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Primordial enrichment and nitrogen abundance inhomogeneities in globular clusters

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Abstract. Globular clusters of the Milky Way tend to be markedly inhomogeneous with respect to the abundance of nitrogen, as well as other elements in the C-through-Al region of the Periodic Table. Stars within the same cluster may differ by as much as a factor of ten in nitrogen abundance. In this paper we discuss the possibility that globular clusters became enriched in nitrogen while they were still forming stars. Idealised equations describing the possible chemical evolution of a globular cluster are presented. They are used to elucidate several "supply and demand" requirements that must be met by a primordial enrichment model for the nitrogen inhomogeneity of these objects.

Keywords : Galaxy: abundances – globular clusters: general – stars: abundances

1. Introduction

Globular clusters (GCs) of the Milky Way are notoriously inhomogeneous with regard to the elements from carbon through aluminium, the abundances of which can differ markedly between two stars in the same cluster, even if they fall side-by-side in a colour-magnitude diagram and have the same effective temperature, surface gravity, and [Fe/H] abundance. Inhomogeneities are the rule rather than the exception regarding the elements C, N, O, Na, Mg, and Al. The properties of these abundance inhomogeneities have been covered in a number of reviews, including Kraft (1979, 1994), Freeman & Norris (1981), Smith (1987), Da Costa (1998), Salaris *et al.* (2002), Gratton *et al.* (2004), and

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Denissenkov (2004a). Recently, inhomogeneities in the abundance of flourine have been discovered in the cluster Messier 4 (Smith *et al.* 2005).

One of the earliest forms of abundance inhomogeneity to be found in globular clusters involves the strength of the $\lambda3883$ and $\lambda4215$ CN bands in the spectra of their red giants. At intermediate metallicities ($-1.8 <$ [Fe/H] < -1.0) the 3883 Å band is the stronger of the two. Once corrected for differences in stellar temperature and gravity, the distribution of spectroscopic CN-band strengths among red giants is bimodal in many clusters (*e.g.* Norris 1981; Norris *et al.* 1981; Smith & Norris 1982a, 1983; Briley 1997). In clusters such as 47 Tucanae and M71 a bimodal pattern of CN band strengths has been traced onto the main sequence (Cannon *et al.* 1998; Briley & Cohen 2001; Harbeck *et al.* 2003). Thus for the purposes of this paper we idealise a globular cluster as consisting of two stellar subgroups: CN-strong stars and CN-weak stars. Quantitative abundance studies have shown that CN-strong stars are typically enhanced by 0.5-1.0 dex or more in their nitrogen abundance[1] [N/Fe] relative to CN-weak stars of comparable M_V and $B - V$, while being depleted in carbon (*e.g.* Briley 1997; Briley *et al.* 1992, 1994, 2004a,b; Cohen *et al.* 2002; Da Costa & Cottrell 1980; Langer *et al.* 1985; Norris *et al.* 1981; Smith *et al.* 1996, 1997). Their enhanced CN bands are therefore due to a substantial nitrogen abundance enrichment which more than compensates for a diminished carbon abundance.

The abundances of carbon and nitrogen can be altered by nuclear reactions of the CNO bi-cycle within the hydrogen-burning shell of globular cluster red giants. The surface abundances of these elements could therefore be altered if some mechanism of mass transport (often referred to as *deep mixing*) is at work throughout the radiative zone within a cluster giant bringing CNO-processed material up to the base of the convective envelope, from where it can be moved rapidly to the surface (*e.g.* Sweigart & Mengel 1979; Langer *et al.* 1983; Denissenkov & Weiss 1996; Weiss *et al.* 2000). Much work has consequently gone into studying the extent to which cluster CNO inhomogeneities can be understood by deep mixing within CN-strong giants (*e.g.* Cavallo & Nagar 2000; Weiss *et al.* 2000; the reviews by Salaris *et al.* 2002 and Denissenkov 2004a; and references therein). However, since the discovery by Hesser (1978) that CN enhancements exist among some main sequence turn-off stars in the cluster 47 Tucanae, it has been difficult to avoid the conclusion that some component of the CN-strong phenomenon must precede the red giant phase of evolution. Since Hesser's original work, evidence of CNO and other element inhomogeneities among main sequence stars, not only in 47 Tuc but other globular clusters as well, has been steadily increasing (Hesser & Bell 1980; Bell *et al.* 1983; Briley *et al.* 1991, 1994, 2004a,b; Cannon *et al.* 1998; Cohen 1999; Briley & Cohen 2001; Gratton *et al.* 2001; Harbeck *et al.* 2003; Da Costa *et al.* 2004; Carretta *et al.* 2004). The data now clearly indicate that a substantial spread in CNO abundances is imprinted upon stars within a globular cluster either prior to their formation or during their main

[1] We adopt here the conventional spectroscopic notation $[\mathrm{A/Fe}] = \log(n_\mathrm{A}/n_\mathrm{Fe}) - \log(n_\mathrm{A}/n_\mathrm{Fe})_\odot$, where n refers to the number density of a particular element A within a stellar atmosphere, and $(n_\mathrm{A}/n_\mathrm{Fe})_\odot$ is the solar abundance ratio.

sequence phase of evolution. This CNO distribution is subsequently modified by some type of deep mixing process that occurs within the stars while they are red giants.

