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The Role of AGB Stars

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Abstract. We give a brief summary of the abundance anomalies seen in globular cluster stars, and try to review how and if AGB stars could be responsible. The abundance anomalies are clearly indicative of hot H burning, such as is expected during hot bottom burning in intermediate mass AGB stars. Nevertheless we conclude that a quantitative fit is very hard to obtain using current AGB models.

Key words. AGB stars – nucleosynthesis – stellar abundances

1. Introduction

The subject of the abundances of stars in globular clusters has a long history, and it is not our aim to recount it here. Although they are famous for the constancy of the [Fe/H] values from star-to-star within a given cluster, in the 70s we started to realise that there were star-to-star variations in some other elements, most notably C and N. Norris, Da Costa, Cottrell and co-workers led the charge to determine what variations were present, and indeed to try to understand them! The initial discovery was variations in the CN strength, with stars seeming to fall into two groups: the CN-strong and CN-weak. It was later discovered that in some cases, there were O depletions and Na enhancements as well. These were in the expected way, with the O depleted stars also being those with enhanced N and Na. Further, we sometimes found Mg-Al variations. All of these were in the sense expected from hot H burning: the CNO cycle producing nitrogen from carbon and, in extreme cases, from oxygen. In the cases where oxygen has been depleted also, we see sodium enhancements, as expected from the operation of the Ne-Na reactions. The Mg-Al variations are a little more complicated. Shetrone (1996) found unexpected isotope variations, which we discuss further below.

All of these abundance variations can be understood as the result of hydrogen burning, at various temperatures (except perhaps for magnesium and aluminium, as discussed below). The question remained, however, as to where this processing took place. The initial observations were made for the brightest stars, of course, and this meant that the data were coming from the tip of the giant branches. One can imagine that the deep tenuous envelope in red-

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giants could lead to very different behaviour than seen for essentially homogeneous main-sequence stars. The physical structure of a red-giant is two almost independent solutions: a degenerate core and a huge envelope. These solutions are joined in a very thin region where the density rapidly drops by orders of magnitude. Sweigart and Mengel (1979) suggested that rotation could lead to mixing in the giant's envelope, and hence there could be a link between the bottom of the convective envelope and the burning regions, with material being slowly circulated between the two. This would allow for the products of H-burning to appear in the envelope, even though formal stellar models did not predict such mixing. This is called the "deep-mixing" or "evolutionary" hypothesis.

The alternative is that the abundance anomalies were put in place when the star was born or perhaps accreted onto the stellar surface from the mass lost by more massive stars. Together, these are sometimes known as the "primordial pollution" hypothesis. We think it is wise to separate these two suggestions. In the case where the existing stars accreted material onto their surfaces, only the surface layers will have different composition to the rest of the star. We shall refer to this as the "pollution" scenario. In contrast, if the whole star forms from material that was ejected by earlier generations (perhaps mixed with some amount of the original material) we shall refer to this as the "primordial enrichment" scenario.

Three important facts should be remembered: wherever the hot H-burning takes place, it must not alter the [Fe/H] value, because this is constant for a given cluster (ω Cen is, as always, an exception). Secondly, in the few cases that have been checked, it appears that the C+N+O abundances are constant despite the variations from star to star. And finally, many abundance anomalies seen in globular cluster stars are **not** seen in field stars. We will return to these points below.

2. Complications

2.1. Evolutionary Effects

Clear evidence exists for the variation of [C/Fe] with luminosity in some clusters, especially the metal poor clusters, such as M92 (Langer et al 1986). An interpretation of these data that does not involve processing within the star, would be so contrived as to be untenable. Hence this is always taken as strong evidence for some mixing and processing within the star.

2.2. Primordial/Pollution Effects

With access to the 8m class telescopes, we have now been able to obtain high resolution spectra of stars near the turnoff. Amazingly, many clusters have turn-off stars which show the same abundance anomalies as the giants, eg the CN bimodality in 47 Tuc (Cannon et al 1998) or the O-Na anti-correlation in NGC6752 (Gratton et al 2000). Again, it is hard to see how such anomalies could originate inside a main-sequence star, so this is taken as strong evidence for either the pollution or primordial enrichment scenario.

2.3. Other Evolutionary Effects and Comparison to Field Stars

It is perhaps an important fact that there is no compelling evidence for variations of any elements with luminosity, other than the CNO group. This indicates that the internal mixing is affecting only the CNO cycle. Hence, if it is accomplished by "deep-mixing" then it is not excessively deep. Furthermore, we know that there is strong evidence for such mixing in the field stars as well, as revealed in the $^{12}C/^{13}C$ ratio measured in stars as well as presolar grains. In this crucial respect, then, the globular cluster stars are **the same** as the field stars. We need to be certain if there is any evidence for variation of anything other than CNO with luminosity in any globular cluster giant stars. There is a hint of a variation of Na in M13 (Pilachowski et al 1996). It is important to clarify this.

