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The Effects of Binary Stars on AGB Nucleosynthesis

in particular the Consequences for Type Ia Supernovae

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Abstract. At least 60% of stars appear to binary and about half of these are close enough to interact. Because of the enormous expansion on the AGB, many of these interactions 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. In most cases binary interaction increases the mass loss from the AGB star and curtails its evolution, either through Roche-lobe overflow, common-envelope evolution or the driving of an enhanced stellar wind but it can also expose parts of stars that would otherwise have remained deep within. Type Ia supernovae are exploding CO white dwarfs which formed as the cores of AGB stars. The source of the supernovas light is the radioactive decay of ^{56}Ni created in the thermonuclear runaway and expelled in the explosion. Much of the core reaches nuclear statistical equilibrium so that the amount of ^{56}Ni created falls off with increasing excess of neutrons at the onset of thermonuclear runaway. Neutron-rich ^{22}Ne is a major contributor to this excess. AGB stars produce primary ^{22}Ne by processing dredged-up carbon through hydrogen and then helium burning before depositing it in the CO core. So any variation in the AGB evolution of the progenitor star can ultimately lead to variation in the peak luminosity of the supernova.

Key words. binaries: close – Stars: AGB and post-AGB – supernovae: general

1. Introduction

Most nuclear burning takes place deep inside stars 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. In single stars three processes can overcome this. First, massive stars ($M > 8\,M_\odot$), that end there lives in supernovae throw off processed layers down to the edge of their collapsing cores.. Second, very massive stars ($M > 25\,M_\odot$) may enter a Wolf-Rayet phase and develop a very strong stellar wind, particularly once helium has ignited.

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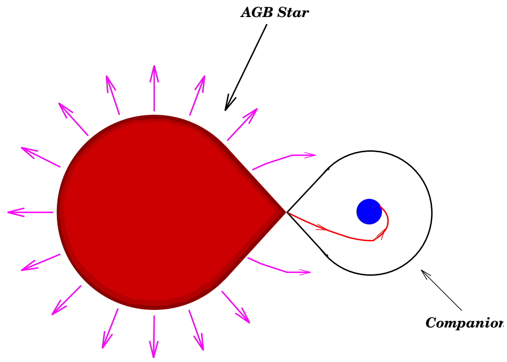

Fig. 1. Mass transfer from an AGB star to it's companion can take place by Roche lobe overflow or in a stellar wind or both.

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. The other major process to enrich the ISM 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 (Stancliffe, Tout & Pols 2004) but the existence of carbon and *s*-process-enriched stars confirms our qualitative ideas. AGB stars also have relatively strong winds so this processed and dredged material is readily returned to the ISM. When almost all the 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.

2. Binary Star Interactions

Binary stars (figure 1) add another dimension to stellar evolution that returns extra products but also reduces what we get from AGB stars by prematurely ending their evolution. 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