Various scenarios have been proposed to account for the CNO element inhomogeneities among GC main sequence stars. The CN-strong stars may have been born with similar abundances to the CN-weak ones, but then had their surface abundances altered by a subsequent acquisition of enriched gas, perhaps via accretion from a gas reservoir maintained within the cluster (D'Antona *et al.* 1983; Thoul *et al.* 2002), by mass transfer from a (former) binary companion (Bell *et al.* 1981; Denissenkov & Weiss 2001; Denissenkov 2004b), or even by the coalescence of a former companion (Campbell 1986). The former of these is sometimes referred to as a *pollution* scenario, since it may be that only the outer regions of the affected stars get enhanced. An alternative which sets the origin of the element enhancements even farther back in time is what may be termed the *primordial enrichment* scenario, in which the cluster CN-strong stars formed from gas that had already been pre-enriched in CNO-processed material by an earlier generation of stars.

The possibility that globular clusters were internally self-enriched during a very early epoch is an enticing one, in part because it evokes events that occurred very early in the history of the Galaxy, and in part because it may have ramifications for the chemical enrichment of more massive stellar systems such as dwarf galaxies. In this paper we investigate some requirements and conditions under which primordial enrichment might provide a feasible scenario for the origin of CN-strong stars in globular clusters. The CN enhancements of these stars tend to also trace inhomogeneities in other elements of the C-through-Al region of the Periodic Table. Their nitrogen overabundances tend to be correlated with enhancements in Na and Al, while being anticorrelated with both carbon and oxygen (see, for example, the reviews cited above). Consequently, we concentrate our discussions upon the element nitrogen, not only because it serves as a tracer of other elements as well, but also because it can be synthesised within stars of a wide range of mass.

2. The synthesis of nitrogen

The element nitrogen is produced by the CNO bi-cycle of hydrogen burning. This series of reactions employs carbon and oxygen as catalysts, and in the process converts both elements to nitrogen. Within the context of a primordial enrichment scenario for globular cluster CN-strong stars, we assume that they have been enhanced in CNO-processed material ejected from a former generation of stars. Depending on the initial C/O abundance ratio, the CNO bi-cycle upon attaining equilibrium can convert from 0.5 (if $n_{\rm O}/n_{\rm C} \approx 1$ initially) to more than 0.95 (if $n_{\rm O}/n_{\rm C} \sim 0$ initially) of the initial C+O atoms into ^{14}N (Caughlan 1965). Based on more modern reaction rates, material that has been fully processed through the CNO bi-cycle can be enhanced in nitrogen by a factor of 10 or more compared to the initial composition (*e.g.* Arnould *et al.* 1999). Such enhancements can be seen within the hydrogen-burning regions of stellar models ranging in mass from 0.8 $M_\odot$ (*e.g.* Sweigart & Mengel 1979; Cavallo *et al.* 1998; Weiss *et al.* 2000), through 5 $M_\odot$ (*e.g.* Iben 1966a), 9-10 $M_\odot$ (*e.g.* Iben 1966b, Denissenkov 2005), and 15 $M_\odot$ (Iben 1966c), or more.

Similar nitrogen enhancements should also be typical for the CNO bi-cycle processing of material having a Population II chemical composition. For example, suppose that in an unevolved CN-weak main-sequence star the carbon, nitrogen, and oxygen abundances are [C/Fe] = 0, [N/Fe] = 0, and [O/Fe] = +0.3, as is typical of the halo field dwarfs with [Fe/H] > -2.0 (Wheeler *et al.* 1989). The initial relative number densities of these elements is then $n_{\rm C} : n_{\rm N} : n_{\rm O} = 4 : 1 : 16$. If the abundances of these elements are altered such that carbon is diminished by a factor of 10, *i.e.* the new carbon abundance is [C/Fe] $= -1.0$, and oxygen by a factor of 2, and each of these elements are processed into nitrogen (neglecting ^{13}C production), then the new element abundance ratios will be $n_{\rm C} : n_{\rm N} : n_{\rm O} = 0.4 : 12.6 : 8$. This results in a nitrogen enhancement of Δ[N/Fe] = 1.1 dex, which is characteristic of the CN-strongest stars in bimodal-CN globular clusters. If the oxygen abundance is depleted by a greater degree, such as a factor of 10 or more, as in the 5 $M_\odot$ asymptotic giant branch (AGB) star model of Denissenkov & Herwig (2003), then the nitrogen could be enhanced by a factor of about 19 (1.27 dex).

Greater nitrogen enhancements might be generated by asymptotic giant branch stars in which not only the initial C and O content is processed into nitrogen by CNO bi-cycle hydrogen burning, but also carbon that has been produced by triple-α reactions within the He-burning shell of such stars. As a consequence, intermediate-mass AGB stars have been widely invoked as the sources of element enhancements in globular clusters (*e.g.* Cottrell & Da Costa 1981; Denissenkov *et al.* 1998; Ventura *et al.* 2001; Ventura *et al.* 2002; Yong *et al.* 2003; Ventura & D'Antona 2005a,b,c), although difficulties have been encountered in matching the precise pattern of GC element inhomogeneities with the yields of such stars (Denissenkov *et al.* 1997; Denissenkov & Herwig 2003; Herwig 2004; Fenner *et al.* 2004). Ventura & D'Antona (2005b) find that in the ejecta of an intermediate-mass star with an initial heavy element mass fraction of $Z = 0.001$, the nitrogen enhancement (averaged over time) relative to the original abundance ranges from $\Delta \log n_{\rm N} = 1.5$ to 1.0 dex as the initial stellar mass ranges from 3.0 to 6.5 $M_\odot$ respectively. The corresponding carbon depletion ranges from –0.1 to –0.8 dex. Denissenkov & Herwig (2003) used a parameterised computer code to simulate nucleosynthesis and mixing within a thermally-pulsing 5 $M_\odot$ AGB star of initial metallicity $Z = 0.0001$ and oxygen abundance [O/Fe] = 0.4. They found final envelope abundances of ^{14}N that are enhanced by $\Delta \log n_{\rm N} \approx 1.8$ dex compared to the initial abundance, depending on the temperature at the base of the outer convective envelope and the amount of mixing between this envelope and a pulse-driven convective zone between the helium-burning and hydrogen-burning shells. The models of Fenner *et al.* (2004) also show that nitrogen enhancements of this order could be obtained from enrichment driven by intermediate-mass AGB stars.

