Asymptotic Giant Branch Stars
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How Binary Stars affect Galactic Chemical Evolution

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Abstract. At least 60% of stars appear to be binary and about half of these are close enough to interact. Because of the enormous expansion on the AGB, many of these interactions will involve an AGB star and a relatively compact companion, anything from a low-mass main-sequence star to a degenerate remnant. Mass loss plays the dominant role in determining the lifetime and the extent of nuclear processing of the AGB phase. Binary interaction will increase the mass loss from the AGB star and curtail its evolution, either through Roche-lobe overflow, common-envelope evolution or the driving of an enhanced stellar wind. These processes will tend to reduce the metals, particularly carbon, returned to the inter-stellar medium. On the other hand merged systems or companions that accrete a substantial amount of mass themselves evolve into AGB stars that can synthesize and return more carbon than the two individuals would have alone. By synthesizing large populations of stars, with nucleosynthesis and binary interaction, we estimate a reduction in carbon yield owing to binary star evolution of as much as 15%.

1. Introduction

The metallicity of the ISM is gradually increasing as stars form, process material through nuclear burning and then return it either in a stellar wind or supernova explosion. The most important contributors to the metallicity are the CNO catalytic elements, carbon, nitrogen and oxygen. These will determine how hydrogen burning proceeds for the next generation of stars. Hydrogen burning itself only mixes these elements, changing their ratios and isotopic fractions. It is not until helium ignites that new CNO elements are produced.

However, helium burning takes place deep inside the star, and is usually encased within a shell of hydrogen burning, so that it is not easy to bring the products to the surface whence they can be returned to the ISM. Three processes can overcome this. First, massive stars ($> 8\,M_\odot$), that end there lives in supernovae throw off a C/O region between helium- and carbon-burning shells. Because of the ease with which a fourth He^4 nucleus is added to C^{12} much of this material has been processed to O^{16} and beyond. Second, very massive stars ($> 25\,M_\odot$) may enter a Wolf-Rayet phase and develop a very strong stellar wind, particularly once helium has ignited. Observations indicate that this wind can strip off the hydrogen envelope and eat into a helium burning core. This core was once convective so its surface is carbon rich. Some calculations (Maeder & Meynet 1994) indicate that Wolf-Rayet stars are the major source of carbon enrichment of the ISM. The other process, that competes for effectiveness, is third dredge-up on the AGB. As the unstable helium-burning shell thermally pulses, the deep convective envelope reaches into a region rich in carbon which can be mixed to the surface. Models differ significantly in the predicted extent of this dredge-up (Frost & Lattanzio 1996) so the actual carbon enrichment remains uncertain. AGB stars also have relatively strong winds so this processed and dredged material is readily returned to the ISM. When almost all the envelope has blown off, the star cools to a white dwarf. Thus mass loss determines the AGB lifetime, its maximum core mass and the number of thermal pulses and dredge-up events.

A binary companion will curtail this evolution by interaction that increases mass loss. The only well quantified effect is Roche-lobe overflow. The initially more massive component of a binary system evolves and grows until it fills its last stable potential surface, most often as a red giant or AGB star, whereupon it begins to transfer mass to its companion. As it loses mass the envelope of a giant expands. If it is still the more massive component of the binary, and mass transfer is conservative, the orbit and Roche lobe shrink. Consequently the process of mass transfer leads, on a dynamical timescale, to the giant overfilling its Roche lobe yet more. The overflow rate rapidly rises and the companion, typically a lower-mass main-sequence star, cannot accrete the material. Its own Roche lobe is quickly filled and a common envelope engulfs the whole system. The two cores, the relatively dense companion and the core of the giant, are then assumed to spiral together by some, as yet undetermined, frictional mechanism. Some fraction of the orbital energy released is available to drive off the envelope. If all of it is ejected while the cores are still well separated we are left with a closer binary system comprising the unscathed companion and a white dwarf which may evolve to a cataclysmic variable. Alternatively, if some of the envelope still remains when the companion reaches the denser depths of the common envelope, they can merge leaving a single, rapidly rotating, giant. FK Comae may be such a merged system. Magnetic braking quickly spins down these merged giants and it is possible that the R stars, none of which appear to be binary (McClure, private communication), may be merged AGB stars. When the entire envelope is lost there can be no further AGB evolution or carbon enrichment. If part of the envelope remains AGB evolution is still curtailed, unless the companion, in

