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Abundance anomalies in NGC 6752

Are AGB stars the culprits?

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Abstract.
At the 7th Torino workshop held at the IoA, Cambridge University, in August 2004, a brief overview was given about the galactic globular cluster abundance anomalies problem, followed by a short report on our test of the popular theory that the observed abundance anomalies in the Galactic globular cluster NGC 6752 are due to 'internal pollution' from intermediate mass asymptotic giant branch stars. In the test we use a chemical evolution model to track the composition of the intracluster medium over time. Custom-made stellar evolution models were calculated using the Monash/Mount Stromlo stellar structure code and the Monash nucleosynthesis code. Yields from these calculations were used as feedback in the chemical evolution model. A novelty of this study is that the stellar evolution of the second generation stars was calculated using the appropriate composition (non scaled-solar), as given by the chemical evolution model. By tracing the chemical evolution of the intracluster gas we are able to test the internal pollution scenario, in which the Na- and Al-enhanced ejecta from intermediate mass AGB stars is either accreted onto the surfaces of other stars, or goes toward forming new stars.
We find that our model *can not* account for the Na-O *or* Mg-Al anticorrelations. In addition, we find that the sum of $C + N + O$ should vary by up to an order of magnitude (between stars with varying levels of anomalies) if the pollution is coming from AGB stars. However, it is observed to be constant in globular clusters for which this has been measured. Thus the results of our model do not compare well with observational data — the qualitative theory is not supported by this quantitative study. This work has recently been completed and published Fenner et al. 2004. Details of the stellar models will be in a forthcoming paper (Campbell et al. 2004).

Key words. AGB stars – Globular cluster – Abundances

1. Introduction: Background on the Globular Cluster Abundance Anomalies

Most Galactic globular clusters (GCs) have a very uniform distribution of heavy elements.

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This indicates that the cluster gas was well mixed when the stars formed. However, in contrast to the Fe group, it has been known since the early 1970s that there is a large spread in Carbon and Nitrogen in many GCs (eg. Bell & Dickens 1974 and Da Costa & Cottrell 1980).

The first 'anticorrelation' was found 25 years ago – C is low when N is high. The observation is explicable in terms of the CN cycle, where C is burnt to ^{14}N. It has also been found that the C abundance decreases with luminosity on the red giant branch (RGB). This is known as the C-L anticorrelation and is also observed in halo field stars (eg. see Figures 4 and 5 in Smith 2002). This is thought to be the result of Deep Mixing — extra mixing of the convective envelope into the top of the H-shell, allowing C-N cycling to alter the composition of the surface. Another effect of C-N cycling is the reduction of the $^{12}C/^{13}C$ ratio (it approaches an equilibrium value ~ 3). This has been observed in GCs and in the field (eg. see Figure 2 in Shetrone 2003).

GCs also show other abundance features. The most famous of these is the O-Na anticorrelation: O decreases with increased Na. This is readily explained by hot(ter) hydrogen burning, where the ON and NeNa chains are operating - the ON reduces O, whilst the NeNa chain increases Na (T $\sim$ 45 million K). Where this occurs is still debatable. The notable thing about this abundance trend is that it only occurs in GCs - *it is not seen in field halo stars* (see Gratton et al. (2000) for a comparison of field and M13 stars).

There also appears to be a Mg-Al anticorrelation in some GCs. This can also be explained through high-temperature (T $\sim$ 65 million K) proton capture nucleosynthesis, via the MgAl chain (Mg depleted, Al enhanced). Again the site for this is uncertain and it does not occur in field stars. Furthermore, the light elements show various (anti)correlations amongst themselves (see eg. Figure 9 in Kraft et al. (1997) for O, Na, Mg, & Al in M13).

All these (anti)corellations point to hydrogen burning – the CN, ON, MgAl, NeNa cycles/chains – at various temperatures. The most popular theory for the site of this burning is at the base of the convective envelope in AGB stars - where hot bottom burning (HBB, first proposed as a site by Cottrell & Da Costa 1981) occurs. HBB provides the proton-capture nucleosynthesis needed, and at low metallicities (like those of GCs) HBB occurs at higher temperatures. Qualitatively it seems to fit the observations (although some deep mixing is required also, to explain the C-L anticorrelation).

