Low-mass supernovae in the early Galactic halo: source of the double r/s-process enriched halo stars?

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ABSTRACT

Several stars at the low-metallicity extreme of the Galactic halo ([Fe/H] = −2.5) show strong enhancements of both s-process and r-process elements. The presence of s-process elements in main-sequence stars is explained via mass transfer from an AGB companion star in a binary system. r-Process elements originate in type-IIsupernovae and also require mass transfer. It is however unclear how pollution by both an AGB star and a supernova could have occurred. Here I show that the initial–final-mass relation steepens at low metallicity, due to low mass-loss efficiency. This may cause the degenerate cores of low-Z, high-mass AGB stars to reach the Chandresekhar mass, leading to an Iben & Renzini-type-1.5 supernova. Such supernovae can explain both the enhancement patterns and the metallicity dependence of the double-enhanced halo stars. Reduced mass loss efficiency predicts more massive remnants in metal-poor globular clusters. The evidence for a high M/L population in the cores of globular clusters is briefly discussed.

Key words: stars: stars: AGB and post-AGB – stars: mass-loss

1 CHEMICAL PECULIARITIES IN HALO STARS

The metallicity distribution of the stars in the Galactic halo ranges from [Fe/H] = −1 for the most metal-rich stars, to [Fe/H] = −5.3 at the minimum (HE 0107−5240: Christlieb et al. 2002). The first halo stars formed from almost unprocessed primordial gas. A short formation time is favoured, because chemical enrichment due to supernovae is rapid. The Milky Way disk formed out of gas pre-enriched to about [Fe/H] ≈ −1. The pre-enrichment may have been due to the Bulge formation (Renzini 2003) but the most metal-rich stars in the halo show that this level of enrichment was already reached by the end of the halo formation. The global metallicity of the Universe reached [Fe/H] ≈ −1 at z = 3 (Renzini 2003).

Some halo main-sequence stars show evidence for abundance alterations. Because main-sequence stars should not have significantly altered their surface abundances, and pollution from planetary companions is unlikely given the dearth of planets at subsolar metallicity (Bodasheev et al. 2003), pollution from a companion star by mass transfer is considered most likely. In some cases high overabundances of s-proces elements (e.g. Pb) are found (Aoki et al. 2000; Van Eck et al. 2001; Lucatello et al. 2003). These elements are formed in Asymptotic Giant branch (AGB) stars (Van Eck et al. 2003), which first appeared 10^8 yr after the halo formation. Other metal-poor stars show evidence for large enhancements of r-process elements, a.o. europium (Sneden et al. 2000) and gold (Cowan et al. 2002). These form in type-II supernovae, and are also explained via pollution from a companion star.

The discovery that several stars show enhancements of both r-process and s-process elements (Hill et al. 2000; Cohen et al. 2003) is puzzling, as they require pollution from both an AGB star and a supernova.

In this paper we will present a calculation which indicates that at low metallicity, inefficient mass loss may allow the degenerate cores of AGB stars to reach the Chandresekhar mass. This would lead to an AGB supernova, polluting low-mass companions by both s-process elements (enriched in the AGB envelope) and r-process elements formed in the subsequent explosion. The next section discusses the double-polluted stars. Section 3 discusses AGB mass loss at low Z, and Section 4 derives initial-final masses for these stars and discusses the possibility of AGB supernovae.

2 DOUBLE POLLUTED HALO STARS

Three stars are known to show the double enhancements: HE2148−1247 (Cohen et al. 2003), CS22948−027 (Hill et al. 2000; Preston & Sneden 2001) and CS29497−034 (Hill et al. 2000), with [Fe/H]=−2.3, −2.45, and −2.90 respectively. CS22898−027 (Preston & Sneden 2001; Aoki et al. 2003), at [Fe/H]= −2.25, may also show double enrichment. The metallicities are at the lower range of the gaussian halo distribution (Ryan & Norris 1991). The process leading to the double en-
hancement appears to require \([\text{Fe}/\text{H}] < -2\). A lower limit to the metallicities of the double enriched stars is not evident. Although there is a tail in the halo distribution extending to \([\text{Fe}/\text{H}] = -4\) (Ryan & Norris 1991) or lower (Christlieb et al. 2002), there are few stars in this tail.

