FLUORINE ABUNDANCE VARIATIONS AS A SIGNATURE OF ENHANCED EXTRA MIXING IN RED GIANTS OF THE GLOBULAR CLUSTER M4

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ABSTRACT

We show that enhanced extra mixing in low-mass red giants can result in a fluorine abundance that is correlated with abundance variations of other elements participating in H burning, such as C, N, O, and Na. This finding is used to explain the fluorine abundance variations recently found in bright red giants of the globular cluster M4.

Subject headings: globular clusters: general — stars: chemically peculiar — stars: evolution — stars: interiors — stars: late-type

1. INTRODUCTION

In many Galactic globular clusters, there are star-to-star abundance variations of C, N, O, Na, Mg, and Al, while the heavier elements show almost no dispersion (see reviews by Denissenkov 2004b; Gratton et al. 2004 and references therein). The signs of these variations, their pairwise correlations, and the constancy of the sum of C+N+O in some clusters (Pilachowski 1988; Smith et al. 1996; Evans et al. 1999) indicate that we are most likely seeing the by-products of H burning in the CNO, NeNa, and MgAl cycles. Regarding their production place and process, the most plausible explanation proposed so far is the high-temperature (T ∼ 10^8 K) burning of hydrogen at the bottom of the convective envelope in intermediate-mass (∼ 4 M_☉) asymptotic giant branch (IM-AGB) stars (D’Antona et al. 1983; Ventura et al. 2001). Some contribution to the star-to-star abundance variations in globular clusters might have also been made by the hydrogen-shell burning in low-mass (M ≲ 2 M_☉) red giant branch (RGB) stars (Sweigart & Mengel 1979; Denissenkov & Denisenkova 1990; Langer & Hoffman 1995). Regarding the present-day RGB stars, where the same abundance anomalies are observed, the former case would imply primordial abundance variations, while the latter explanation would require in situ mixing. The physical interpretation of these results is therefore significant for understanding the origin of these anomalies as well as for constraining parameters of extra mixing in RGB stars.

Recently, Smith et al. (2005b) have added ^19F to the list of nuclides whose abundances vary from star to star in globular clusters. They have found a deficit of the fluorine abundance ([F/Fe] < 0) anticorrelated with the abundance of Na in seven bright red giants of the globular cluster M4. The range of the fluorine abundance variation is ~0.8 dex. Since ^19F is effectively destroyed in the reaction ^19F (p, α)^16O in the hot-bottom H burning in the IM-AGB stars, while low-mass stars have so far been considered its net producers (Forestini et al. 1992; Jorissen et al. 1992), Smith et al. (2005b) and Ventura & D’Antona (2005b) have interpreted these measurements as a strong indication that the star-to-star abundance variations in globular clusters originated in the IM-AGB stars.

In this paper, we propose another possible interpretation of the new observational data by demonstrating that low-mass RGB stars could also produce the F-Na anticorrelation in exactly the same way as they may contribute to the global O-Na anticorrelation (Denissenkov & VandenBerg 2003; Denissenkov et al. 2006).

2. IM-AGB AND RGB POLLUTION SCENARIOS

In some globular clusters, the O-Na and Mg-Al anticorrelation and the N-Na correlation have been found not only in evolved RGB stars but also in main-sequence (MS) turnoff and early supergiant stars. Because these stars have interior temperatures that are too low for the NeNa and MgAl cycles to work, they must have abundance variations that predate the RGB phase; these are either present ab initio or reflect accretion of material from IM-AGB stars (Briley et al. 1996, 2002; Gratton et al. 2002; Ramirez & Cohen 2002; Cohen et al. 2002; Grundahl et al. 2002; Harbeck et al. 2003).

