CHEMICAL ABUNDANCES IN GIANTS STARS OF THE TIDALLY DISRUPTED GLOBULAR CLUSTER NGC 6712 FROM HIGH-RESOLUTION INFRARED SPECTROSCOPY

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ABSTRACT

We present abundances of C, N, O, F, Na, and Fe in six giant stars of the tidally disrupted globular cluster NGC 6712. The abundances were derived by comparing synthetic spectra with high-resolution infrared spectra obtained with the Phoenix spectrograph on the Gemini South telescope. We find large star-to-star abundance variations of the elements C, N, O, F, and Na. NGC 6712 and M4 are the only globular clusters in which F has been measured in more than two stars, and both clusters reveal F abundance variations whose amplitude is comparable to or exceeds that of O, a pattern which may be produced in M > 5 M⊙ AGB stars. Within the limited samples, the F abundance in globular clusters is lower than in field and bulge stars at the same metallicity. NGC 6712 and Pal 5 are tidally disrupted globular clusters whose red giant members exhibit O and Na abundance variations not seen in comparable metallicity field stars. Therefore, globular clusters such as NGC 6712 and Pal 5 cannot contribute many field stars and/or field stars do not form in environments with chemical enrichment histories like those of NGC 6712 and Pal 5. Although our sample size is small, from the amplitude of the O and Na abundance variations we infer a large initial cluster mass and tentatively confirm that NGC 6712 was once one of the most massive globular clusters in our Galaxy.

Subject headings: Galaxy: abundances — globular clusters: individual (Messier Number: NGC 6712) — stars: abundances

Online material: color figures

1. INTRODUCTION

The formation and evolution of our Galaxy remains one of the great unanswered questions in modern astronomy. Eggen et al. (1962) suggested formation via the monolithic collapse of a gaseous protocloud on a timescale of 10⁸ yr. Searle & Zinn (1978) challenged this notion by proposing that the halo formed through the accretion of independent fragments over a longer period, 10⁹ yr. These seminal works studied Galactic archeology using the kinematics and metallicities of stars and globular clusters in the disk and halo. Today, Galaxy formation is discussed within the context of ΛCDM cosmology and hierarchical structure formation (White & Rees 1978; Freeman & Bland-Hawthorn 2002) with the ongoing accretion of the Sagittarius dwarf galaxy being the most prominent example (Ibata et al. 1994).

Another mechanism for populating the disk and halo is through the destruction of globular clusters via tidal shocks, two-body relaxation, etc. (Gnedin & Ostriker 1997). Although the current mass in globular clusters is small, the initial globular cluster population may have been considerably larger than the present population (Gnedin & Ostriker 1997). The globular cluster Palomar 5 exhibits large tidal tails that extend over 10⁷ and contain more mass than the remaining cluster (Odenkirchen et al. 2001, 2003). Therefore, Pal 5 is in the process of being tidally disrupted and is currently contributing stars to the disk and halo.