In the following sections we describe a chemical evolution model for NGC 6752 in which we attempt to verify the 'internal pollution' theory.

2. The Pollution Model

As heavy elements are primarily produced by massive stars, the observations mentioned above suggest that there was a generation of massive stars which polluted the pristine protocluster gas, followed by a later release of lighter elements, presumably from lower mass stars. In our model we assume a two stage star formation/pollution history, similar to that used in the dynamical evolution study by Parmentier et al. (1999).

2.1. Stage 1: Initial Pollution by 'Generation A' (Pop. III) Stars

The initial mass distribution used to model the first stars that pollute the primordial gas was based on the work of Nakamura & Umemura (2001). They predict a bimodal initial mass function (IMF) for a Z=0 population. In addition to being bimodal, it is also 'top-heavy', favouring massive star formation.

Stellar yields were taken as input for the chemical evolution (CE) model. The yields of Umeda & Nomoto (2002) were used for the $150-270\,M_\odot$ range, Chieffi & Limongi (2002) for the $13-80\,M_\odot$ range, and Karakas (2003, priv. comm.) for the intermediate mass stars (nb: these were Z = 0.0001 models but played a negligible role in polluting the early cluster due to the top-heavy IMF).

Star formation occurred in a single burst, with newly synthesised elements returned on timescales prescribed by mass dependent lifetimes (Gusten & Mezger 2001). In this way the cluster gas was brought up to [Fe/H] = -1.4 , the current value (e.g. Gratton at al. 2001), from which the next generation of stars formed.

2.2. Stage 2: Pollution by 'Generation B' Stars

Stage 2 in the model sees a population of stars forming from a mix of the ejecta of the Z=0 stars (from stage 1) and Big Bang material. A standard IMF (Kroupa et al. 1993) was adopted for Generation B. However, it was assumed that the GC only retained the ejecta from stars with mass $< 7M_{\odot}$ — the winds and ejecta from SNe are assumed to have escaped the system due to their high velocities. Thus, only the yields from intermediate mass stars impact upon the chemical evolution from then on. Yields from a specifically calculated grid of models were used as self-consistent feedback in the CE model. They are described below.

3. Stellar Models: Generation B AGB Stars

3.1. The 'Standard' Set of Models

A custom-made set of low- and intermediate-mass stars were computed for the second epoch of star formation in the cluster, using the Mount Stromlo Stellar Structure Code (eg. see Frost & Lattanzio 1996) and the Monash University Stellar Nucleosynthesis Code. This generation of stars has a unique chemical composition given by the first stage of pollution - they lack nitrogen, are α-enhanced, and are low metallicity. The models (Campbell et al. 2004) were computed using the 'exact' (non-scaled-solar) composition that resulted from the evolution of the chemical pollution model described above. This required removing all scaled-solar assumptions from the codes and computing new opacity tables specifically for these stars (OPAL tables were used Iglesias & Rogers 1996). For this fiducial/standard set of models, Reimers' mass-loss law Reimers (1975) was used during the RGB and Vassiliadis & Wood's law (1993) for the asymptotic giant branch (AGB). Nuclear reaction rates were mainly taken from the REACLIB Data Tables (Thielemann et al. 1991).

3.2. Stellar Yields and The Effects of Switching Reaction Rate Compilations & Mass Loss Prescriptions

To estimate the sensitivity of the GCCE model to the various prescriptions used in the stellar model calculations, some experiments were run in which the following were altered: 1) the reaction rates for the NeNa chain, MgAl chain and $^{22}Ne + \alpha$ reactions and 2) the mass-loss formula used for the AGB evolution. Reaction rates and mass-loss are two of the key uncertainties in the stellar models. NACRE rates (Angulo et al. 1999) were used as the alternative compilation, and the mass loss laws were altered for AGB evolution (see Figure 1 caption for details). Figure 1 shows the results of both tests as compared to the yields from the standard set of models.It was found that altering the mass-loss formula on the AGB had a greater impact on the stellar yields than changing reaction rate compilations. The effects of these changes are further diluted when the yields are integrated in the CE model.