In IM-AGB stars, the envelope material processed in hot-bottom H burning is immediately delivered to the interstellar medium via a strong stellar wind. On the other hand, in RGB stars the H-burning shell is separated from the bottom of the convective envelope by a radiative zone. However, extensive spectroscopic data on the surface chemical composition of low-mass RGB stars as a function of luminosity, supported by appropriate stellar models, show that most of these stars experience some extra mixing that connects the H-burning shell with the convective envelope (Sweigart & Mengel 1979; Charbonnel 1994, 1995; Gratton et al. 2000; Denissenkov & VandenBerg 2003). Near the RGB tip, before undergoing the core He flash and becoming a horizontal-branch star, a low-mass red giant loses a considerable amount of its envelope mass with a stellar wind (D’Cruz et al. 1996), thus depositing products of the H-shell burning to the interstellar medium. In globular clusters, both the IM-AGB stars and the low-mass RGB stars more massive than the present-day MS turnoff stars (i.e., 0.9 M_☉ ≲ M ≲ 2 M_☉) have already completed their lives. So, either of them could pollute the globular-cluster interstellar medium with the ashes of H burning.

Here is a brief summary of the most important pros and cons for the IM-AGB and RGB pollution scenarios: A much higher temperature of H burning in IM-AGB stars can naturally explain the origin of the Mg-Al anticorrelation. Extra mixing in RGB stars could result in that anticorrelation only if their evolution started with a ^25Mg- and/or ^26Mg-dominated Mg isotopic composition.
and if rates of some key reactions of the MgAl cycle, e.g., $^{25}\text{Mg}(p, \gamma) ^{26}\text{Al}$ and $^{26}\text{Al}(p, \gamma) ^{27}\text{Si}$, were considerably faster compared to their recommended experimental values (Langer & Hoffman 1995; Denissenkov & Tout 2000; Denissenkov & Weiss 2001).

Unlike the RGB stellar winds, the ejecta from IM-AGB stars might have had high enough levels of He enrichment to explain both the sizable populations of He-rich MS stars in the globular clusters $\omega$ Cen and NGC 2808 and the peculiar morphologies (extended blue tails, gaps, etc.) of the horizontal branches in these and other globular clusters, such as M13 and NGC 6752, that show strong CNO and Na abundance anomalies (D'Antona et al. 2002, 2005). However, it should be noted that these interpretations require an unusually top-heavy IMF for the first generation of stars in globular clusters (e.g., D'Antona & Caloi 2004; Prantzos & Charbonnel 2006) and IM-AGB stellar models with a reduced dredge-up efficiency (Karakas et al. 2006). For $\omega$ Cen, even these assumptions seem to be insufficient (Bekki & Norris 2006).

The evolutionary timescale of IM-AGB stars is much shorter ($\sim 10^8$ yr) compared to that of low-mass stars (e.g., $\sim 4 \times 10^9$ yr for a 1.2 $M_\odot$ metal-poor star). Therefore, a central reservoir of gas lost by IM-AGB stars can be accumulated in a globular cluster before it will cross the (proto-) galactic disk and the disk ram pressure will sweep the gas out (Thoul et al. 2002). In the “standard self-enrichment scenario” (Ventura & D’Antona 2005b), it is proposed that a second generation of stars with abundance anomalies directly inherited from IM-AGB stars is formed out of this gas. In the RGB scenario, the pollution of an MS dwarf by an RGB star is considered to be most likely a result of mass transfer in a binary system (Denissenkov 2004a). Although the fraction of binaries in the present-day globular clusters is only $\sim 10\%$, it could initially be as large as $\sim 100\%$ (Ivanova et al. 2005). The binary fraction has since been decreased as a combined result of stellar evolution and dynamical binary-binary and binary–single star interactions. This model predicts that the fraction of binaries surviving in a cluster of a given age is inversely proportional to its core density. This may qualitatively explain why $\omega$ Cen and M13 have the strongest star-to-star abundance variations despite their rather low core densities. The alternative model of mass accretion by a single MS dwarf passing through the central gas reservoir fails to explain this fact (Thoul et al. 2002).

