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Duplicitous Nucleosynthesis

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Abstract. The effect of a binary companion on stellar nucleosynthesis is considered. Synthetic stellar evolution and nucleosynthesis algorithms are outlined which allow the large binary-star parameter space to be explored by a *population nucleosynthesis* approach. This is demonstrated by a comparison of single- and binary-star stellar yields. Future prospects for the field of binary star nucleosynthesis are outlined.

Key words. stars: abundances – stars: AGB – stars: binaries – nucleosynthesis

1. Introduction

Studies of nucleosynthesis, stellar populations and the chemical history of the Galaxy usually assume that stars are single. However up to half of all stars are in binary or hierarchical systems (Duquennoy & Mayor 1991), of which a significant fraction interact by mass transfer at some stage of their lifetimes. Mass-transfer occurs by accretion from the stellar wind of a companion or Roche-lobe overflow (RLOF) if the stars are close enough (see Pols, this volume, for a review of binary evolutionary processes). Novae and type Ia supernovae occur as a consequence of mass transfer and *are* usually included in Galactic chemical evolution (GCE) models, novae being a major source of the CNO isotopes ^{13}C, ^{15}N and ^{17}O while SNe Ia produce about two-thirds of the ^{56}Fe in the Galaxy.

Companion stars have a secondary effect which often *is* overlooked. Interaction by RLOF occurs when the radius of a star, R, exceeds its Roche-lobe size, R_{L}, which is a function of the mass ratio q and the binary separation a (e.g. Eggleton 1983). During stellar evolutionary phases when R is large matter flows from the larger star to the smaller. The accreting star may or may not be able to accept the matter, depending on its own evolutionary state, so the accreting matter will either sit on the surface of the star, mix down into the star or be lost to the interstellar medium (ISM). The former processes will lead to a chemically peculiar star while the latter contributes to the chemical yield of the system.

A barrier to the study of binary star populations is the large parameter space to be explored. Single stars are *relatively* easy to model with consideration of a few variables such as initial mass M, initial metallicity Z, perhaps a mass-loss prescription, *s*-process pocket size (Gallino et al. 1998), remnant star mass (Belczynski, Kalogera, & Bulik 2002), type II supernova yield (for $M \gtrsim 8\,\mathrm{M}_{\odot}$, e.g. Woosley & Weaver 1995) and convective overshooting (or enhanced dredge-up; Herwig 2000). For binaries the situation is even more complicated. There are two initial masses M_1 and M_2 (or $q = M_2/M_1$), the initial separation a (or period P related to a and $M_{1,2}$ by Kepler's

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law), initial eccentricity e and initial metallicity Z. Then there are free parameters associated with binary-specific processes such as the efficiency of common-envelope loss α_{CE}, the effect of tides (Zahn 1977) and the tidal effect on the mass-loss rate B_{W} (Tout & Eggleton 1988), the supernova kick velocity distribution (Hansen & Phinney 1997), the wind accretion rate (Bondi & Hoyle 1944), thermohaline mixing of accreted material (Kippenhahn, Ruschenplatt, & Thomas 1980; Proffitt 1989), wind collisions (Huang & Weigert 1982), stellar mergers, type Ia supernovae (Iwamoto et al. 1999), novae (José & Hernanz 1998) and consideration of the Eddington limit.

A typical single star evolutionary sequence may take an hour to perform on a modern desktop PC, assuming the thermally pulsing asymptotic giant branch (TPAGB) is ignored. If this is assumed as a lower limit[1] then 100 stars, which is sufficient to model a single star population with variable M but all other parameters fixed, takes 100 hours. Extension to the binary parameter space requires a minimum of variation of $M_{1,2}$ and a, a total of $100^3 = 10^6$ stars, i.e. 10^6 hours (more than a century of CPU time). Such resolution is required if we are to probe the nucleosynthesis of chemically peculiar stars because the number of binaries interacting at any one time is small compared to the number of stars in the population. High resolution is also required because binary evolution is chaotic in that alteration of $M_{1,2}$ or a by a small amount can lead to a completely different evolution of the system – such small changes should be resolved. Note that for chemical yields such high resolution is not usually required unless novae are considered: there are few novae systems which produce a large fraction of the minor CNO isotopes.

