mass transfer.

Table 2 illustrates this at the example of a $16\,{\rm M}_{\odot}$ star, evaluating the final helium core masses assuming various evolutionary histories. Without significant mass loss as a single star, it evolves a $4.3\,{\rm M}_{\odot}$ helium core by the end of its life. While this value may depend on the rotation rate of the star or on convective core overshooting, let us disregard these effects here and only consider the consequences of mass loss. For

Table 2. Finale helium core masses for a $16\,{\rm M}_{\odot}$ star as function of its evolutionary history, i.e. assuming it evolves as a single star, as a primary of a Case B binary, or of a Case A binary.

evolutionary path	final He-core mass
single star	$4.3\,{\rm M}_{\odot}$
binary: Case B	$3.6\,{\rm M}_{\odot}$
binary: Case A	$2.0...2.8\,{\rm M}_{\odot}$

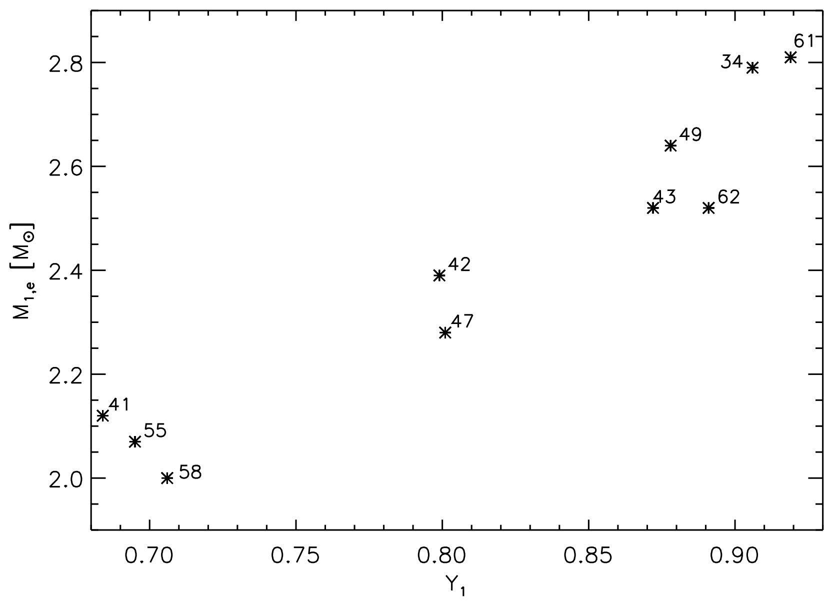

Figure 3. Masses during core helium burning for primaries of Case A systems with an initial mass of $16\,M_{\odot}$, as function of their central helium abundance at the onset of Case A mass transfer. See Wellstein et al. (2001), for more details.

Case A primaries, this effect is drastic (cf. Fig. 3); depending on the exact time during the core hydrogen burning evolution of the primary when the mass transfer starts, it may reduce the final helium core mass by more than 50%. But also for Case B primaries the effect of mass loss is significant (about 20% in this example). Here, it is due to the indirect effect of the envelope loss. In single stars, the mass of the helium core grows substantially during the core helium burning phase, as the hydrogen burning shell source adds mass to it. As Case B primaries lose their entire hydrogen envelope at the beginning of core helium burning, the helium core can not grow in this case. Therefore, Case B primaries end up with smaller cores than single stars of the same initial mass.

We point out that this is an important effect in (binary) population synthesis models. Table 3 gives an overview of the expected shifts of the critical mass limits for compact object formation for close binary primaries of solar metallicity. The white dwarf/neutron star limit is based on models of Wellstein et al. (2001). Due to persisting uncertainties in the mass loss rates of Wolf-Rayet stars, the neutron star/black hole

Table 3. Critical initial masses for the white dwarf–neutron star and neutron star–black hole transition, for various evolutionary paths (see text).

evolutionary path	WD/NS-limit	NS/BH-limit
single stars	$\sim 8\,M_\odot$	$\sim 25\,M_\odot$ (?) except 40...80 $M_\odot$ (?)
binary: Case B	10...12 $M_\odot$	∞ (?)
binary: Case A	12...16 $M_\odot$	∞ (?)

limit is significantly more uncertain. Current models predict an initial mass limit for black hole formation in single stars of the order of $25\,M_\odot$ (Fryer 1999), which is consistent with the SN 1987A being the explosion of a $20\,M_\odot$ star (Arnett et al. 1989). However, due to a turnover in the final mass–initial mass relationship in single star models (Schaller et al. 1992, Maeder & Meynet 2000), stars born in the mass range 40...80 $M_\odot$ may perhaps end up as neutron stars, but massive black holes may be formed for the highest stellar masses (Brown et al. 2001). There are two major uncertainties involved in this prediction, the mass loss rates of Wolf-Rayet stars, and the physics of convection in the stellar interior (cf. Fig. 5 in Wellstein & Langer 1999) For Case A and Case B binaries, the prediction of Wellstein & Langer (1999) and Wellstein et al. (2001) is much simpler: primaries of all initial masses above the white dwarf limit are expected to form neutron stars. Note that a reduction of the Wolf-Rayet mass loss rate as suggested by recent studies of Wolf-Rayet winds (Hammann & Koesterke 1998) did not alter these conclusions (Wellstein & Langer 1999).