The strongest observational evidence against the RGB pollution scenario is the Li-Na anticorrelation recently discovered in MS dwarfs of the globular cluster NGC 6752 by Pasquini et al. (2005). It points out that in the most polluted MS stars with $[\text{Na/Fe}] \approx +0.7$ the Li abundance is only depleted by a factor of $\sim 2$. Whereas in our computations of extra mixing in metal-poor RGB stars the final Li abundance has never exceeded $\sim 10\%$ of its initial value, the ejecta from the new IM-AGB star models with the full spectrum of turbulence convection by Ventura & D’Antona (2005a) do contain a sufficiently high Li abundance to explain this anticorrelation.

Unfortunately, neither the AGB nor the RGB pollution scenario can quantitatively reproduce all of the observed star-to-star abundance variations in globular clusters simultaneously. For example, when destroying $^{16}\text{O}$ in the IM-AGB stars the hot-bottom burning depletes $^{24}\text{Mg}$ to an even greater extent (Denissenkov & Herwig 2003). It also keeps $[\text{C/Fe}] \approx -0.5$ (Denissenkov & Weiss 2004) when $[\text{O/Fe}]$ has been decreased from $+0.4$ to less than $-0.6$. Besides, the third dredge-up in AGB stars should increase the sum of $\text{C+N+O}$ (Fenner et al. 2004). None of these theoretical predictions is supported by observations. A more detailed critical analysis of the advantages and shortcomings of the IM-AGB pollution scenario is made by Prantzos & Charbonnel (2006). As an alternative, these authors propose winds of massive stars ($M > 10 M_\odot$) as the more attractive pollution scenario for globular clusters.

At present, IM-AGB star models are being modified toward complying with constraints imposed by the element abundance anomalies in globular clusters. In particular, Ventura & D’Antona (2005b) have succeeded in keeping the total $\text{C+N+O}$ abundance within a factor of $\sim 3$ close to its initial value when they used the IM-AGB models with convection described by the full spectrum of turbulence, as proposed by Canuto & Mazzitelli (1991), and assumed “a modest extra mixing from the base of the convective envelope.” However, although their $5 M_\odot$ metal-poor AGB model does also predict strong enhancements of the surface Na and Al abundances accompanied by sufficiently low abundances of O and F, it still destroys $^{24}\text{Mg}$ more efficiently than $^{16}\text{O}$ (see Table 1 in Ventura & D’Antona 2005a). This is at odds with observations even in the globular cluster M4, where $[\text{Mg/Fe}]$ does not show any anticorrelation with $[\text{Na/Fe}]$, while $[\text{O/Fe}]$ decreases with increasing $[\text{Na/Fe}]$ (Smith et al. 2005b).

In low-mass RGB stars, extra mixing starts to manifest itself when the H-burning shell, advancing in mass, erases the chemical composition discontinuity left behind by the bottom of the convective envelope at the end of the first dredge-up (Gratton et al. 2000; Shetrone 2003). At this moment, the evolution of red giants slows down for a while, which produces a prominent feature (the RGB bump) in the differential luminosity functions of globular clusters (Zoccali et al. 1999; Riello et al. 2003). Therefore, extra mixing in low-mass stars is said to work on the upper RGB, above this bump luminosity. Below the bump luminosity, on the lower RGB, extra mixing is thought to be shielded from the H-burning shell by a gradient in the mean molecular weight associated with the composition discontinuity (Sweigart & Mengel 1979; Charbonnel et al. 1998; Denissenkov & VandenBerg 2003), or to operate very slowly (Chamamé et al. 2005; Palacios et al. 2006).