In any case, even if there is some Na being produce by deep-mixing and the Ne-Na cycle, we would never see that in a heterogeneous collection of field stars, since it is barely seen in M13. Note that the mixing required to reach Na is not much deeper than required to reach the CNO region. The problem with the deep-mixing scenario was the attempt to try to explain the Mg-Al abundance variations.

2.4. Mg and Al

In simple terms, it was occasionally seen that some stars in globular clusters showed a Mg-Al anti-correlation, with Mg down and Al up. An example is M13 (Shetrone 1996). This can be understood from the operation of the Mg-Al cycle, with the heavy Mg isotopes ^{25}Mg and ^{26}Mg capturing protons to form the two Al isotopes, ^{26}Al and ^{27}Al respectively. The ^{26}Al ends up as either ^{26}Mg (from β-decay) or ^{27}Al (through either $^{26}\mathrm{Al}(\beta^+\nu)^{26}\mathrm{Mg}(\mathrm{p},\gamma)^{27}\mathrm{Al}$ or $^{26}\mathrm{Al}(\mathrm{p},\gamma)^{27}\mathrm{Si}(\beta^+\nu)^{27}\mathrm{Al}$). This seems to fit the observations, at least qualitatively, but it does require high temperatures, well above the average hydrogen-shell temperature. It was thus very difficult to understand these variations within the evolutionary hypothesis. David Arnett once said "To the extent that its possible, it is the isotopes that keep the theorists honest." It was with this principle in mind that Shetrone (1996) investigated the Mg isotopes in M13. Although he was unable to separate the two heavy Mg isotopes, he was able to separate them, as a pair, from the more abundant ^{24}Mg. Surprisingly, he found that it was actually ^{24}Mg that was decreasing when the total Mg was decreased. To do this requires much higher temperatures than needed for the postulated proton captures on the heavy Mg isotopes. This is a serious problem for the mixing hypothesis, because mixing deep enough into the shell to alter the ^{24}Mg abundance would alter the evolution of the star dramatically.

2.5. The Inevitable, if Unsatisfying, Combined Hypothesis

It seems that we are led to a combined hypothesis. The appearance, in some clusters, of abundance correlations in main-sequence and turnoff stars is strong evidence for a pollution or primordial origin. On the other hand, in many clusters there is an unambiguous variation of C and N with luminosity, which argues just as strongly for deep mixing within the star. So in some clusters we now believe that both processes are occurring. However, as we said earlier, the internal mixing also occurs in field stars, at least for CN cycling. Maybe O and Na are affected also, the data are not convincing for globular clusters and any correlation would be even harder to see in a collection of field stars. In this respect, the "evolutionary" hypothesis is now the standard picture, if we do not require it to go any deeper than would produce CN and possibly O-Na abundance variations. So we are left with trying to distinguish between the pollution and primordial scenarios, and then to find the stars responsible for them.

3. Pollution or Primordial Enrichment?

There is a simple observation that argues against pollution. Recall that by this we mean that the current stars have swept up and accreted gas onto their surfaces, and we are seeing the composition of the accreted material rather than the entire star. Main sequence stars of low mass have very thin convective envelopes. When they ascend the giant branch the envelope moves much further in, covering about 70% of the star's mass. So if the abundance anomalies were just present in the thin convective envelope initially, they would be diluted when the first dredge-up occurred, and mixed with the interior, which would have the original composition. For example, see the CN analysis of M71 by Briely et al (2001), which shows that this does not occur. Thus it appears that the entire star has the composition of the photosphere. Hence the working hypothesis that we are forced toward is the following: there is a source of primordial enrichment in (some) globular clusters which results in processing some of the original gas through hot H-burning. Some stars form with the original composition, and some form almost exclusively from the enriched material. Indeed, Yong et al (2002) estimate that the stars forming from the enriched material must contain as little as 10% of the original material. They note that the "enriched" stars in NGC6752 are under-abundant in oxygen by a factor of ten compared to the "normal" stars. Hence they argue that even if the enriched material had no oxygen at all, we would need 90% enriched material and 10% original material to recover the observed oxygen under-abundance. This is rather extreme, but it is the conclusion we are forced to make. Why the material at this stage is so poorly mixed within the cluster, and why there is a second burst of star formation, remain problems to be solved! But lets push on. Later in the evolution, both the "normal" and the "enriched" stars experience deep-mixing, at least to the extent that it alters the CN abundances (and possibly O and Na), but this is no deeper than seen in field stars. It remains for us to find the source of the enriched gas.