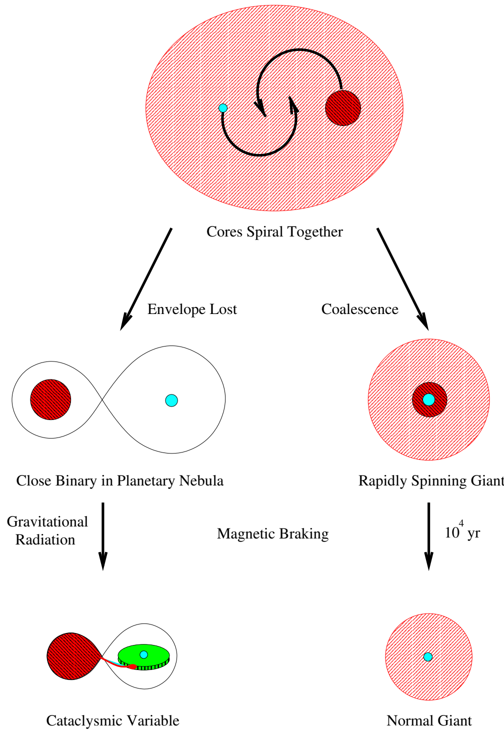

Fig. 2. Common-envelope evolution. After dynamical mass transfer from a giant, a common envelope enshrouds the relatively dense companion and the core of the original giant. These two spiral together as their orbital energy is transferred to the envelope until either the entire envelope is lost or they coalesce. In the former case a close white-dwarf and main-sequence binary is left, initially as the core of a planetary nebula. Magnetic braking or gravitational radiation may shrink the orbit and create a cataclysmic variable. Coalescence results in a rapidly rotating giant which will very quickly spin down by magnetic braking.

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 (figure 2). 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 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 2000) and some symbiotic stars (Mikolajewska, Mikolajeski & Kenyon 1989). 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. AGB stars, by their very nature, attain the largest radii and so they are most affected by interaction with a companion.

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 several million systems. The procedure is described by Izzard & Tout (2003) who examined the yields of CNO elements. For AGB stars in binary systems the carbon yield drops by about 15% though this is compensated for almost exactly by the increase in the yield from other binary stars such as novae and type Ia supernovae. Nitrogen which is produced mostly by massive AGB stars that undergo hot-bottom burning drops by 25%. Overall oxygen rises because of supernovae.

We now turn to the particular case of type Ia supernovae. They are a major contributor to the chemical evolution of the Universe and are believed to have binary star progenitors. They are also intimately connected with AGB stars because they are, almost certainly, thermonuclear explosions of CO white dwarfs that formed as the cores of AGB stars.

3. Type Ia Supernovae

Luminous type Ia supernovae (hereinafter SNe Ia) are amongst the brightest objects in the Universe. Observations indicate that their absolute magnitudes lie in a narrow range, $M_{\rm B} = -18.5 \pm 0.5$, or $\pm 60\%$ in luminosity (from Table 1 of Rowan-Robinson (2002)). Furthermore observations reveal a correlation between maximum absolute brightness and light curve shape (Phillips 1993) that facilitates an effective reduction in the standard deviation of absolute luminosities to $\pm 15\%$. This small spread, coupled with the fact that they can be seen to great distances make SNe Ia excellent standard candles for study of the cosmology of the Universe. Observations have, quite precisely, determined the rate of expansion, immortalised in the Hubble constant, (Branch 1998) and have further determined that this rate is accelerating with time, a measurement that has led to the invocation of a cosmological constant contributing about 70% of the critical density of the Universe to be added to matter's contribution of 30% (Perlmutter et al. 1999; Riess et al. 1998).

The SNe Ia are quite different to other more common types that result from core collapse in an evolved massive star. SNe Ia are explained by the thermonuclear explosions of about a solar mass of degenerate material that is converted to ^{56}Ni and then expelled to the ISM. Their light curves show the decay of this via ^{56}Co to ^{56}Fe. There must be enough nuclear energy available to overcome the binding energy of the white dwarf. In practice about $0.8\,M_\odot$ of iron-group material, mostly in nuclear statistical equilibrium is expelled to the ISM. If $1\,M_\odot$ of material, originally one fifth carbon and four-fifths oxygen, is converted to ^{56}Fe then 1.8×10^{44} J of energy are available and the decay of this from ^{56}Ni releases 2×10^{43} J of this, enough to power the supernova at $5 \times 10^9\,L_\odot$ for 80 d.

3.1. White-Dwarf Progenitors

White dwarfs may be divided into three major types: (i) helium white dwarfs, composed almost entirely of He, form as the degenerate cores of low-mass red giants ($M \leq 0.9\,M_\odot$) which lose their hydrogen envelope before helium can ignite; (ii) carbon/oxygen white dwarfs, composed of about 20% C and 80% O, form as the cores of asymptotic giant branch stars or naked helium burning stars that lose their envelopes before carbon ignition (with progenitors of typically $0.9 - 8\,M_\odot$); and (iii) oxygen/neon white dwarfs, composed of heavier combinations of elements, form from giants that ignite carbon in their cores but still lose their envelopes before the degenerate centre collapses to a neutron star (with progenitors of typically $8 - 10\,M_\odot$).