The main problem of the RGB pollution scenario is that for the majority of upper RGB stars, the observed pattern of surface abundance anomalies can only be produced by in situ mixing that only penetrates to the outer part of the H shell, where the CN branch of the CNO cycle is operating. This is what Denissenkov & VandenBerg (2003) have called “canonical extra mixing.” They demonstrated that its depth and rate (diffusion coefficient) can be parameterized by any pair of correlated values within the close limits specified by $\Delta \log T \approx 0.19$ and $D_{\text{mix}} \approx 4 \times 10^8 \text{ cm}^2 \text{s}^{-1}$ to $\Delta \log T \approx 0.22$ and $D_{\text{mix}} \approx 8 \times 10^8 \text{ cm}^2 \text{s}^{-1}$. Here, $\Delta \log T$ is the difference between the logarithms of temperature at the base of the H-burning shell and at the maximum depth of extra mixing. Thus, canonical extra mixing can be responsible for the evolutionary decline of $[\text{C/Fe}]$ in upper RGB stars, both in the field and in star clusters. It can also explain the decrease in surface Li and $^3\text{He}$ abundances with increased $L$, the strong reduction of the $^{12}\text{C}/^{13}\text{C}$ isotopic ratio, and the slight increase in the N abundance, but it does not affect O, Na, Mg, and Al.

However, if extra mixing in upper RGB stars penetrated the H-burning shell deeper than in the canonical case, it could dredge up material deficient in O and enriched in Na (Denissenkov & Denisenkova 1990), and even in Al, under certain assumptions (Langer & Hoffman 1995; Cavallo et al. 1996; Denissenkov & Tout 2000; Denissenkov & Weiss 2001). Denissenkov & VandenBerg (2003) have proposed that in some upper RGB stars canonical extra mixing may be switched to its enhanced mode with much faster and somewhat deeper mixing. If the extra mixing in these stars is driven by differential rotation of their radiative zones, then such enhanced extra mixing could be caused by...
their spinning up as a result of tidal synchronization in close binaries (Denissenkov et al. 2006).

There is also an unexplored possibility that the depth and rate of canonical extra mixing do not remain constant along the whole upper RGB but increase toward its tip. This hypothesis is supported by the following arguments. First, observations show that in some globular clusters the anticorrelated abundance variations of C and N in red giants become larger when stars approach the RGB tip. Moreover, the values of \([\text{N}/\text{Fe}] \approx 1\) in some of these stars indicate the dredge-up of material in which not only C but also a fraction of O has been converted into N (Smith et al. 2005a). Second, at least in the globular cluster M13, the relative number of upper RGB stars with the O-Na anticorrelation increases with luminosity (Johnson et al. 2005). Note that all of the metal-poor field stars used by Denissenkov & VandenBerg (2003) to calibrate the parameters of canonical extra mixing have log \(L/L_\odot \leq 2.8\), i.e., they are located a magnitude below the RGB tip. Hence, if canonical extra mixing got enhanced within the last magnitude of the upper RGB, then Denissenkov & VandenBerg (2003) would not have seen it.

To summarize the above discussion, we think that the IM-AGB pollution scenario is the most plausible one among those proposed so far to explain the primordial (i.e., those seen on the MS) star-to-star abundance variations in globular clusters. Having said that, we remind the reader that this scenario still needs a non-standard heavy-top IMF and it fails to reproduce the observed \([^{16}\text{O}/^{24}\text{Mg}]\) ratios. On the other hand, there is direct observational evidence of extra mixing in upper RGB stars. Before these stars move onto the horizontal branch they will lose a considerable amount of their mass. In binaries, the lost mass can be accreted by their MS secondary components, thus contributing to the MS star-to-star abundance variations. Canonical extra mixing is only expected to change the surface abundances of Li, C, and N. However, the extra mixing may get enhanced either in a binary RGB star as a result of its tidal spin-up or in every low-mass star when it approaches the RGB tip. The envelope material lost by RGB stars that were slightly more massive than the MS turnoff stars in the present-day globular clusters and that experienced enhanced extra mixing in the past could be enriched in N and Na and be deficient in C, O, and, as we will demonstrate below, in F. If large amounts of that material had been accreted by globular-cluster MS dwarfs (e.g., by those that were once members of primordial binaries), then the RGB pollution scenario, being the secondary compared to the IM-AGB one, might have contributed to the star-to-star abundance variations and is therefore worth investigating.