The Wolf-Rayet mass loss rates continue to be uncertain, and it is conceivable that they are presently still overestimated (although the opposite is equally likely). The prediction of neutron star remnants from Case A and B primaries poses a problem to explain the half a dozen or so known low mass black hole binaries, i.e. black holes of typically 5...7 $M_\odot$ with a low mass companion (Bailyn et al. 1998). However, it is questionable whether even lower Wolf-Rayet mass loss rates can alleviate this problem. The reason is that if Wolf-Rayet stars lose mass at any rate, the helium burning convective core can not grow in mass. As this reduces the rate of mixing of α-particles into the core during late core helium burning, it leads to a rather high final C/O-ratio at core helium exhaustion. High C/O-ratios, however, imply smaller iron core masses and thus an increased probability of forming a neutron star rather than a black hole when the iron core collapses (Woosley & Weaver 1993, 1995; Brown et al. 2001). Therefore, a Case C scenario may be the most likely explanation for the low mass black hole binaries at this time (Brown et al. 1999). Unfortunately, due to the uncertain post-main sequence radius evolution of massive stars (cf. Langer & Maeder 1995), current stellar evolution models can not strongly constrain the number of expected Case C events in massive binaries.

5. Spins of compact objects

During recent years, evolutionary calculations for rotating single stars have been carried out through all evolutionary stages, which leads to predictions for the initial spin rates of compact remnants. For stars in the initial mass range 10...20 $M_\odot$, Heger et al. (2000) found iron core specific angular momenta of the order of $10^{16}\,\mathrm{cm^2\,s^{-1}}$, with lower values for higher masses (e.g., $3\,10^{15}\,\mathrm{cm^2\,s^{-1}}$ for 25 $M_\odot$) due to angular momentum loss associated with main sequence stellar wind mass loss (cf. Langer 1998). The collapsar model for γ-ray burster by MacFadyen & Woosley (1999) seems to require higher angular momenta than those obtained in single star models for stars massive enough to produce black holes. As the mass loss rate of main sequence stars is lower for stars of lower metallicity, the situation may be more optimistic in the early universe.

A recent preliminary investigation of the so far neglected effects of magnetic fields (Spruit, in preparation) leads to specific angular momenta which are up to one order of magnitude lower (Heger, Spruit and Woosley, in preparation). This may help to bring anticipated pulsar rotation rates close to observed ones (cf. discussion in Heger et al. 2000).

Models for a rotating white dwarf progenitor ($M_{\rm initial} = 3\,M_\odot$) — without B-fields — have been computed by Langer et al. (1999), predicting a specific angular momentum of $2\,10^{15}\,\mathrm{cm^2\,s^{-1}}$ for the emerging white dwarf. The corresponding rotational velocity of $30\,\mathrm{km\,s^{-1}}$ is not in contradiction with upper limits derived by Heber et al. (1997) and Koester et al. (1998) for local white dwarf samples. Clearly slower rotating individual white dwarfs could be either braked by internal magnetic fields (this scenario has not been modelled yet) or stem from stars below $M_{\rm initial} \simeq 1.5\,M_\odot$: Those stars, like the sun, lose most of their angular momentum during their main sequence evolution by magnetic braking and are thus expected to lead to much slower spinning white dwarfs as 3 $M_\odot$ stars — which may actually have a reflection in planetary nebulae morphologies; cf. García-Segura et al. (1999, 2001).

How does binary evolution affect the remnant spins? Qualitatively, there are two important effects. First, as mass loss is coupled to angular momentum loss even if magnetic fields play no role (Langer 1998), the mass loss due to the Roche lobe overflow is expected to spin the primary down, at least for Case A and Case B mass transfer where the mass loss time scale is of the order of the thermal time scale or longer. And second, any accretion onto the secondary star is expected to rapidly spin it up to critical rotation (Packet 1981).

Recently, Wellstein (2001) has computed the first massive binary models which include these effects in detail, using the rotational physics of Heger et al. (2000) for both stellar components, and including tidal synchronisation for a complete description of spin-orbit coupling. Primaries in Case A and B models for $16\,\mathrm{M}_\odot + 15\,\mathrm{M}_\odot$ systems in which both stars start out with an equatorial rotational velocity of $200\,\mathrm{km\,s}^{-1}$ evolve into low mass Wolf-Rayet or helium star stars with spin periods like that of our sun (they also happen to have a radius of about $1\,\mathrm{R}_\odot$). From those models, we expect Case A primaries to give birth to slowly rotating neutron stars.

On the other hand, the accretion of matter in an advanced stage of core hydrogen burning for close binary secondaries opens the possibility that the effect of a reduced specific angular momentum due to main sequence stellar wind mass loss, as it occurs in massive single stars (see above) is damped, and that they retain enough angular momentum to produce a γ-ray burst. Similar arguments may hold for the case that both star of a binary merge in an advanced evolutionary phase. The mentioned $15\,\mathrm{M}_\odot$ secondaries grow in mass up to $\sim 23\,\mathrm{M}_\odot$, and obtain rotation rates of up to $500\,\mathrm{km\,s}^{-1}$.

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