In a close binary system, mass transfer can increase the mass of a white dwarf. As its mass approaches the Chandrasekhar limit ($M_{\rm Ch} \approx 1.44\,M_\odot$) degeneracy pressure can no longer support the star which collapses releasing its gravitational energy. In ONe white dwarfs the collapse is hastened by electron captures on to magnesium and they lose enough energy in neutrinos to collapse sufficiently, before oxygen ignites, to avoid explosion (accretion induced collapse, AIC). The CO white dwarfs, on the other hand, reach temperatures early enough during collapse, typically at $1.38\,M_\odot$ if initially cold enough, for carbon fusion to set off a thermonuclear runaway under degenerate conditions and release enough energy to create a SN Ia. Accreting He white dwarfs reach sufficiently high temperatures to ignite helium well below $M_{\rm Ch}$ ($M \approx 0.7\,M_\odot$, Woosley, Taam & Weaver (1986)) but an explosion under these conditions is expected to be quite unlike a SN Ia and the apparent lack of such objects suggests ignition is always gentle enough to avoid explosion.

3.2. The Standard Model

Accreting white dwarfs have been known for some time as the engines of cataclysmic variables, the source of novae and dwarf novae (Warner 1995) and so are the first candidate to be considered. However if the accreting material is hydrogen-rich, accumulation of a layer of only $10^{-5} - 10^{-3}\,M_\odot$ leads to ignition of hydrogen burning sufficiently violent to eject most, if not all of or more than, the accreted layer in the well known novae outbursts of cataclysmic variables. The white dwarf mass does not significantly increase and ignition of its interior is avoided. However if the accretion rate is high $\dot{M} > 10^{-7}\,M_\odot\,{\rm yr}^{-1}$ hydrogen can burn as it is accreted, bypassing novae explosions (Paczyński & Żytkow 1978), and allowing the white dwarf mass to grow. Though, if it is not much larger than this, $\dot{M} > 3 \times 10^{-7}\,M_\odot\,{\rm yr}^{-1}$, hydrogen cannot burn fast enough so that accreted material builds up a giant-like envelope around the core and burning shell which eventually leads to more drastic interaction with the companion and the end of the mass transfer episode. Rates in the narrow range for steady burning are found only when the companion is in the short-lived phase of thermal-timescale expansion as it evolves from the end of the main sequence to the base of the giant branch. Super-soft X-ray sources (Kahabka & van den Heuvel 1997) are probably in such a state but cannot be expected to remain in it for very long and white dwarf masses almost never increase sufficiently to explode as SNe Ia.

The standard model overcomes this problem by postulating that, when the mass-transfer rate exceeds that allowed for steady burning, only just the right fraction of the mass transferred is actually accreted by the white dwarf. The standard mechanism currently invoked is a strong wind from the accretion disc that expels the material from the system before it reaches the white dwarf (Hachisu, Kato & Nomoto 1996). An alternative might be that the white dwarf does indeed swell up to giant dimensions but that the resulting common-envelope evolution is very efficient so that the small amount of excess material can be ejected without the cores spiralling in. This is quite consistent with the findings of Nelemans & Tout (2005) and Nelemans et al. (2000) that such efficiency is necessary for at least one phase of common-envelope evolution in the formation of close double white dwarf systems.

3.3. Merging CO White Dwarfs

A more promising scenario is mass transfer from one white dwarf to another. In a very close binary orbit gravitational radiation can drive two white dwarfs together until the less massive fills its Roche lobe. If both white dwarfs are CO and their combined mass exceeds $M_{\rm Ch}$ enough mass could be transferred to set off a SN Ia. However if the mass ratio $M_{\rm donor}/M_{\rm accretor}$ exceeds 0.628 mass transfer is dynamically unstable because a white dwarf expands as it loses mass. Based on calculations at somewhat lower, steady accretion rates, Nomoto & Iben (1985) have shown that the ensuing rapid accretion of material allows carbon to burn in mild shell flashes converting the white dwarf to ONe and ultimately leading to AIC and not a SN Ia. For smaller mass ratios accretion proceeds on the gravitational radiation timescale but even this is fast enough to allow gentle burning of the carbon unless the second white dwarf is of unusually low mass (Martin, Tout & Lesaffre 2006). This model too can be saved by postulating a mechanism to limit the accretion rate. A popular possibility is rapid rotation of the stellar surface (Yoon & Langer 2004).