3. \(^{19}\text{F} AND EXTR A MIXING IN UPPER RGB STARS

3.1. Model Parameters for the M4 Red Giants

The stellar evolution code, input physics, and simple diffusion model of extra mixing in upper RGB stars used here have been described by Denissenkov et al. (2006). The code has since been developed to allow studies of the pre-MS and horizontal-branch (HB) evolution. As in many other similar codes, our zero-age HB models are constructed using information about the internal structure of the RGB tip models in which the core He flash has just set in.

We have found that for a model star with the initial mass \(M = 0.83 \, M_\odot\) and helium and heavy-element mass fractions \(Y = 0.24\) and \(Z = 0.002\), our RGB evolutionary track and zero-age HB evolutionary tracks fit the color-magnitude diagram (CMD) of evolved stars in M4 reasonably well (Fig. 1). Our adjusted stellar parameters give a theoretical metallicity \([\text{Fe/H}] \approx -1.0\) and an age of evolved stars \(\approx 14\) Gyr. In Figure 1, we have applied the cluster reddening \(E(B-V) = 0.40\) and the distance modulus \((m-M)_{\text{V},0} = 12.83\). Our adopted parameters are in good agreement with those used by Alcaino et al. (1997), who fitted the M4 main-sequence CMD with a 14 Gyr isochrone of Bergbusch & VandenBerg (1992) for \(Y = 0.2388\), \([\text{Fe/H}] = -1.03\), \(E(B-V) = 0.42\), and \((m-M)_{\text{V},0} = 12.80\). The spectroscopic metallicity of M4 is \([\text{Fe/H}] = -1.18\) (Ivans et al. 1999).

3.2. \(^{19}\text{F} AND CANONICAL EXTRA MIXING

Abundance profiles of some nuclides participating in the H-shell burning, including \(^{19}\text{F}, in a bump-luminosity model star are plotted in Figure 2. The vertical line marked \(\Delta \log T = 0.19\) is shown at a depth characteristic of canonical extra mixing. The nearly vertical line at the left of the plot shows the profile for H; this coincides with the lower edge of the H-burning shell. Canonical extra mixing occurs when the H-burning shell erases the composition discontinuity at the mass coordinate \(M \approx 0.266 \, M_\odot\). Most or all stars more luminous than this would show a reduced abundance of \(^{12}\text{C}\) (Denissenkov & VandenBerg 2003). However, we see that canonical extra mixing will not change the surface abundance of \(^{19}\text{F}.

3.3. \(^{19}\text{F} AND ENHANCED EXTRA MIXING

Note that all of the seven red giants studied by Smith et al. (2005b) are located within 1 magnitude of the RGB tip (Fig. 1; asterisks). As we have already mentioned in § 2, there are some arguments supporting the idea that at least the depth of canonical extra mixing increases in the vicinity of the RGB tip. In particular, the decline of \([\text{C}/\text{Fe}]\) becomes stronger within the last magnitude of the RGB, which is accompanied by extremely high N abundances \((\text{N}/\text{Fe}) \gtrsim 1\), supposedly signifying the dredge-up...
of material with O partially processed into N (Smith et al. 2005a). Smith et al. (2005b) claim that they have found a similar decline of the C abundance \( A(12C) \) with the absolute bolometric magnitude in their M4 stars (circles with error bars in the left panel of Fig. 3).