In a primordial enrichment scenario, stellar ejecta with nitrogen enhancements such as these must be combined with some amount of unenriched ambient gas to produce the nitrogen overabundances observed in globular cluster CN-strong stars.

3. A chemical evolution scenario

We make a number of assumptions in order to develop a scenario for the nitrogen enrichment of a globular cluster. Star formation within a GC is assumed to extend over a period of time long enough for chemically enriched gas to be incorporated into the formation of some fraction of cluster stars. A first generation of unenriched stars forms having the same abundance as the initial gas. At some later time within the protocluster there is assumed to be a reservoir of gas that can form a second generation of stars, namely the low-mass CN-strong stars. This reservoir is assumed to start with the same metal abundance as the first-generation stars, but is then subjected to enrichment in CNO-processed material by a hypothetical population of stars that we do not attempt to identify in this section. The primary function of this enriching population is to eject nitrogen-enhanced material into the intracluster gas reservoir prior to the onset of formation of CN-strong stars. This material is also likely to be enriched in the proton-addition element Na and possibly Al, both of which can be manufactured along with nitrogen within the CNO-burning regions of stars (*e.g.* Denisenkov & Denisenkova 1990; Langer *et al.* 1993; Cavallo *et al.* 1996, 1998). The enriched ejecta, having been processed through the CNO bi-cycle of hydrogen burning will be depleted in carbon and oxygen, as required by observations of globular cluster CN-strong stars.

The intracluster gas reservoir is not assumed to be a closed system, and we denote as G the rate at which ambient unenriched gas is made available to the cluster for star formation. Second-generation stars are taken to form at a rate S_2 by mass. The rate at which mass is lost from the CNO-processing stars that contribute to cluster enrichment is denoted $Q_{\rm cno}$. The chemical evolution of the cluster is taken to proceed on a timescale that is short compared to the main-sequence lifetimes of the second-generation stars, so that there is no recycling of gas from second-generation stars back into the intracluster gas reservoir. With these conditions the rate of change of the mass M_g of the gas reservoir is

$$dM_g/dt = G - S_2 + Q_{\rm cno}. \tag{1}$$

The evolution of the nitrogen mass fraction z in the gas is taken to be given by the equation

$$d(zM_g)/dt = Gz_1 - S_2 z + Q_{\rm cno} z_{\rm n}, \tag{2}$$

where z_1 is the nitrogen abundance of the first-generation stars, and $z_{\rm n}$ refers to the nitrogen abundance in the CNO-processed gas that is ejected by the enriching stars. The enriching stars are assumed to have initial chemical compositions the same as those of the first-generation stars within the cluster. This would be particularly likely if, for example, the enriching stars formed as part of the first cluster generation. Upon setting $z_{\rm n} = \eta z_1$, where η is taken to be a constant reflecting the degree of CNO-processing within the enriching stars, the above two equations can be combined to give

$$z(G + Q_{\rm cno}) + M_g dz/dt = z_1(G + \eta Q_{\rm cno}). \qquad (3)$$

Most of the CN-strong stars in globular clusters have nitrogen abundances that are much higher than the CN-weak stars. Consequently what is of interest here are circumstances under which equation (3) will predict a high nitrogen content in the intracluster gas right from the commencement of second-generation star formation. Equation (3) shows that the higher is the initial mass of the gas pool responsible for the second-generation stars, the lower will be the initial abundance of these stars. The optimal way of achieving high nitrogen abundances in the earliest second-generation stars is to therefore start with a minimal pool of progenitor gas so that the ejecta from the enriching stars will be only minimally diluted. To produce a substantial population of second-generation stars under such a circumstance may then require that gas be added to the intracluster reservoir as star formation proceeds. One might even speculate upon a steady-state situation in which an influx of star-forming gas is balanced by second-generation star formation.

If the second-generation stars are formed from a reservoir that starts with negligible mass ($M_g \approx 0$), then the early nitrogen abundance in the gas reservoir can be quite high

$$z_{\rm i} = z_1(G_{\rm i} + \eta Q_{\rm cno,i})/(G_{\rm i} + Q_{\rm cno,i}), \qquad (4)$$

where the subscript i refers to the initial value of a given quantity. The above equation would pertain to a situation in which the remnant of the original protocluster gas cloud sustains no chemical enrichment, but is instead expelled from the new cluster while the first generation of stars are forming. It may be that the massive first-generation stars through ionisation, stellar wind activity, and eventual supernova explosions, cause this expulsion. Once all of the first-generation supernova activity has ceased, then the protocluster begins acquiring a new reservoir of gas capable of star formation. This new intracluster gas is then assumed to become enhanced with nitrogen from a population of enriching stars. Such stars should expel their ejecta relatively quiescently so that the renewed intracluster gas pool can remain intact while forming the CN-strong stars.