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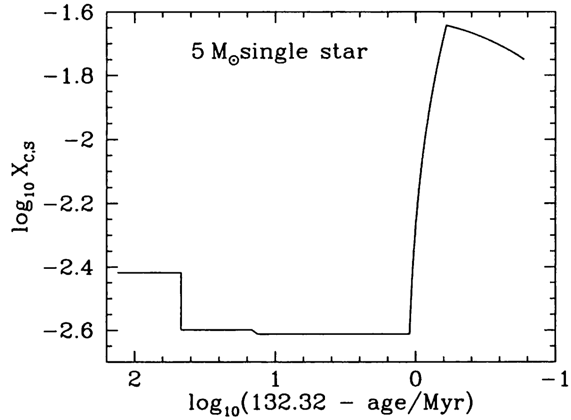

Figure 1. The mass fraction of carbon at the surface of a $5\,M_\odot$ star throughout its evolution. Age is measured from the zero-age main-sequence and the time axis is chosen to expand the AGB.

merging with the envelope, adds even more mass than was lost. In this case AGB evolution is prolonged and the merged star returns more carbon to the ISM than a single AGB star of the same initial mass.

Similar events follow mass transfer that begins on the first giant branch, though the denser envelope makes coalescence more likely. Any Roche-lobe overflow that begins before the giant branch proceeds in a stable manner and may eliminate AGB evolution altogether. However the companion that accretes the transferred mass can itself go through an AGB phase at a later stage. Another effect of a binary companion was proposed by Tout & Eggleton (1988) to account for inverted mass ratios in some RS CVn binaries and for the formation of wider Algol-like systems. They proposed that the companion, probably by forcing the giant to spin faster, can enhance its stellar wind by orders of magnitude. This appears to be necessary to account for the distribution of Barium stars (Karakas, Tout & Lattanzio 1998). Though some of the material is accreted by the companion, the AGB lifetime is generally shortened and less carbon is ejected. Indeed this affects much wider systems than Roche-lobe overflow.

With account taken of all these processes we can expect half of the 60% of stars that are binary systems to experience interaction during their lifetimes. To test the overall effect of the many convoluted paths we have developed a population-synthesis model with both binary interaction and nucleosynthesis.

2. Nucleosynthesis in single stars

Fig. 1 shows the evolution of the surface carbon abundance of a $5\,M_\odot$ star. The nucleosynthesis is based on the model developed by Groenewegen & de Jong (1993). For a population I star the initial mass fraction of carbon is $X_{\rm C,I} = 0.00382$. The surface abundance remains at this value until central hydrogen is exhausted and the star crosses the Hertzsprung gap to join the red giant branch, where a deep convective envelope reaches into regions previously

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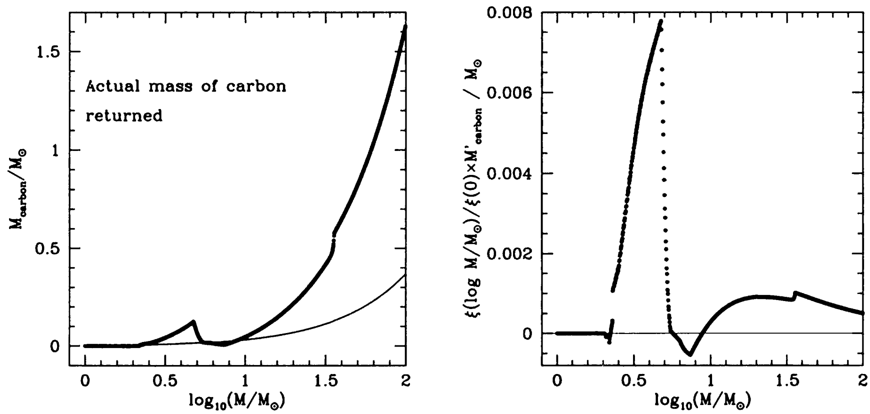