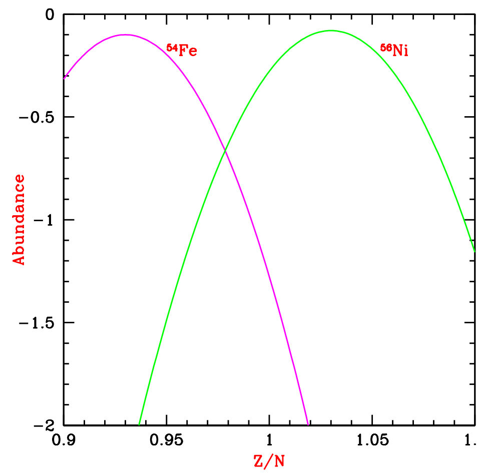

Fig. 3. Nuclear statistical equilibrium as a function of proton to neutron ratio.

4. The Peak Luminosity

In order to predict its variation we must understand why the peak luminosity of SNe Ia varies. For some time this was put down to the variation of the C/O ratio in the progenitor white dwarfs, a result of the range in mass of their progenitors. However current explosion models (Röpke & Hillebrandt 2004) show that this makes little difference. Out to $0.8\,M_\odot$ the whole core burns to nuclear statistical equilibrium (NSE) in a deflagration which ends when the density drops to a point where a detonation begins. In degenerate matter this density does not depend on composition. There may be differences in the inner $0.2\,M_\odot$ where weak interactions are important but these are small and once the detonation begins there is only incomplete burning to silicon. NSE determines which of the iron-group isotopes are formed. If the number of protons present is comparable to the number of neutrons then ^{56}Ni dominates. As the relative number of neutrons N increases relative to the number of protons Z so the equilibrium moves to favour the more neutron-rich ^{54}Fe. Because ^{54}Fe is stable it cannot power the SN in the same way as ^{56}Ni and so as N rises relative to Z the SNe become fainter.

In general neutron-rich material is dominated by ^{23}Na from carbon burning and ^{22}Ne from CNO elements that have been processed during helium burning. During hydrogen burning 98% of CNO elements are converted to ^{14}N which then acquires two alpha particles during helium burning. Timmes, Brown & Truran (2003) show that the variation in metallicity in the local SNe Ia host galaxies ($1/3 < Z/Z_{\odot} < 3$) is just enough to account for the variations in the peak luminosities of the SNe. Low metallicity gives rise to fewer neutrons and so brighter SNe.

5. The Importance of AGB star Evolution

During their thermally pulsing AGB evolution stars dredge carbon rich material from the intershell region between the helium and hydrogen burning shells. This is the origin of carbon stars. As the core grows this ^{12}C is converted first to ^{14}N, by the CNO cycle, as it passes through the hydrogen burning shell and then to ^{22}Ne as the ^{14}N captures two alpha particles and β-decays. In the most massive AGB stars ^{22}Ne acts as a neutron source but in lower mass stars it can be incorporated in the CO core. Even if it is destroyed the neutrons released add to the neutron excess in the core by incorporation in neutron-rich *s*-isotopes. A CO core that grows significantly inside a carbon star can in this way accumulate a significant amount of ^{22}Ne or other neutron-rich isotopes. And if it were to ignite as a SN Ia it would be correspondingly fainter than a core grown to a similar size in a less carbon-rich star. This rather than the variation in the initial metallicity may dominate the variation of peak luminosity in SNe Ia. Work is underway to quantify the effect.

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