A variant on this scenario would be one in which some gas remains within a cluster during first-generation star formation, but as a result of high-mass stellar activity is converted into a state incapable of star formation. After the massive stars cease supernova activity and their remnants are no longer capable of significant energy input into the intracluster gas, this reservoir may convert back to a phase in which it can again sustain star formation. At such a time, quiescent ejecta from nitrogen-enriching stars can start to be incorporated into the gas, leading to a new generation of stars that are now CN-strong. For this scenario to be viable it is required that no elements heavier than silicon from the first-generation stars get incorporated into the gas that remains within the cluster to fuel subsequent CN-strong star formation. Otherwise, the homogeneity of globular clusters that is generally seen in elements such as Ca or iron (Suntzeff 1993) would be violated.

4. Some specific solutions to the chemical evolution equation

To solve the chemical evolution equations (1) and (3) it is necessary to specify the functions $G(t)$ and $Q_{\rm cno}$ or their ratio. Since neither of these is well known for a primordial globular cluster we take the approach below of making a few additional simplifying assumptions that allow some of the more straightfoward analytic solutions to be derived.

4.1 Case A: Constant star formation and gas influx rates

One set of assumptions that allow equations (1) and (3) to be solved is to set the terms G and $Q_{\rm cno}$ to be constant, and to have the rate of formation of second-generation stars be proportional to the gas influx rate, *i.e.* $S_2 = \alpha G$, where α is a constant. Following the above discussion we further set the initial mass of the second-generation gas pool to be zero. Under these conditions equation (1) gives

$$M_g = ([1-\alpha]G + Q_{\rm cno})t. \quad (5)$$

Substituting this relation into equation (3) gives a differential equation for z in which the right-hand term is a constant

$$z(G + Q_{\rm cno}) + ([1-\alpha]G + Q_{\rm cno})t dz/dt = z_1(G + \eta Q_{\rm cno}). \quad (6)$$

This can be rewritten in the form

$$(A/D)z + t dz/dt = (B/D)z_1, \quad (7)$$

where

$$A = G + Q_{\rm cno},$$

$$B = G + \eta Q_{\rm cno},$$

and

$$D = (1-\alpha)G + Q_{\rm cno}$$

are all constants. By making a substitution of $y = \ln t$, equation (7) can be rewritten as

$$(A/D)z + dz/dy = (B/D)z_1.$$

Upon multiplying both sides by an integrating factor $e^{Ay/D}$ this equation can be further transformed into

$$d[ze^{Ay/D}]/dy = (B/D)z_1 e^{Ay/D}.$$

Integration from $t = 0$, $y = -\infty$, $z = z_{\rm i}$ to time t shows the general solution to be that z is a constant as a function of time:

$$z = (B/A)z_1 = [\eta + G/Q_{\rm cno}]/[1 + G/Q_{\rm cno}]z_1. \quad (8)$$

This expression is just what one gets for the initial abundance z_i upon setting $t = 0$ in equation (6).

Since the abundance of the intracluster gas remains constant, even as the gas mass increases with time according to equation (5), all of the second-generation stars will have the same nitrogen abundance. This scenario therefore provides one way of producing a CN bimodality within a globular cluster. The nitrogen abundance of these stars will depend in part upon the factor η, which parameterises the degree to which the ejecta from enriching stars has been subjected to CNO-processing. It will also depend on the ratio $G/Q_{\rm cno}$, which governs the degree to which ejecta from the enriching stars are diluted with the ambient gas that is becoming available to second-generation star formation. If the influx of ambient gas provides the major source for new star formation then $G \gg Q_{\rm cno}$ and $z \approx z_1$, *i.e.* the second-generation stars will have only slightly different abundances from those of the first generation. If instead, the two sources of gas contribute almost equally such that $G \approx Q_{\rm cno}$, then $M_g \approx (2-\alpha)Gt$, and $z \approx (1/2)(1+\eta)z_1$. In this case the nitrogen abundance of the second-generation stars will be an average of the abundances of the first-generation stars and the ejecta from the enriching stars. The highest abundance that the second-generation stars can attain is when $Q_{\rm cno} \gg G$, in which case $z \approx \eta z_1$, and the CN-strong stars will have a nitrogen abundance comparable to that of the enriching stars. In this case $M_g \approx Q_{\rm cno}t$, and essentially all of the gas for producing second-generation stars must come from the ejecta of the enriching stars.

4.2 Case B: Star formation balanced by gas influx

Suppose that star formation just balances the rate of arrival of gas into the intracluster reservoir, such that $dM_g/dt = 0$ and $S_2 = G(t) + Q_{\rm cno}(t)$. If $G(t)$ and $Q_{\rm cno}(t)$ are functions of time, then S_2 must be a function of time also to keep the star formation rate balanced against the gas arrival rate. If furthermore we set $M_g = 0$ at all times, then equation (3) becomes

$$z(t) = z_1[G(t) + \eta Q_{\rm cno}(t)]/[G(t) + Q_{\rm cno}(t)].$$

This equation allows $z(t)$ to be found if $G(t)/Q_{\rm cno}(t)$ are known. It reverts to equation (8) for Case A if G and $Q_{\rm cno}$ are constant. In a more realistic case, the gas term $G(t)$ may decrease with time with respect to $Q_{\rm cno}(t)$, which is set by the former generation of stars. Then $z(t)$ will increase to an eventual limit of $z \to \eta z_1$ when $G(t) \to 0$. The lower the initial value of $G/Q_{\rm cno}$ the more limited will be the range in metallicity among the second-generation stars, and the greater the difference in mean metallicity between the first- and second-generation stars.