4. Results

Figure 2a compares the GCCE model results with observational data for the O-Na anticorrelation. As can be seen, the predicted variations in Na and O do not match the observations. The spread in Na is easily achieved (actually too much is produced), but the oxygen is not depleted enough. Although O is significantly depleted in the 5.0 and 6.5 $M_{\odot}$ stellar models, through HBB on the AGB, these stars are not very numerous in a standard IMF. Biasing the IMF towards higher mass AGB stars may allow the matching of the Na-O anticorrelation but the Mg-Al anticorrelation would still be a problem. This anticorrelation is not matched by the model either (Figure 2b). The spread in Al is achieved (although offset), but the Mg increases - the opposite to the observations.

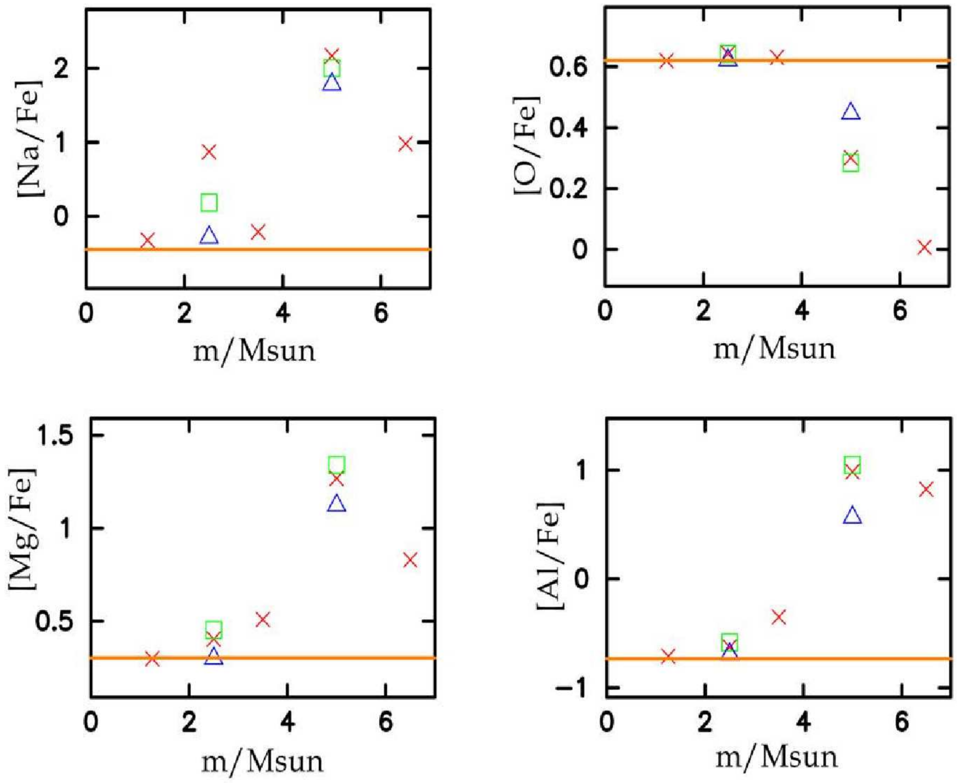

Fig. 1. Comparison of stellar model yields for selected elements. The standard set (crosses) uses Vassiliadis & Wood's (VW) mass-loss rate on the AGB and the fiducial nuclear reaction rates. The squares represent yields for the case where the NACRE rates were used in combination with the VW mass-loss (for masses 2.5 & 5 $M_{\odot}$ only). Triangles represent yields from models with our fiducial rates but use Reimers' mass-loss formula on the AGB (2.5 & 5 $M_{\odot}$). The line is the initial composition of the stars.

In addition to these problems, it is noted that HBB AGB stars are known to produce primary C (which arrives at the surface through third dredge-up, TDU). Indeed, AGB stars are predicted to enhance the abundance of C by about an order of magnitude. This alters the sum of $C + N + O$ in the polluting material (which CNO cycling alone does not do). Therefore, if it is these stars suppling the material for the GC pollution, we would expect a variation in the sum of $N_C + N_N + N_O$ from star to star, depending on the amount of polluting material each has recieved. The CE model results in Figure 3 support this prediction.