Cohen et al. (2003) discuss possible scenarios for double enhancements. A triple system including one massive pre-supernova and one pre-AGB star, plus the remaining low-mass star, appears very unlikely. They therefore suggest reverse mass-transfer from the low-mass star to the post-AGB white dwarf, leading to accretion-induced collapse, and a type-Ia supernova. A third star in a close orbit around the AGB primary may instead be considered for the mass donor, leading to a more traditional type-Ia scenario, but this again leads to an unlikely close triple system. There is also no evidence that type-Ia SNe manufacture significant amounts of r-process elements, arguing against both these scenarios.

Pollution from an AGB companion (s-process elements) occurs via wind accretion. The peak transfer efficiency occurs for binaries with periods around 3000 days (Pols et al. 2003; Han et al. 1995) stress the additional importance of a common envelope phase in mass transfer, but orbital eccentrics show that all but the closest binaries (\(d < 1\) AU) avoid a common envelope (Karakas et al. 2006; Pols et al. 2003). Roche lobe overflow is also unlikely (Han et al. 2002), firstly because it tends to happen on the first giant branch (before the onset of the s-process enhancements) and secondly because it is unstable for donor stars more massive than the secondary, as would have been the case here. For the more likely wider orbits, the wind interaction has little or no effect on the primary AGB star, which continues to evolve as in the case of a single star.

The wide orbit argues against the accretion-induced collapse, because of the need to transfer a large amount of mass from a distant low-mass main-sequence star in order to reach the Chandrasekhar mass. A scenario which does not require either a triple system or reverse mass transfer, and explains the metallicity dependence of the double-enrichment process, could be of interest.

3 AGB MASS LOSS AT LOW METALLICITY

3.1 Mass loss expectations

Stars on the AGB burn helium and hydrogen in shells around their inert C/O core. Mass loss increases during the AGB: once the mass-loss rate in the wind significantly exceeds the nuclear burning rate (\(\sim 10^{-7} \text{M}_\odot \text{yr}^{-1}\)), the evolution comes to a sudden end (Willson 2000). The remaining envelope is quickly removed and nuclear burning will cease. The C/O core at this point forms the subsequent white dwarf.

The dependency of the mass loss on the stellar parameters is not well known. Several formalisms have been proposed in the literature, depending typically on the radius, mass and luminosity of the star. The one used most extensively is the Bloecker (1995) relation

\[
M = -4.8 \times 10^{-9} \frac{L R L_{\text{E}}^2}{M} \text{M}_\odot \text{yr}^{-1},
\]

with quantities in solar units. Such relations are generally derived for Galactic stars. An explicit metallicity dependence is not included.

The mass loss of AGB stars is a two-step process. First, pulsations extend the atmosphere and drive a small mass loss. Secondly, dust forms in the extended atmosphere; radiation pressure on the dust now drives the large mass-loss rates observed. At low metallicity, the efficiency of the dust formation is reduced and this will limit the mass-loss rates. Bowen & Willson (1991) derive mass-loss rates at low \(Z\) from theoretical pulsation models. They find that at low metallicity (\([\text{Fe}/\text{H}] < -1\)) the dust does not play a significant role and the wind becomes purely pulsation driven. Stars with lower metallicity are found to have lower mass-loss rates. This will allow the core to grow to a larger mass and reach higher final masses.

The AGB wind depends on the stellar radius. As low-metallicity stars have smaller radii (Iben 1984) gives for AGB stars the relation \(R \propto Z^{0.088}\), this implies a further metallicity dependence of the mass loss, even for dust-free, pulsation driven winds.

3.2 Observational Evidence

There are few direct observations of mass loss at low metallicity. The best data set comes from ISO observations of AGB stars in the Magellanic Clouds (Trams et al. 1996), from which both mass-loss rates and luminosities were derived (van Loon et al. 1999). Comparison with Galactic stars is not straightforward, because within the Galaxy distances tend to be poorly known and the luminosities are uncertain. The ISO data shows that both LMC and SMC stars reach similar mass-loss rates to those shown by Galactic stars near the tip of the AGB (van Loon 2000), although the unknown dust-to-gas ratios and expansion velocities could hide some difference. The luminosity of the LMC and SMC stars tends to be high, reaching up to \(L = 5 \times 10^4 \text{L}_\odot\).