4.3 The required enrichment for CN-strong stars

The equations for both Case A and B have a similar form showing that z depends on the enhancement factor η and the ratio of the gas influx rates $G/Q_{\rm cno}$. If we take $z/z_1 = 10$ on the basis of the observed [N/Fe] abundances of CN-strong giants, and $\eta = 20$ as representing the largest enhancement in nitrogen that can be expected from CNO-processing of an initial Population II composition mix of $n_{\rm C} : n_{\rm N} : n_{\rm O} = 4 : 1 : 16$, then equation (8) requires that $G/Q_{\rm cno} = 1.1$. Thus the gas which forms the CN-strong stars must be roughly half-and-half pristine gas plus CNO-processed gas. This places a rather restrictive limit on the degree to which the CNO-processed ejecta can be diluted with ambient gas in order to satisfy the nitrogen overabundance of the CN-strong stars. It also places constraints on the enriching stellar population, since this population must be capable of contributing substantially to the protocluster gas reservoir in order to supply enough raw material for CN-strong stars.

The restrictions are reduced somewhat if intermediate-mass AGB stars are taken to be the source of protocluster enrichment, because higher values of the enhancement factor η then become available if carbon synthesised in the helium-burning shell is further CN-cycled into nitrogen. Following the models of Denissenkov & Herwig (2003) and Ventura & D'Antona (2005b) for such stars, let us suppose that $\eta = 32$, *i.e.* nitrogen is enhanced by a factor of 1.5 dex in the ejecta of the AGB stars relative to their initial composition. A value of $G/Q_{\rm cno} = 2.4$ will then produce $z/z_1 = 10.1$ for the CN-strong stars; in this case such stars are about 29% processed material. In the case of an even more extreme enhancement of $\eta = 50$, the required enrichment of $z/z_1 = 10$ can be obtained with $G/Q_{\rm cno} = 4.4$, such that 19% of the CN-strong stars would be contributed by the enriching AGB progenitors.

5. Speculations about the enriching stars

The parameterised nature of the previous discussion did not require us to specify the type of star(s) that contributed to the nitrogen enrichment of a globular cluster. This is still a source of uncertainty for the primordial enrichment hypothesis. In this section we discuss several possible options for the enriching stars. The preceding calculations indicate that they must have been capable of producing ejecta with very high nitrogen overabundances. This leads us to first consider intermediate-mass asymptotic giant branch stars as the possible promoters of GC enrichment. As noted in Section 2, AGB stars have been considered in this context by a number of authors. Here we address a specific question: can a first generation of such stars, formed within a globular cluster, account for the total mass inferred to be present in second-generation CN-strong stars? This question has implications for the initial stellar mass function within globular clusters.

5.1 First-generation intermediate-mass cluster AGB stars

We consider here the case in which the enriching AGB stars were members of a first-generation stellar population that formed within a cluster. In other words, the cluster produced self-enrichment. The cluster stars are assumed to have formed according to a stellar mass *spectrum* that was a power-law of the form

$$dN/dm = Km^{-1-x}, \quad (9)$$

where dN refers to the number of stars formed with masses in the range m to $m + dm$, K is a constant, and a single value of x applies over the full range of stellar masses.[2] Intermediate-mass stars with masses between $m_{\rm le}$ and $m_{\rm ue}$ are assumed to have produced and ejected CNO-processed material during the asymptotic giant branch phase of evolution. This gas was then incorporated into a second generation of stars that are assumed to have formed according to a mass spectrum identical to that of the first generation. The total mass initially incorporated into the enriching intermediate-mass stars is

$$M_{\rm E} = M_1 \left(\frac{m_{\rm ue}^{1-x} - m_{\rm le}^{1-x}}{m_{\rm u}^{1-x} - m_{\rm l}^{1-x}} \right),$$

where $m_{\rm l}$ and $m_{\rm u}$ are the lower and upper limits to the mass spectrum of the first (and second) generation stars, and M_1 is the total mass of first-generation stars. The number of these first-generation enriching stars is

$$N_{\rm E} = M_1 \left(\frac{x-1}{x} \right) \left(\frac{m_{\rm ue}^{-x} - m_{\rm le}^{-x}}{m_{\rm u}^{1-x} - m_{\rm l}^{1-x}} \right).$$

If all of these stars leave white dwarf remnants of equal mass $m_{\rm wd}$, then the combined mass ejected by them is

$$M_{\rm ej} = M_{\rm E} - m_{\rm wd} N_{\rm E}.$$

This is the *maximum* amount of CNO-processed material that can be contributed to the second generation of stars.

In a bimodal-CN globular cluster the number of CN-strong giants tends to be comparable to the number of CN-weak giants, although cluster-to-cluster variations in this ratio are certainly seen (*e.g.* Norris 1987). Furthermore, in the bimodal-CN cluster 47 Tucanae, CN-strong stars appear to be as common as CN-weak stars along the upper main sequence (*e.g.* Harbeck *et al.* 2003). In the case of a globular cluster in which the CN-strong stars are equal in number to first-generation (CN-weak) stars along the entire main sequence, the combined mass of present-day second-generation stars that must be accounted for is

$$M_{\rm 2p} = M_1 \left(\frac{[0.8\ M_\odot]^{1-x} - m_{\rm l}^{1-x}}{m_{\rm u}^{1-x} - m_{\rm l}^{1-x}} \right),$$

[2]Equation (9) corresponds to a stellar mass *function* of the form $dN/d\log m \propto m^{-x}$, such that x is equal to the exponent of the mass function.

where the main sequence turn-off mass is taken to be 0.8 $M_\odot$.