[1] Most evolutionary codes consider only the isotopes required to calculate stellar structure. Detailed nucleosynthesis, usually performed by a post-processing code, takes many hours more, leading to run-times of about 1 day on a 3 GHz Xeon processor (Amanda Karakas, private communication). One hour is a *very* conservative estimate.

2. Population Nucleosynthesis

In order to avoid the ever-increasing CPU demands, a *synthetic* approach can be applied to stellar evolution. This involves fitting the results of full stellar evolutionary calculations to analytic formulae. This results in a huge speed increase because the hard work of solving the differential equations of stellar structure is not required once the initial model set has been constructed. Stellar evolutionary variables such as luminosity L, radius R, core mass M_{C} etc. are fitted to functions of M, Z and t for each phase of stellar evolution (Hurley, Pols, & Tout 2000). This is then coupled to a model for binary star evolution (Hurley, Tout, & Pols 2002) or an N-body globular cluster code (Hurley et al. 2001).

Nucleosynthesis is modelled in parallel to the evolution. The detailed evolution and post-processing nucleosynthesis models of Karakas, Lattanzio, & Pols (2002) are used as a basis for analytic fits to the surface abundance changes at first, second and third dredge-up as well as evolutionary variables during the TPAGB phase (Izzard et al. 2004). An analytic burning algorithm follows the CNO, NeNa and MgAl cycles during hot-bottom burning. The abundance of the s-process isotopes in the intershell region is fitted to the results of Lugaro et al. (2004). Accretion of material by winds or RLOF, wind collision and thermohaline mixing are all modelled. Yields for supernovae and novae as well as surface abundances for massive stars are fitted to published results (Izzard 2004). As an example the synthetic model runs a factor of about 10^7 times faster than the `STARS` evolution code (Stancliffe et al., this volume) and includes the TPAGB phase, binaries and nucleosynthesis of elements from H to Bi.

There are two advantages a synthetic code has over a detailed code. One is the possibility of exploring a large parameter space as mentioned above: 10^6 stars takes less than one day, includes the effect of binary stars *and* estimates of the nucleosynthesis of many isotopes. The other advantage is the ability to try out new physics to quickly determine the effect of varying uncertain free parameters. A good example is the minimum core mass for third dredge-up which was predicted by Izzard et al. (2004) to be $0.07\,M_\odot$ less than the value from Karakas et al. (2002) for the LMC ($Z = 0.008$). This is borne out by the latest detailed models of Stancliffe et al. (2004, see also Stancliffe et al., this volume) which show this behaviour. The synthetic code can tell us what the detailed models *should* be doing and where we are going wrong. There are disadvantages to using a synthetic code, the main one being a loss of accuracy compared to detailed evolutionary sequences. As long as major uncertainties remain, especially in binary star physics, this is not a problem because full evolutionary codes are just as inaccurate (if more precisely inaccurate). One may as well be fast, inaccurate and open-minded rather than slow, inaccurate and constrained to a small portion of the parameter space.

3. The Effect of a Close Companion

Mass transfer leads to truncation of phases of evolution where $R > R_L$. Non-conservative RLOF can then contribute directly to the chemical yield. Conservative RLOF pollutes the secondary and alters its surface abundances and subsequent evolution. Table 1 shows the evolutionary state of the Roche-lobe overflowing star at first RLOF as a fraction of all binary systems. A standard set of distributions for $M_{1,2}$ and a has been assumed. The primary M_1 has its mass distributed by the IMF of Kroupa, Tout, & Gilmore (1993) with minimum mass $M_{\rm min} = 0.1\,M_\odot$ and maximum mass $M_{\rm max} = 80\,M_\odot$. The secondary M_2 has $q = M_2/M_1$ distributed flat between $q_{\rm min} = M_{\rm min}/M_1$ and 1. The separation distribution is flat in $\ln a$ between 3 and $10^4\,R_\odot$. Also $Z = 0.02$, $e = 0$ and other variables are set according to the default population of Izzard (2004). RLOF on the main sequence occurs in convective low-mass stars so is not a contributor to chemical yields or (in this model) chemically peculiar stars. The stellar radius R becomes large as the star approaches or is on the giant branch so the majority of RLOF occurs when stars become red giants. Stars which overflow their Roche-lobe on the first giant branch lose their convective envelope and are exposed as a helium white dwarf. First dredge-up is unlikely to occur and there is probably no subsequent core helium-burning or AGB phase. There will be no second or third dredge-up, hot bottom-burning or *s*-processing. The yields of these stars will not be as processed as if they had been single stars.