Mass loss at even lower metallicities (\([\text{Fe}/\text{H}] < -0.7\)) is very poorly studied. However, the superwind phase will lead to the formation of a planetary nebula (PN) and these can be observed to very large distances. There is a good relation between the number of PNe and the luminosity of the host galaxy: for the most populated systems (Bulge, LMC), \(\log\{N(\text{PN})\} \approx \log L_\odot / L_{\odot} - 6.9\) (Magrini et al. 2002). However, local galaxies with low \(Z\) show some evidence for a deficiency in the number of PN (Magrini et al. 2003). This becomes apparent only for \([\text{Fe}/\text{H}] < -1\) (Fig. I), well below the LMC or SMC metallicity. Plotting the deficiency as function of ratio of C-type over M-type AGB stars (Fig. I right panel) shows a clear relation: this ratio is an effective tracer of the metallicity of the AGB population (Groenewegen 1994).

The deficiency of PNe suggests that the mass-loss rates do not reach as high values for metallicities \([\text{Fe}/\text{H}] \sim -1\). Lower peak mass-loss rates will give rise to less dense PNe which will fade faster. Conversely, the lack of a relation at \([\text{Fe}/\text{H}] > -1\) suggests that all these AGB stars reach similar mass-loss rates (although not necessarily at the same luminosities) regardless of metallicity. This change of behaviour at \([\text{Fe}/\text{H}] \sim -1\) is in excellent agreement with the predictions of Bowen & Willson (1991).

4 AGB SUPERNOVAE

We can estimate the effect of metallicity on the initial–final-mass. The goal is to obtain qualitative estimates: approximate, simple relations will suffice. In a more detailed calculation, more complicated relations could be substituted but these introduce their own uncertainties. The largest uncertainties comes from the mass-loss estimates, and not including hot bottom burning.

The relation between the luminosity corresponding to a certain mass-loss rate, and the metallicity, is taken from Bowen & Willson (1991). Between \(Z = Z_\odot\) and \(Z = 0.1 \times Z_\odot\), this luminosity
Figure 1. Left: The ratio between number of planetary nebulae and luminosity of the parent stellar population (y-axis), as function of metallicity (x), for nearby galaxies (Magrini et al. 2003). Encircled points indicate spiral galaxies affected by internal extinction. Right: The same ratio, as function of the ratio of carbon over M-type stars on the AGB, a tracer of the metallicity of the AGB population.

increases by a factor of 1.3, in part because the wind is no longer dust driven. At lower Z, the luminosity required to support the same mass-loss rate scales as (Bowen & Willson 1991):

$$\log L(Z)/L(Z_\odot) = 0.12 - 0.13 \log Z/Z_\odot; \quad Z/Z_\odot \leq 0.1.$$  (2)

The effect on the final mass of the star is derived from the core mass–luminosity relation, which we take from Boothroyd & Sackmann (1988):

$$L/L_\odot = 59250 \left( M_c/M_\odot - 0.495 \right)$$  (3)

The increase of the final mass is very small for low core mass, but becomes significant for core masses corresponding to the heaviest white dwarfs. We use an approximate present initial–final mass relation corresponding to solar metallicity:

$$M_f = 0.5 + \frac{1}{12} M_i.$$  (4)

The true relation is shallow at low core mass and steepens at high core mass (Vassiliadis & Wood 1993), so this is a significant simplification which may be more realistic at high than at low $M_c$.

The result is shown in Fig. 2. At solar metallicity, the most massive AGB stars reach final masses around 1 $M_\odot$. Already at $Z/Z_\odot = 0.1$, the most massive remnants approach the Chandrasekhar limit. This should be taken with caution as the most massive AGB stars may show higher luminosity than predicted from their core masses, due to the effects of hot bottom burning (Bloecker & Schoenberner 1991). At $Z/Z_\odot < 0.01$, the Chandrasekhar mass is reached for 5 $M_\odot$ stars and at $Z/Z_\odot < 0.001$, for 4 $M_\odot$.