If the enrichment scenario is to be viable, then a substantial fraction of $M_{\rm 2p}$ must be composed of ejecta from the first-generation enriching stars. This in turn provides a constraint on the type of stellar mass spectrum that is required. In the preceding section it was found that for typical Population II CNO-processed material (with η from 20 to 30) values of $G/Q_{\rm cno}$ from 1.1 to 2.4 were required for the CN-strong stars. This means that the mass ratio $M_{\rm ej}/M_{\rm 2p}$ is required to have a value either >0.3 or >0.5. The mass ratio $M_{\rm ej}/M_{\rm 2p}$ is plotted versus the power-law index x in Figure 1 for several combinations of $m_{\rm le}$ and $m_{\rm ue}$. All of the calculations adopt $m_{\rm l} = 0.1$ $M_\odot$, $m_{\rm u} = 60.0$ $M_\odot$, and $m_{\rm wd} = 1.0$ $M_\odot$. Mass ratios are shown for the two cases ($m_{\rm le}$, $m_{\rm ue}$) = (4.5, 6.0) $M_\odot$ and (3.0, 7.0) $M_\odot$. In the latter case, if an AGB-star primordial scenario requires that $M_{\rm ej}/M_{\rm 2p}$ >0.5 then the stellar mass function exponent x must be less than 0.9, while in the former case $x < 0.5$ is mandated. The need for relatively low values of x in a primordial enrichment scenario has previously been discussed by Smith & Norris (1982b), Briley *et al.* (2001), and D'Antona (2003).

Whether globular clusters actually formed stars with mass functions that satisfied these enrichment criteria is difficult to say. Such mass functions are not typical of the Galactic local field star population (*e.g.* Kroupa 2001). By contrast, the mass functions observed today among main sequence stars in Milky Way globular clusters typically have exponents in the range $-1.0 < x < 1.35$ (*e.g.* the compilation by Djorgovski *et al.* 1993). Negative values of x are often attributed to the evaporation of stars by dynamical relaxation or tidal stripping induced by the Galaxy (*e.g.* Piotto & Zoccali 1999; Koch *et al.* 2004), and consequently may not be representative of the initial mass function. The range of mass functions among globular clusters may be linked to dynamical evolution effects (Capaccioli *et al.* 1991; Djorgovski *et al.* 1993). Several clusters with well-known CN-bimodalities include NGC 6752 ($x = 0.3$), M3 ($x = 1.35$), and M13 ($x = 1.0$), where the quoted values of x are those derived for the global mass function by Djorgovski *et al.* (1993). If these values were characteristic of the initial mass function up to stellar masses above 10 $M_\odot$, then an intermediate-mass AGB-star enrichment scenario might be feasible for NGC 6752, but not for M13 and M3.

Similar constraints on x result if we consider the carbon abundance depletions that are commonly found in globular cluster CN-strong stars. In the archetype bimodal-CN cluster NGC 6752, the [C/Fe] abundance in the CN-strong giants is 0.3 dex less than in the CN-weak giants (Da Costa & Cottrell 1980; Norris *et al.* 1980), *i.e.* the carbon abundance in the CN-strong giants is half that of the CN-weak giants. If the CN-strong giants are an admixture of pristine (first-generation) gas plus CNO-processed gas in which there is no carbon, then $M_{\rm ej}/M_{\rm 2p} = 0.5$ is again required, leading to similar constraints on the mass function exponent x as found previously[3]. In the cluster M13 the situation

[3]We have ignored in these calculations the possibility that significant numbers of CN-strong stars might have formed with masses greater than that of the present-day main sequence turnoff. If such was

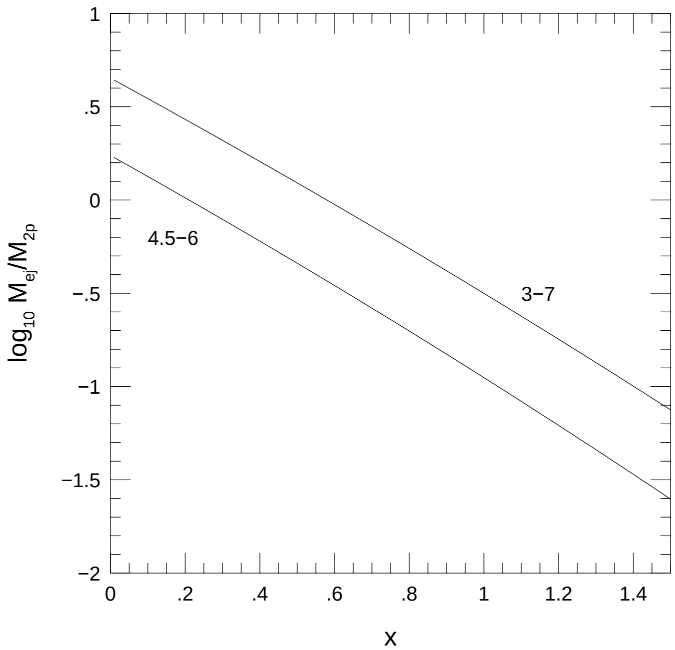

Figure 1. The ordinate gives the ratio $M_{\rm ej}/M_{\rm 2p}$ discussed in the text, where $M_{\rm ej}$ is the total mass of gas ejected by various first-generation AGB stars within a globular cluster, and $M_{\rm 2p}$ is the mass of second-generation cluster stars still on the main sequence. The diagram shows how this ratio depends upon the stellar mass distribution. Both generations of stars are assumed to have identical mass distributions of the form $dN/dm \propto m^{-(1+x)}$, with the parameter x being plotted along the abscissa. The number of second-generation main sequence stars with masses less than 0.8 $M_\odot$ has been set equal to the number of first-generation stars in the same mass regime. Two curves are shown, corresponding to mass ranges for the AGB stars of 4.5-6.0 $M_\odot$ and 3.0-7.0 $M_\odot$.

with regard to carbon depletions in the CN-strong stars may require even more extreme mass functions, because in this case the difference in [C/Fe] between CN-weak and CN-strong main sequence stars may be much greater than 0.3 dex (Briley *et al.* 2002; Briley *et al.* 2004a).