Chemical abundances place strong constraints on the fraction of halo and disk stars that may come from disrupted globular clusters and/or the types of globular clusters that may populate the disk and halo. Specifically, every well-studied Galactic globular cluster exhibits large star-to-star abundance variations for the light elements from C to Al (Smith 1987; Kraft 1994; Gratton et al. 2004). Although the amplitude may vary from cluster to cluster, the abundances of C and O are low when N is high, O and Na are anticorrelated, as are Mg and Al. Indeed, Strömgren photometry reveals that every globular cluster has large star-to-star variations in the c₁ = (u − v) − (v − b) index at all evolutionary stages (Grundahl et al. 2000). The Strömgren u filter includes the 3360 Å NH molecular lines, and Yong et al. (2008a) recently showed that the N abundances are directly correlated with the c₁ index. Therefore, it is likely that all globular clusters possess large N abundance variations at all evolutionary stages. Although hydrogen burning at high temperatures may explain the observed abundance patterns (Langer et al. 1993; Langer & Hoffman 1995; Denissenkov et al. 1998; Karakas & Lattanzio 2003), the...
source of the nucleosynthesis and the nature of the pollution mechanism remain unknown. Intermediate-mass (\(~3–8 \, M_\odot\) asymptotic giant branch (AGB) stars were the assumed polluters owing to the mono-metallic nature of most globular clusters, even though detailed AGB models have so far mostly failed to match the observations (Fenner et al. 2004; Karaka et al. 2006a). Nevertheless, these abundance patterns seen in every cluster have rarely, if ever, been observed in field stars to date (Pilachowski et al. 1996; Gratton et al. 2000). Smith et al. (2002a) conducted a detailed abundance analysis of four bright giant stars in Pal 5 and found variations of O, Na, and Al. (No abundance measurements have been performed on stars in the tidal tails of Pal 5.) While most stars lost from a tidally disrupted cluster would be main-sequence stars, abundance variations of O, Na, and Al have now been identified on the main sequences of globular clusters (Gratton et al. 2001; Cohen & Meléndez 2005). Since no radial gradients are associated with the O to Al abundance variations (with the exception of 47 Tucanae; Norris & Freeman 1979; Briley 1997), observations of red giants in the cluster should be equivalent to observing red giants in the tidal tails. That abundance variations of O, Na, and Al are found in Pal 5 suggests that clusters like Pal 5 cannot provide many field stars and/or field stars do not form in environments with chemical enrichment histories similar to that of Pal 5. Of great interest for our understanding of Galactic and globular cluster formation would be the identification of clusters undergoing tidal disruption in which no light element abundance variations are detected.

Of the large sample of globular clusters studied by Paresce & De Marchi (2000) using the Hubble Space Telescope, all have mass functions (as inferred from their luminosity functions) which peak at 0.25 \(M_\odot\). Not surprisingly, the mass function of Pal 5 is flatter than for other clusters, which reveals significant depletions of low-mass stars that were presumably stripped by the Galactic tidal field (Koch et al. 2004). The globular cluster NGC 6712 is a small and sparse globular cluster whose mass function peaks at 0.75 \(M_\odot\) instead of at 0.25 \(M_\odot\) (de Marchi et al. 1999; Andreuzzi et al. 2001). That is, NGC 6712 is the only cluster whose mass function decreases with decreasing mass. With an orbit penetrating deep into the bulge, \(R_{\text{pericentric}} = 0.9\) kpc (Dinescu et al. 1999), tidal forces have stripped away a substantial fraction of NGC 6712’s lower mass stellar population. Calculations suggest that NGC 6712 may have lost up to 99% of its original mass (Takahashi & Portegies Zwart 2000). All that remains of NGC 6712 is a remnant core of a cluster that was probably once one of the most massive in the Galaxy. The presence of a high-luminosity X-ray source and a surprisingly large blue straggler population reinforce the idea that NGC 6712 was once much more massive and concentrated (Paltrinieri et al. 2001). Therefore, NGC 6712 has almost certainly contributed stars to the disk and/or halo. Previous abundance analyses of NGC 6712 only considered one post-AGB star (Jasniwicz et al. 2004; Mooney et al. 2004), whose composition may not reflect the composition of the cluster due to the rich nucleosynthesis occurring in the late phases of stellar evolution. In this paper, we present the first detailed chemical abundance analysis of bright red-giant stars in this tidally disrupted globular cluster.

2. OBSERVATIONS, DATA REDUCTION, AND ANALYSIS

NGC 6712 lies in the direction of the Galactic bulge in a region of high visual extinction. While the brightest giants are relatively faint at visual wavelengths (\(V \approx 13.5\)), these giants are very bright at infrared wavelengths (\(H \approx K \approx 8.3\)). Budworth (1988) measured proper motions from which membership probabilities \(>90\%\) optical (\(V \approx B \approx V\)) and infrared (\(K\)) color-magnitude diagrams were constructed using the Budworth (1988) and 2MASS (Skrutskie et al. 2006) photometry. The six brightest stars were observed using the Gemini South telescope and the Phoenix spectrophotograph (Hinkle et al. 2003) in service mode in 2007 July and August. The program stars are listed in Table 1 and the log of observations is shown in Table 2. We used the 0.35\" slit, which provided a spectral resolution of \(R = 50,000\). All program stars were observed at two positions along the slit separated by 5\" on the sky through two filters: the H6420 filter provided wavelength coverage from 15520 to 15585 Å and the K4308 filter provided wavelength coverage from 23300 to 23400 Å. The exposure times per star ranged from 520 s for the H-band observation of V10 to 36 minutes for the K-band observation of LM10. The signal-to-noise ratios (S/Ns) exceed 150 per resolution element for each setting in each star. For each observing setting on each night, our observing program included a radial velocity standard, a hot star for telluric line removal, 10 flat field exposures, and 10 dark exposures. Wavelength-calibrated spectra were produced using standard reduction procedures for infrared data described by Smith et al. (2002b) and Meléndez et al. (2003) with the IRAF\(^2\) package of programs. Examples of reduced spectra are shown in Figure 1.