Carbon ignition in the degenerate core will cause these stars to explode. Iben & Renzini (1983) named such objects 'type 1.5 supernovae'; physically they could be considered an extension of type II SNe. The early work did not include the superwind which was later found to terminate the AGB before these events could occur. However, an absence of a superwind at the lowest metallicities means that AGB supernovae could still play a role in the early evolution of the Universe.

5 DISCUSSION

5.1 Double enriched stars

We have presented calculations which indicate the possibility that massive AGB stars in the early halo would have given highly massive remnants, leading to a population of AGB supernovae. In the context of the mixed r/s-enhanced halo stars, this suggests that the same companion star was responsible for the double pollution. For an initial mass in excess of 3–4 $M_\odot$, the companion would first have developed into an AGB star. The wind of this star would have carried the s-process elements. After the core reached the Chandrasekhar limit, a supernova explosion occurred. r-Process elements formed during the explosion also polluted the companion star. The explosion may disrupt the binary system and so this model does not automatically predict that all such stars are binaries. However, if a binary, the companion should be a supernova remnant with appropriate mass.

Compared to the previously posposed models for the double enriched stars, the present model has the advantage of not requiring a close triple but only a binary, and it includes an explanation for the low metallicities of the doubly enriched stars. r-Process elements appear to be produced in low-mass (10 $M_\odot$) type-II supernovae (Pagel & Tautvaisienė 1995); the similar masses suggest their production could also be expected in AGB supernovae.

5.2 Lithium

Preston & Sneden (2001) find that CS 22898−27 has a more or less normal lithium abundance for its metallicity, and wonder whether this is easily explained assuming pollution from an AGB star. AGB
stars experience lithiu-rich phases during hot bottom burning. However, the lithium is easily destroyed again and at different phases, the surface abundances can vary from very high to strongly depleted. The total lithium yield of low metallicity, hot bottom burning stars can be very close to the original Spite plateau abundance. Thus, the normal lithium abundance can be a coincidence.

For hotter s-process enriched stars, the lithium 6708 Å line coincides with a CeII line and derived abundances may be upper limits in such cases.

### 5.3 Supernova rates

The effect on the supernova rate could be significant. Assuming a Salpeter IMF with $\alpha = -2.35$, the ratio of stars exploding as SN on the AGB, compared to the normal type-II’s is shown in Fig. 2. At the extreme $Z$, the contribution of these AGB-SN exceeds the normal type-II SN by a factor of a few. The AGB stars will however explode much later and would therefore play less of a role in the fast enrichment of the gas.

### 5.4 Globular clusters

Old low-$Z$ population should show the effect of the higher final masses, and contain a population of heavy white dwarfs and an overpopulation of neutron stars. This would affect globular clusters: dynamical evidence for the presence of a high-$M/L$ population of heavy remnants in the core of M15 ([Fe/H] = −2.25) is presented by Phinney (1993), Dull et al. (1997) and Baumgardt et al. (2003). A high $M/L$ was also found in the core of NGC 6752 ([Fe/H] = −1.56), which could be caused by an excess population of heavy white dwarfs or neutron stars. Ferraro et al. (2003).

### 6 CONCLUSIONS

From our present knowledge of AGB mass loss, the early Universe may have contained a population of supernovae which is not found in the local, high metallicity Universe. These AGB-SN are possible sites for the r-process, and provide a simple explanation for the small sample of low-metallicity Universe, which show evidence for both s-process and r-process enrichment.

The absence of dust driven winds at [Fe/H] = −1 is supported both by models (Bowen & Wilson [1991]) and observations (this paper). The prediction that stellar remnants are more massive at lower metallicities appears robust, Regardless of whether these remnants reach the Chandrasekhar limit. The presence of high-mass white dwarfs in globular clusters is likely, and could explain the evidence for an excess $M/L$ in the cores of both M 15 and NGC 6752.

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**Figure 2.** Left: initial-final mass relations for intermediate-mass stars at low $z$. Right: The inferred ratio of AGB supernovae over normal type-II supernovae, as function of metallicity.
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