Figure 2. Carbon yields over 10^9 yr for stars with metallicity $Z = 0.02$ in the range $1 - 100\,M_\odot$. On the left merging solid circles show the mass of carbon ejected while the thin line represents the total mass ejected multiplied by $X_{\mathrm{C,I}}$. On right they are the difference between these two M'_{carbon}, or the yield, weighted by the initial mass function.

affected by hydrogen burning. Here CNO equilibrium has converted much of the carbon to nitrogen and dredging this material lowers the surface abundance. Any wind from the star at this stage contains less carbon than the original ISM.

At the beginning of the AGB a second dredge-up event takes place for stars more massive than about $4.5\,M_\odot$. As the helium shell burns out to catch up with the hydrogen burning shell the latter is temporarily extinguished and the deep convective envelope reaches down into the intershell region, further reducing the surface carbon fraction. When the core mass reaches a critical value ($0.562\,M_\odot$ in our model) third dredge-up following thermal pulses begins and carbon enriched material is dredged to the surface. However, in stars initially over about $4\,M_\odot$, the temperature at the base of the convective envelope eventually reaches temperatures at which hydrogen burning can take place. This hot-bottom burning converts a substantial fraction of the dredged carbon to nitrogen and, as is apparent in the figure, some of the envelope carbon too. The total mass of carbon M_{carbon} ejected is the product of the mass-loss rate and the surface abundance $X_{\mathrm{C,S}}$ integrated over the lifetime of the star. In these exploratory models we have used a Reimers' (1975) mass-loss rate throughout the post-main-sequence evolution. Alternatives that concentrate mass loss towards the tip of the AGB would return more carbon.

Fig. 2 shows the integrated mass of carbon returned as a function of initial mass. Massive stars return the most carbon but they are fewer so we weight the ejected mass of carbon by the initial mass function $\xi(\log M)$ of Kroupa, Tout & Gilmore (1993) to give the relative contributions. We look at the yields over the first 10^9 yr since the stars formed because this is the typical time for ejected material to be recycled into new stars. Stars less massive than $2\,M_\odot$ do not evolve at all in this time. Between $2\,M_\odot$ and $2.2\,M_\odot$ they have not begun third dredge-up and so eject only material deficient in carbon owing to first dredge-

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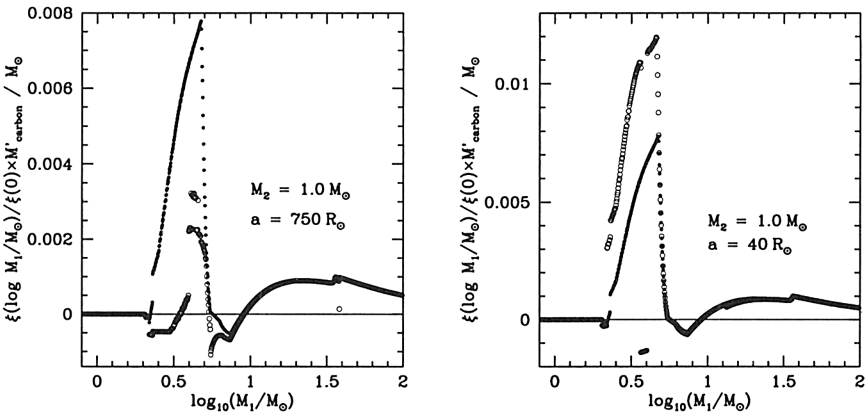