4. The Attraction of AGB Stars

AGB stars have many features which, at face value, make them suitable as the source of the primordial enrichment. Firstly, they do not alter the [Fe/H] value of any gas they return to the interstellar medium. Their winds are also much less energetic than supernovae, so that the cluster is more likely to retain the gas. Finally, for intermediate mass stars which experience hot bottom burning (hereafter HBB) they process their large envelopes through hot H-burning, showing the effects of the CNO and Ne-Na and Mg-Al reactions at the surface. Qualitatively, this is what is required, and this has been known for some time. The problems come when one tries to fit the details quantitatively.

4.1. Summary of AGB Nucleosynthesis

For reference, we remind the reader of AGB star nucleosynthesis. Firstly. the repeated third dredge-up results in additions of primary carbon to the stellar surface. Assuming that the star is massive enough for HBB (ie mass above about $4M_\odot$, depending on the composition), this carbon is burned into nitrogen. In extreme cases, oxygen in the envelope is also burned into nitrogen. Further, the CNO cycling in the hydrogen shell results in almost every initial CNO nucleus being burned to nitrogen. When the nitrogen is then processed through the helium shell it captures two alpha particles to end up as ^{22}Ne, or three alpha particles to form ^{25}Mg or ^{26}Mg. Subsequent HBB burns the ^{22}Ne into ^{23}Na and the Mg into Al. Recall that we need ^{24}Mg to decrease if we are to match the observations of M13, and hence we need very hot HBB. This indeed does occur in low metallicity stars, as shown in Figure 1 which shows the results for a $6M_\odot$ model with a composition appropriate to the Small Magellanic Clouds.

Note the composition of the star shown in Figure 1 is approximately what is required. There is the burning of C and O into N, an increase in Na as well as a decrease in ^{24}Mg together with an increase in ^{27}Al. So where is the problem?

4.2. Quantitative Problems

Denissenkov and Herwig (2003) pointed out the problems nicely. To deplete enough oxygen is very difficult. It is true that going to lower metallicity will help (Ventura et al 2002) but fine tuning is required. Much of the agreement is lost when a realistic IMF is used, rather than a single stellar mass (Fenner et al 2004). Note that in the case shown in Figure 1 we don't get as much sodium increase as we would expect. This is because of leakage into the Mg-Al cycle, and is yet another problem for the models. Note also that the amount of Al produced is very small.

The large helium abundance might be a problem, also. The AGB star's envelope is now about 36% He by mass, and this will affect the evolution of the stars that form from this material. It seems likely that if there are two populations of star, one with a He content of about 23% and one with about 35%, then these would have been noticed during the detailed studies of colour-magnitude diagrams and on-going attempts to determine their age accurately. Note that D'Antona et al (2002) have investigated this phenomenon and conclude that it is ac-