The constraint which Figure 1 imposes on the initial mass function of a globular cluster is implicitly based on the assumption that all of the ejecta from the first-generation intermediate-mass AGB stars was completely CNO processed, and became entirely incorporated into the second generation stars. The required values of x become even lower if only a small fraction of the ejecta mass $M_{\rm ej}$ was mixed into the sites of second-generation

the case, then even smaller values of x would need to be invoked to accommodate the enrichment by cluster intermediate-mass AGB stars.

star formation. A factor that will provide some partial counterbalance to this effect is that the main sequence mass functions in globular clusters show a flattening out among stars less massive than $\approx 0.33\ M_\odot$ (Paresce & De Marchi 2000). This reduces the total mass $M_{2\mathrm{p}}$ of second-generation enriched stars to be formed. Nonetheless we are still faced with an uncertainty as to whether the values of x derived today among main sequence stars with masses less than $0.8\ M_\odot$ were relevant for stars with initial masses more than $3\ M_\odot$.

5.2 Alternatives to cluster AGB star enrichment

If a first generation of intermediate-mass AGB stars within a cluster such as M13 was unable to produce all of the CNO-processed material contained in a second-generation of CN-strong stars, where else might such material have come from? There are several possibilities that we wish to mention. Firstly, CNO-processed gas may have been ejected by more massive first-generation stars (with masses greater than $8\ M_\odot$) that were formed *within* the cluster. Secondly, enriched material might have originated from a large number of intermediate-mass AGB stars that formed in sites *exterior* to the protocluster, but contemporaneously with the first-generation cluster stars. Thirdly, novae have the potential of contributing CNO-processed material.

5.2.1 *Massive WN star enrichment*

The CNO process of hydrogen burning acts within a wide range of main sequence stars. So in principle there may be more sources for N-rich ejecta within protoclusters than just intermediate-mass AGB stars. Among massive stars, possible sources include Wolf-Rayet stars of the N sequence. A WN star is thought to originate as a massive O star. Stellar winds remove the original outer envelope of the star that has not been subjected to hydrogen-burning, exposing interior regions in which nitrogen has been produced via the CNO bi-cycle reactions. This nitrogen-rich material is then progressively ejected by the stellar wind until carbon-rich regions are exposed where triple-α helium burning has occurred. The star then enters the WC stage (*e.g.* Conti 1976; Maeder 1991; Lamers *et al.* 1991).

Wolf-Rayet stars are thought to be significant sources of helium and carbon for Galactic chemical enrichment, but their contribution to nitrogen enrichment is considered to be relatively minor by comparison with AGB stars (*e.g.* Dray *et al.* 2003). However, since they could eject nitrogen-rich material into a young cluster well before intermediate-mass AGB stars can contribute, they may have been the earliest available source of cluster nitrogen enhancement. Brown & Wallerstein (1993) discussed WR stars as possible sources for C, N, Na and Al enrichment of the massive globular cluster ω Cen, and Wallerstein, Leep, & Oke (1987) extended this to include the CNO elements in the bimodal-CN globular clusters M4 and M13.

Low metallicities are thought to inhibit the radiatively-driven stellar winds of massive stars that are needed to expose the CNO-processed interior. This is because the mass-loss rates depend upon wind opacity and hence the metal abundance (Kudritzki & Puls 2000; Vink & de Koter 2005). Comparisons between the incidence of WR stars in the Large Magellanic Cloud and the Small Magellanic Cloud (SMC) suggest that at the lower metallicities of the later galaxy, only the highest-mass stars have winds strong enough to lead to a WN phase of evolution (Massey & Duffy 2001). The minimum initial mass required for entering a WN phase may be as high as 65 $M_{\odot}$ in the SMC (Massey *et al.* 2003). The calculations of Dray & Tout (2003) indicate that at a metallicity of [Fe/H] < -1.7, stars with initial masses of ≤ 50 $M_{\odot}$ will not go through a WN phase without the occurrence of some form of mass loss in addition to a radiatively-driven wind. Lower mass O stars can become WR stars if they are members of a binary system and lose their outer hydrogen-rich envelope due to mass transfer. The viability of a WN-induced enrichment scenario for globular clusters may well depend on such an alternative avenue for mass loss from massive proto-GC stars, as well as a high upper limit to the initial stellar mass function. It is worth noting in this context that WR stars, both WN and WC, have been found in some low-metallicity blue compact dwarf galaxies, such as I Zw 18 (Izotov *et al.* 1997, Brown *et al.* 2002), which has a metallicity of $Z_{\odot}/50$.

5.2.2 *Non-cluster enriching stars*

If globular clusters formed from condensations that were themselves part of much larger gas complexes, then AGB and other stars exterior to a protocluster may have been able to contribute enriched gas that was ultimately transported into the site of cluster star formation. This postulates that protoclusters were not closed systems, but may have had extended periods of star formation during which gas could have been acquired from a greater environment. In fact, an equivalent assumption was made in Section 2 by allowing the initial mass of the gas reservoir that forms CN-strong stars to be zero; an inflow of gas into the protocluster is then required, unless the ejecta from the first-generation cluster stars can alone provide all of the raw material needed for second-generation star formation.