In order to test the hypothesis that canonical extra mixing gets enhanced near the RGB tip, we have proceeded as follows. First, starting with a model at \( \log \frac{L}{L_\odot} = 1.75 \) (this value is slightly less than the bump luminosity; it corresponds to \( M_{\text{bol}} = 0.37, M_V = 0.72, \) and \( V = 13.55 \)), we have computed its evolution up to \( \log \frac{L}{L_\odot} = 2.74 \) (\( M_{\text{bol}} = -2.10, M_V = -1.37, \) and \( V = 11.46 \)). In this computation, the depth and rate of extra mixing had their canonical values \( \Delta \log T = 0.19 \) (Fig. 2) and \( D_{\text{mix}} = 4 \times 10^8 \text{ cm}^2 \text{ s}^{-1} \). Abundance profiles in the radiative zone in the final model are shown in Figure 4. After that, we have continued our stellar evolution computations toward the RGB tip with increased depth and rate of extra mixing. The parameter \( \Delta \log T \) has been reduced to 0.05, while for \( \log D_{\text{mix}} \) we have considered the following higher values: 9.2, 9.3, 9.4, 9.5, and 9.6. Looking at Figure 4, one can already conclude that such enhanced extra mixing will dredge up material in which deficits of \(^{16}\text{O}\) and \(^{19}\text{F}\) should correlate with overabundances of N and Na. Curves in the left panel of Figure 3 demonstrate how the surface C abundance declines with \( M_{\text{bol}} \) in our models with enhanced extra mixing. In Figure 5, a combined evolution of \([\text{C/Fe}]\) is shown as a function of \( M_V \) for the post–first dredge-up (dotted curve), canonical extra mixing (dashed curve), and enhanced extra mixing (solid curve) phases. Here, points with error bars are data for bright red giants of the globular cluster NGC 7006 from the work of Smith et al. (2005b), the four brightest of them having \( \frac{[\text{N/Fe}]}{[\text{Fe/Fe}]} \) (given the large uncertainties of the \([\text{C/Fe}]\) data in NGC 7006, the difference in metallicities \( [\text{Fe/H}]_{\text{NGC 7006}} - [\text{Fe/H}]_{\text{M4}} \approx -0.5 \) is unimportant for the comparison).

Interestingly, if we take the fluorine abundances measured by Smith et al. (2005b) in the M4 red giants at their face values and plot them as a function of \( M_{\text{bol}} \), we find a correlation of \( A(19\text{F}) \) with \( M_{\text{bol}} \) (circles with error bars in right panel of Fig. 3) that looks no worse than the correlation between \( A(12\text{C}) \) and \( M_{\text{bol}} \).
Even more interesting is that the curves in the right panel representing results of our evolutionary computations with enhanced extra mixing could nicely reproduce that correlation if it were real. We also find a theoretical anticorrelation between \([\text{Na/Fe}]\) and \([\text{F/Fe}]\) that is qualitatively similar to the observational one revealed by Smith et al. (2005b; Fig. 6).

It should be noted that even for the fastest extra mixing with \(\log D_{\text{mix}} = 9.6\) considered by us, the depletion of \([\text{O/Fe}]\) is not strong enough to match its observed variations in M4. Indeed, we find \([\text{O/Fe}]\) \(\approx 0.17\), while in the new data from Smith et al. (2005b) the change of \([\text{O/Fe}]\) is \(\approx -0.4\) between the M4 giants with the highest and lowest Na abundance. This discrepancy can be attributed to the simplicity of our model of extra mixing. In real stars, the mixing depth and rate are probably changing with time rather than being constant. They may also vary from star to star if there is some stochastic parameter, such as the star’s rotational velocity, that the properties of extra mixing depend on.

Dashed lines in Figures 3 and 6 show how the results of our computations change when we reduce the mixing depth from 0.05 to 0.025 (the latter value corresponds to \(M_P \approx 0.3674 \ M_\odot\) in Fig. 4) while keeping \(\log D_{\text{max}} = 9.5\). The deeper extra mixing yields \(\Delta[\text{O/Fe}] \approx -0.31\), which is closer to the observed variations. Even a stronger O depletion could be obtained if we assumed that the enhanced extra mixing started at a slightly lower luminosity. That would give more time for extra mixing to operate as the evolutionary timescale shortens toward the RGB tip.