Main Sequence	3.6%
Hertzsprung Gap/First Giant Branch	3.5%
Core Helium Burning	0.02%
Asymptotic Giant Branch	1.4%

Table 1. The stellar evolutionary phase of the Roche-lobe overflowing star at first RLOF as a percentage of all binary systems.

About 1.4% of binary systems suffer RLOF when one star is on the AGB. As a fraction of all binary systems which have an AGB phase[2] about 20% undergo RLOF of which about half are in the early AGB phase, the rest in the TPAGB phase. The remaining systems are too wide for R to equal R_L but mass transfer by stellar winds may still be efficient (e.g. Ba star formation, see Bonacic, this volume). RLOF on the TPAGB phase leads to no (or reduced) third dredge-up, HBB or *s*-processing. RLOF on the EAGB rules out second dredge-up as well.

A common envelope system is the likely outcome of mass transfer from a giant star. The stellar cores spiral together in the envelope, which is driven off by an unknown mechanism. Depending on the system parameters and the choice of the free parameter $\alpha_{\rm CE}$ the envelope might not be lost before the cores merge. If one star has a CO core then a new TPAGB star can be formed, this mechanism accounts for about 0.3% of all TPAGB stars. Unrelated to RLOF, it is also possible to accrete material onto a CO white dwarf by a stellar wind (with $R < R_L$) faster than it can be accepted, so a new stel-

[2] Many systems contain stars of too low mass to evolve to the AGB in a Hubble time, a few are too massive so ignite carbon prior to the AGB (and then explode) and some will interact prior to the AGB so will never make it.

lar envelope is formed. This accounts for about 0.1% of TPAGB stars.

Accretion increases stellar mass, so speeds up the evolution of the accreting star. It also mixes processed material into the stellar envelope. This material may be enhanced in e.g. carbon and barium due to third dredge-up in the donor star. As a direct result we observe extrinsic carbon stars (Izzard & Tout 2004) and barium stars (Karakas et al. 2000) although models of the orbital parameters of the Ba stars still has some way to go to explain the observations (Bonacic, this volume).

3.1. Chemical Yields

The return of a mass of isotope *i* from a stellar system to the ISM is called its *stellar yield* and is a vital ingredient in GCE models. A simple definition is used here

$$\text{Yield of } i = \frac{\text{Mass Output as Isotope } i}{\text{Mass Into Stars}}, \quad (1)$$

summed over all the systems in a stellar population. The weighting with respect to mass input ensures that single and binary stars are treated equally – a binary-star population is more massive than a single-star population for an equal number of systems. The distributions of M_1, q, a, e and Z are those described above. The effect of having a binary companion on the yields is then calculated for each isotope *i*.

There are more than 130 isotopes or elements in the model, so here I shall focus on two which are produced in TPAGB stars, ^{14}N and Ba. TPAGB stars greater than about 5 $M_\odot$ possess convective envelopes hot enough to burn the CNO isotopes to equilibrium (98% ^{14}N) at their base. Such stars are thought to be a major source of nitrogen in the universe. The integrated yield of nitrogen for a single-star population is 1.294×10^{-3} while for a binary-star population with the same initial mass in stars it is 9.878×10^{-4}, a drop of 24%. Barium is produced in lower-mass stars, around $1-3\,M_\odot$, but the effect on its yield is similar. A single star population has a yield of 8.241×10^{-9}, a binary-star population has a yield of 6.683×10^{-9}, a drop of 19%.

Isotope	B vs S (all stars)	B vs S (AGB only)
^{12}C	+33%	−43%
^{13}C	+35%	−27%
^{14}N	−24%	−48%
^{15}N	+73%	−49%
^{16}O	+14%	−52%
^{17}O	+6%	−58%
^{20}Ne	+0.6%	−54%
^{21}Ne	−4%	−54%
^{22}Ne	−21%	−55%
^{23}Na	−21%	−54%
^{24}Mg	+15%	−57%
^{25}Mg	−15%	−55%
^{26}Mg	−10%	−55%
^{56}Fe	+144%	−57%
Ba	−19%	−55%

Table 2. The percentage difference between single and binary star yields (as defined by equation 1) by isotope (a positive value indicates more yield from binaries). The middle column is the difference for the complete population, the rightmost column is for the AGB contribution only.