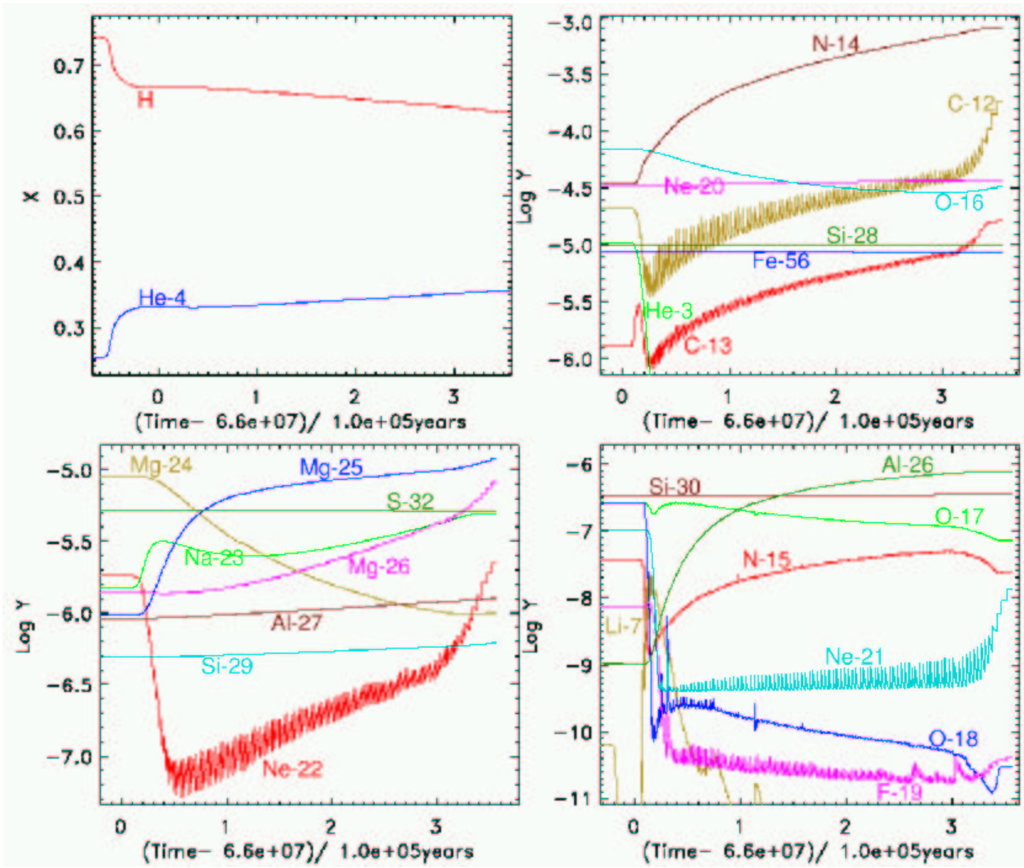

Fig. 1. Various photospheric abundances for a $6M_\odot$ Z=0.004 model during the AGB evolutionary phase.

tually consistent with horizontal branch morphology. A clear tracer of hot H-burning is the lithium abundance, of course. Material which has been exposed to hot H-burning should have no Li present. Observations of Li on the main-sequence of globular clusters are urgently required, because the depletion factor between the "normal" and "enriched" stars should tell us the relative amounts of these materials in these stars. Perhaps the strongest argument against AGB stars being responsible is an old one, which seems to have been forgotten. From early in the study of globular cluster abundances, various authors have checked the sum of C+N+O. Although there are not a large number of stars (or clusters) that have been studied, the results available show a constant value for C+N+O in the CN-strong and the CN-weak stars. This was shown for M92 by Pilachowski et al (1988) for NGC288 and NGC362 by Dickens et al (1991), for M3 and M13 by Smith et al (1996), and for M4 by Ivans et al (1999). Although these observations are not easy, and may have reasonable uncertainties, the tell-tale signs from AGB stars would be enormous increases in C+N+O. Note that the star shown in Figure 1 shows an increase by a factor of well over ten, and for lower metallicity stars the increase will be even larger. Let us now argue against ourselves! To really predict the effect of AGB stars we would need a distribution of masses, rather than attempting to extrapolate from a single mass. An attempt at a self-consistent calculation of the chemical evolution of NGC6752 has been begun by Fenner et al (2004). They find that the combined C+N+O increases rapidly, by about 0.6 dex within 30 million years, and then more slowly by another factor of two or so. This spread is dangerously close to that seen between typical CN-weak and CN-strong stars. Of course, the initial rise is mostly nitrogen, from HBB stars and the latter rise is mostly carbon, from dredge-up in lower mass stars without HBB. Elsewhere in this volume Dave Burstein has argued for large enhancements of nitrogen in globular clusters. Maybe intermediate mass AGB stars are the source of this nitrogen.

Before leaving this section we mention two more things. AGB stars are known as sources of s-process elements and ^{19}F. However, for the intermediate mass stars involved in HBB we do not expect the production of s-process elements to be very large. The intershell convective region, where ^{22}Ne(α,n)^{25}Mg acts as the neutron source, becomes smaller in more massive stars. Further, the duration of the pocket decreases also. Even if the ^{13}C source is active in these stars as well, it is likely that the Ne source will dominate, and that it will nevertheless be unimportant. Finally, although low mass stars are known to produce ^{19}F, it is very efficiently destroyed in stars with HBB. So we would predict that any HBB star, or ejecta therefrom, would be severely depleted in fluorine.

5. Conclusions

It seems that the abundance anomalies seen in globular cluster stars now require both a primordial enrichment as well as some internal "deep-mixing". We note, with some relief, that there is no real reason to postulate that the deep mixing is any deeper than seen in field stars, and that thus there is no *fundamental* difference between stars in globular clusters and field stars.

A real difference, of course, is the environment. And it appears that somehow, another generation of stars (or the more massive end of the current generation?) has returned to the cluster material which has been exposed to hot H-burning. We think that the pollution mechanism, where only the surface layers have accreted enriched material, can be ruled out. We are left to find the site for the hot H-burning. This problem has been with us for a long time, and although AGB stars have many of the requirements, they seem to fail in a quantitative analysis (Fenner et al 2004). However, variations in the α-elements from one cluster to another may be evidence for variations in the IMF. If we are free to adjust the IMF (as may be needed to explain the large amounts of N that Dave Burstein discussed) then maybe an AGB solution is possible.

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