Therefore, given the revealed \(A(19\text{F})-M_{\text{bol}}\) correlation, we propose that the fluorine abundance variations in the red giants of the globular cluster M4 may actually be a signature of enhanced extra mixing in low-mass RGB stars. Moreover, we strongly encourage spectroscopists to increase the size of the sample of bright red giants with known fluorine abundances in globular clusters, because if \(A(19\text{F})\) indeed correlates with \(M_{\text{bol}}\), this will be direct evidence of enhanced extra mixing in these stars. On the other hand, if the fluorine abundance is not found to decline with increasing luminosity near the RGB tip, this will not necessarily reject our hypothesis that its deficit is due to enhanced extra mixing in upper RGB stars. The possibility will still remain that the star-to-star abundance variations of \(19\text{F}\), like those making up the O-Na anticorrelation, were (at least partly) produced by enhanced extra mixing in the low-mass red giants that had been slightly more massive than the present-day MS turnoff stars in globular.
clusters and that had completed their lives in the past (the RGB pollution scenario).

Note that for a Salpeter IMF the total mass lost by upper RGB stars before they will arrive at the zero-age HB is comparable to the mass delivered to the interstellar medium by the IM-AGB stars (Denissenkov 2004a). This estimate assumes that every upper RGB star loses 0.2 $M_\odot$ before it undergoes the core He flash.

For comparison, our HB model stars with $(B - V) < 0.7$ on the CMD of the globular cluster M4 in Figure 1 all have $M < 0.61 M_\odot$, i.e., each of them has lost more than 0.22 $M_\odot$.

We have also examined the possibility that the F/Na anticorrelation could have been produced by larger-than-expected temperature errors. The F abundances were computed using the temperatures determined by Ivans et al. (1999), who obtained them by measuring the line-depth ratios of temperature-sensitive species following Gray & Johnson (1991). The stated random errors in the temperature were about 50 K. Using the sensitivity of the abundances to temperature, we find that the dispersion in the F or Na abundances could have been produced if the random errors in temperature were as large as 125 K. Since both lines have the same sense of temperature dependence, however, such large random errors would produce an erroneous correlation between the F and Na abundances, instead of the observed anticorrelation.

4. CONCLUSION

In this work, we have shown that the reduced abundances of $^{19}$F (i.e., $[F/Fe] < 0$) anticorrelated with $[Na/Fe]$ found by Smith et al. (2005b) in the red giants of M4 do not rule out in situ mixing on the RGB. On the contrary, they support the hypothesis that canonical extra mixing may switch to its enhanced mode when a star approaches the RGB tip. The enhanced extra mixing could result from the tidal spin-up of upper RGB stars in close binaries (Denissenkov et al. 2006). Another possibility is that canonical extra mixing gets enhanced toward the RGB tip due to some internal physical processes in single stars. We emphasize that there is observational evidence of this, one example of which could be a correlation of $[F/Fe]$ with $M_{bol}$ like that plotted in the right panel in Figure 3, provided that it is confirmed in future spectroscopic observations. At present, the reduced fluorine abundance cannot be considered as a strong argument in favor of the IM-AGB pollution scenario as the only plausible contributor to the star-to-star abundance variations in globular clusters. On the contrary, if $[F/Fe]$ is correlated with $M_{bol}$ in low-mass stars near the RGB tip, this will support the original hypothesis of Denissenkov & Denisenkova (1990) that extra mixing in upper RGB stars can penetrate the H-burning shell deep enough to dredge up material enriched not only in N but also in Na, and deficient not only in C but also in O and F. A small number of stars in the fast evolutionary phase at the RGB tip could explain the absence of field upper RGB stars in which the anticorrelated O and Na surface abundances are produced and dredged up in situ (Gratton et al. 2000).

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