Yields can be calculated for each of the 130 isotopes in the model, Table 2 shows a selection. In some cases the effect of a binary companion *increases* the yield, the most obvious example is ^{56}Fe due to type Ia supernovae. Table 2 also shows the difference in yield *from AGB stars alone* between single and binary stars. There are two effects at work here. The AGB stars that form in binaries are likely to overflow their Roche lobes before significant third dredge-up occurs, reducing the yield of species such as ^{12}C, ^{14}N, ^{22}Ne and Ba. Also there is the evolutionary effect of a companion which removes the AGB phase altogether, so there is less overall contribution from AGB stars in binaries than in single stars.

The single:binary star relative yields also depend on the plethora of poorly-constrained stellar distributions and free parameters mentioned in Section 1. A full analysis is beyond this paper or this meeting, the reader is referred to Izzard (2004) for the gory details, but a few general remarks are possible. The sin-

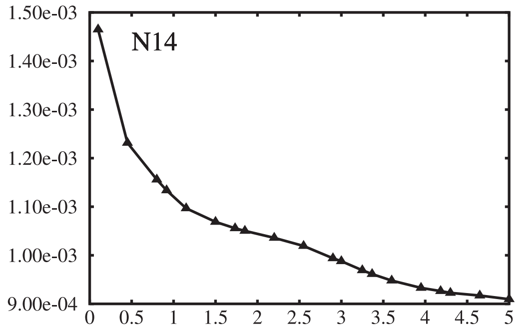

Fig. 1. Yield of ^{14}N (ordinate) vs common-envelope efficiency parameter α_{CE} (abscissa). Each point represents a population of 10^6 binary stars distributed as described in section 3: only α_{CE} varies between each population.

gle/primary star IMF is most important for determining the individual single or binary star yields but if it is assumed that the single- and primary-star mass distributions are the same then changing them has little difference on the relative yields. The secondary mass and separation distributions, if varied within reason, lead to a change in the relative yields of about 20-30% for most isotopes. Exceptions are the isotopes produced in novae and type Ia supernovae with changes (up and down, depending on the distribution) by up to a factor of 4.

Free parameters also affect the yields. In general the *total* uncertainty in the binary yield due to *all* the free parameters is not greater than in a single star population, it is just spread between more parameters. As an example, Figure 1 shows the yield of ^{14}N vs the common-envelope efficiency parameter α_{CE}. Over most of the range of α_{CE} there is little effect on the yields but for $\alpha_{\mathrm{CE}} < 1$, when the chance of a common envelope being ejected is smaller, more AGB stars survive common envelope evolution so there is more nitrogen by up to about 50%. Similar plots can be made for each isotope and each free parameter, there are far too many to list here.

4. Conclusions and Future Prospects

Clearly the effect of a binary companion on nucleosynthesis is a complicated one and is riddled with uncertainty. With regard to GCE the effect of a binary companion is small for most isotopes (20-30%). Nova and type Ia supernova yields are sensitive to the initial distributions of the mass ratio and separation.

What are the future prospects for binary star nucleosynthesis? In order to constrain the many uncertain physical parameters a new look at the role played by binaries in the formation of stars with exotic surface abundances is required. The tools exist to make model populations of millions of stars such as the R-stars, extrinsic S- and C-stars, Ba stars, CH stars etc. which may exist only because of binary interaction (see Pols, this volume). Some extension is required to deal with *r*-process enhanced and extremely metal-poor, carbon-enriched stars (Tsangarides, this volume). I have also written a simple GCE code (`gce.pl`) which interfaces directly with the synthetic nucleosynthesis code to allow one to determine, very quickly and without the need for tables of stellar yields, the effect of a change in the model physics on the evolution of isotopes in the ISM.

One problem which I have also tried to address is the lack of a unified set of observations with which to compare the models (the *Stellardb*; see Ödman and Izzard, this volume). Even given a set of observations and theoretical predictions it then remains to compare the two in an unbiased manner taking into account observational selection effects. This is a non-trivial task but once complete it will be possible to perform χ^2 type analyses to tell us the best combination of free parameters which represents the stars we see. This information will then be fed back into the detailed modelling to improve it and our understanding of the Universe.

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