Figure 3. Open circles are the weighted yields from binary systems in which the primary mass M_1 varies as before. The companion has mass $M_2 = 1\,M_\odot$ and the separations are $a = 750\,R_\odot$ (left) and $40\,R_\odot$ (right). Solid circles are the yields from a single star of mass M_1.

up. From here up to $5\,M_\odot$ third dredge-up and mass loss on the AGB lead to a large peak in the carbon yield. The rise is due to the increasing amount of dredge-up while the decline is due to hot-bottom burning which eventually leads to the negative valley between 5 and $8\,M_\odot$. Above $8\,M_\odot$ supernovae begin to contribute. We take their carbon yields from Maeder (1992). Just above $30\,M_\odot$ there is an additional contribution from a Wolf-Rayet phase but we include somewhat less than predicted by Maeder & Meynet (1994). Their contribution would raise the yields by a factor of two or so above $25\,M_\odot$. The AGB peak contributes about twice as much as the massive stars. Integrating over the whole single-star population we find that $X_{C,I} = 0.00382$ is raised to $X_C = 0.0125$.

3. The effect of a binary companion

To illustrate the effects of binary evolution we consider two particular cases illustrated in Fig. 3. To each of the stars in Fig. 2 we give a companion of mass $M_2 = 1\,M_\odot$ at a separation of either $a = 750\,R_\odot$ or $40\,R_\odot$. In the former case all the stars fill their Roche lobes on either the first giant branch or the AGB and experience common-envelope evolution. Below $3\,M_\odot$ the entire envelope is lost on the giant branch after first dredge-up. The substantial positive yield of the single star becomes a negative one. For more massive primaries the cores merge while a fraction of the envelope still remains and so partial carbon enrichment is subsequently possible. The area under the AGB peak is reduced by a factor of six, substantially decreasing the average carbon yield for such a hypothetical population. At $a = 40\,R_\odot$ all the stars fill their Roche lobes before or early on the red giant branch while their envelopes are still relatively dense. Apart from primaries in the small range from 3.5 to $4\,M_\odot$ these stars go on to experience common-envelope evolution but the companions merge with the envelope before very much mass has been ejected. The AGB lifetime is

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increased and carbon enrichment enhanced so that the peak is doubled in area. The exceptions between 3.5 and $4\,M_\odot$ come about because above $3.5\,M_\odot$ the stars first fill their Roche lobes while crossing the Hertzsprung gap where mass transfer begins stably on a thermal timescale. Above $4\,M_\odot$ these stars go on to common-envelope evolution as the star becomes a fully fledged giant. Below $4\,M_\odot$ sufficient mass has been transferred by this point that the mass ratio has fallen below the critical value (about $M_1/M_2 = 0.7$) for the Roche lobe to expand faster than the giant envelope. Common-envelope evolution is avoided. However the, now quite massive, companion itself evolves up the AGB and fills its own Roche lobe. Common-envelope evolution ensues but the orbit is now so much wider and the envelope less dense that it is all ejected before carbon enrichment can begin. Above $8\,M_\odot$ most of the carbon comes from the final supernovae and, at these separations, the binary companion has little effect.

In practice binary systems have a wide range of masses and separations and the overall picture is rather convoluted. To model it we synthesize populations of two million systems in which the masses are each chosen randomly from the IMF and the separations from a distribution ranging from 5 to $5 \times 10^6\,R_\odot$ that peaks around $5\,000\,R_\odot$. The procedure used to model binary evolution is described by Tout et al. (1997) and Karakas et al. (1998). If we do not include Tout & Eggleton's (1988) binary enhanced mass loss the average mass fraction of carbon in all the material ejected by 10^9 yr is $X_\mathrm{C} = 0.0119$ or a drop of 7% in the yield. If we do include the enhanced mass loss these figures become $X_\mathrm{C} = 0.0112$ and 15%.

4. Conclusion

Neither of these differences is particularly large especially when compared with the likely errors in our single star yields. However they do represent a significant systematic effect. It will be necessary to include binary evolution whenever we believe we can predict carbon yields to within 20% or so.

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