However, $C+N+O$ has been observed to be constant in clusters measured so far, eg. in M4 (Ivans et al. 1999), M13 (Smith et al. 1996), & M92 (Pilachowski 1988). Thus, unless GC AGB stars do not undergo TDU, this is a strong argument against AGB pollution causing the anomalies.

5. Summary

Using detailed nucleosynthetic yields we have computed the chemical evolution of the intracluster medium in the globular cluster NGC

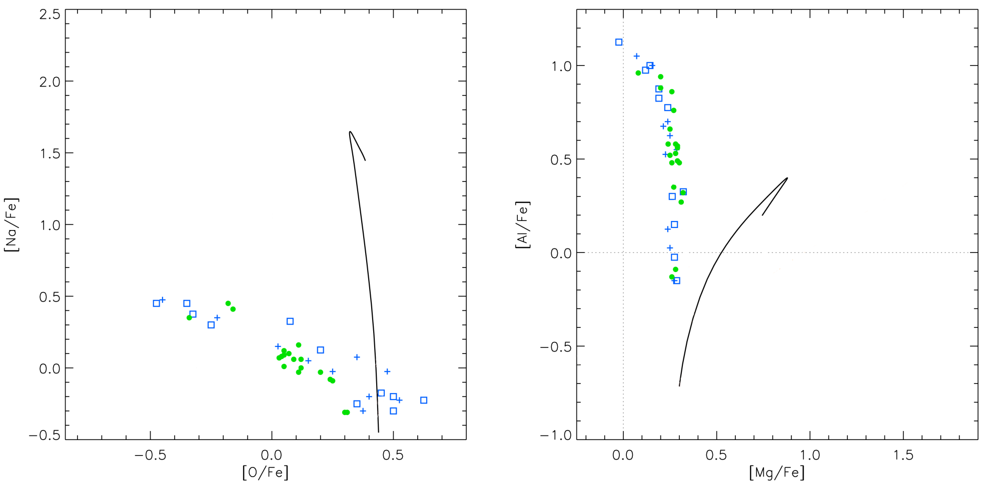

Fig. 2. Left panel: The O-Na anticorrelation in NGC 6752. The solid line is the predicted trend given by tracking the chemical evolution of the intracluster medium. Symbols are observational data from Grundahl et al. 2002 (squares represent stars brighter than the RGB bump, crosses fainter than the RGB bump). Dots are observational data from Yong et al. 2003 (RGB tip stars). **Right panel:** The Mg-Al anticorrellation in NGC 6752. Symbols are the same as Figure 2a.

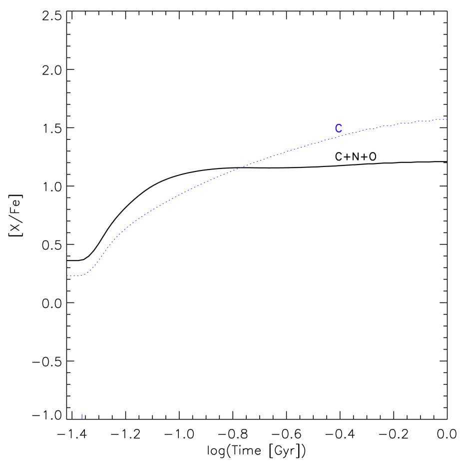

Fig. 3. The evolution of $C + N + O$ and carbon in the intracluster medium.

6752. Abundance spreads in Na and Al were found, however too much Na was produced, while the Al was offset from the observations. The O-Na and Mg-Al anticorrelations were not matched. In particular, neither O nor Mg are sufficiently depleted to account for the observations. Altering the IMF to favour more massive AGB stars may allow the matching of the Na-O anticorrelation but the Mg-Al anticorrelation would still be a problem. Furthermore, our stars bearing the imprint of AGB ejecta are predicted to be strongly enhanced in both C, N and He, also in conflict with the observational data. Thus, although the second generation intermediate-mass AGB stars do show the hot hydrogen burning (via HBB) that is required to explain the observations, this quantitative study suggests that HBB in AGB stars may *not* be the site. Changing the mass-loss prescriptions and reaction rate compilations in the stellar models does not alter this conclusion.

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