5.2.3 *Novae*

Another possible site for nitrogen synthesis could be novae, as discussed within the context of globular clusters by Smith & Kraft (1996). In the material accreted onto a white dwarf from a binary companion, nitrogen synthesis can proceed via the hot CNO cycle in a thermonuclear runaway. These events can lead to the CNO bi-cycle occurring at temperatures in excess of 10^8 K. Depending on the manner in which temperature varies with time and the degree of convective mixing within the accreted layer on the white dwarf, Lazareff *et al.* (1979) find that ^{14}N enhancements in excess of 25 times can be achieved.

6. Summary and discussion

The above discussions have highlighted two challenges posed to a primordial enrichment scenario. The first is what might be termed a *dilution constraint*, and the second is a consequent *supply* problem. A dilution constraint results from the very large nitrogen over-abundances of the CN-strong stars. As discussed in Section 4.3, the observed over-abundances imply that the ratio of CNO-processed to unprocessed material incorporated into CN-strong stars must have been very high. The factor of ten enhancement in nitrogen found in some CN-strong giants approaches the maximum N enhancement achievable through CNO-processing of material initially having a composition typical of Population II field stars. Therefore, CNO-processed material from an enriching stellar generation cannot have been diluted with large proportions of unprocessed gas prior to the formation of second-generation stars. However, for stellar mass functions with $x > 0.6$ there is insufficient enriched material ejected by first-generation AGB stars within a globular cluster to allow as many as one-half to two-thirds of the low-mass cluster stars to be CN-strong. This can leave a supply problem.

Various options, some already introduced above, can be offered for trying to overcome these difficulties.
(a) As noted in Section 3, the dilution problem can be minimised if the second-generation stars formed from a gas pool that initially had very little ambient (unprocessed) gas within it. If stellar ejecta were deposited within a large ambient gas pool then the resulting dilution of CNO-processed material could be too large to produce the nitrogen enhancements seen in the CN-strong stars. A more optimal situation from a dilution point-of-view would be one in which all of the original gas is removed from a protocluster after first-generation star formation. The cluster then acquires the gas needed for a second episode of star formation from the enriched ejecta of the first stellar generation, possibly combined with a new (but modest) influx of gas from the surrounding environment.
(b) A relatively flat initial mass function can be invoked for first-generation stars in response to the supply problem. Intermediate-mass AGB stars might provide enough enriched ejecta to form the required cluster CN-strong stars if they followed an initial mass function with $x < 0.6$ (as discussed in Section 5.1).
(c) It may be that second-generation CN-strong stars formed according to a mass function that differed from that of the first-generation stars. Differences could be invoked either in the value of the exponent x, or in the upper or lower limits to the stellar masses ($m_{\rm u}$ or $m_{\rm l}$). For example, in the cluster 47 Tuc, wherein CN-strong giants have so far been found down to masses of $\approx 0.6\ M_\odot$ (Harbeck *et al.* 2003), the CN-strong initial mass function might be truncated at some lower mass of $m < 0.6\ M_\odot$. The total number of CN-strong stars could then be much less than the total number of CN-weak stars, even though the two populations are equally numerous on the upper main sequence. Minimising the

number of CN-strong stars in a cluster reduces the supply of enriched ejecta needed from first-generation stars. However, such *ad hoc* assumptions leave other questions, such as why the formation of very low-mass stars should be less effective in the second cluster generation than in the first.
(d) The previous options try to avoid a supply problem by invoking certain constraints on the stellar mass function. However, it might be that the number of enriching stars was underestimated in Section 5 for reasons unrelated to the stellar mass function. For example, the stars that contributed CNO-processed gas to a cluster might have formed not only within the protocluster itself, but throughout some much greater mass of gas exterior to the cluster formation site. Such a circumstance might occur within scenarios such as those of Searle & Zinn (1978) or Harris & Pudritz (1994), in which globular clusters formed from extremely massive halo clouds. Additional regions of massive star formation may thereby have existed within close proximity to a protocluster.

Drawing upon the above suggestions we conclude by suggesting one scenario for meeting the supply and dilution difficulties. A proto-globular cluster forms out of a highly condensed sub-region of a larger cloud complex. Massive stars that form within the protocluster could drive gas out of it into the larger encompassing cloud complex by a variety of mechanisms, such as ionisation heating, stellar winds, or supernova activity. Gas is thereby cleared from the cluster interior, while the interaction of the outflowing gas with the greater cloud complex leads to shock-induced star formation in a shell surrounding the cluster. This might occur somewhat along the lines of the scenario proposed by Brown *et al.* (1991, 1995), although in their model a protocluster is surrounded by a "hot protogalactic environment." Within this shell are formed stars of intermediate or high mass which eject CNO-processed material via stellar winds during an AGB or WN phase of evolution. Some of this wind material will be directed into the interior of the shell and towards the young protocluster. Once the first-generation supernovae within the protocluster have been exhausted, and their disruptive effects have ceased, gas now starts to accrete onto the cluster from both the surrounding stellar shell and the greater cloud complex. A generation of CN-strong stars now forms from the mixture of CNO-processed material and ambient gas that is flowing into the protocluster. This scenario invokes two of the conditions noted above for maximising the nitrogen enrichment in the second-generation stars. (1) Ambient gas is added to CNO-processed gas to help overcome the supply problem. (2) The input of this ambient gas for the second generation starts from near zero, on a par with the supply of CNO-processed gas. This helps alleviate the dilution problem. This scenario employs stars external to the protocluster (Section 5.2.2) to supply CNO-processed material. If the stars which are induced to form in the shell surrounding the protocluster do so according to a more top-heavy mass function than the cluster stars themselves, then the supply requirement could be further overcome.

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