Radial velocities were measured by cross-correlating the cluster spectra against the radial velocity standards. For each star, we obtained a radial velocity measure from the H band and the K band and the velocities measured from each region were in good agreement for a given star. In Table 3, we report the radial

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TABLE 1

| Star | R.A. (J2000.0) |Decl. (J2000.0) | \(B^a\) | \(V^a\) | \(J^b\) | \(H^b\) | \(K^b\) |
|------|--------------|--------------|------|------|------|------|------|
| V10 | 18 52 57.33 | 08 41 43.9 | 15.74 | 13.68 | 9.428 | 8.366 | 8.114 |
| V8 | 18 53 05.65 | 08 41 12.2 | 15.24 | 13.32 | 9.391 | 8.596 | 8.274 |
| V21 | 18 52 58.79 | 08 42 06.1 | 15.62 | 13.45 | 9.536 | 8.516 | 8.283 |
| LM5 | 18 52 59.31 | 08 41 34.5 | 15.61 | 13.63 | 9.906 | 9.037 | 8.764 |
| LM8 | 18 53 06.91 | 08 40 54.2 | 15.67 | 13.78 | 10.307 | 9.378 | 9.193 |
| LM10 | 18 53 09.38 | 08 43 12.8 | 15.44 | 13.60 | 10.265 | 9.416 | 9.217 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

\(a\) B and \(V\) magnitudes from Cudworth (1988).
\(b\) J, H, and \(K\) magnitudes from 2MASS (Skrutskie et al. 2006).

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\(^2\) IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
velocities and for our six stars we find a mean cluster radial velocity $V_{\text{rad}} = -109.0 \text{ km s}^{-1}$ ($\sigma = 5.0 \text{ km s}^{-1}$), which is in good agreement with the value in the Harris (1996) catalog (February 2003 Web version), $V_{\text{rad}} = -107.5 \text{ km s}^{-1}$, as well as the value measured by Jasiewicz et al. (2004) for their post-AGB star, $V_{\text{rad}} = -116.4 \text{ km s}^{-1}$.

The stellar parameters were derived in the following way. The effective temperature, $T_{\text{eff}}$, was calculated using the Ramírez & Meléndez (2005) $T_{\text{eff}}$ : color : [Fe/H] calibrations for giant stars. We used the $(B - V)$, $(V - J)$, $(V - H)$, and $(V - K)$ colors from the Cudworth (1988) and 2MASS (Skrutskie et al. 2006) photometry, $E(B - V) = 0.43$ (Cudworth 1988), and [Fe/H] = −1.01 from the Harris (1996) catalog. The final $T_{\text{eff}}$ was the mean of the individual $T_{\text{eff}}$ values from each color weighted by the uncertainties for each color calibration. The surface gravity, $\log g$, was determined using $T_{\text{eff}}$, a distance modulus of $(m - M)_V = 15.6$ (Harris 1996), bolometric corrections $BC(V)$ from Alonso et al. (1999) and assuming a mass of 0.8 $M_\odot$. The microturbulent velocity was determined using the following relation, $\xi_t = 4.2 - (6 \times 10^{-4} T_{\text{eff}})$, adopted from the optical analysis by Meléndez et al. (2008) of thick disk and bulge stars with comparable stellar parameters. The stellar parameters are given in Table 4.

We found that errors in the distance modulus of ±0.2 led to changes of 0.08 dex in $\log g$ and that changes of ±0.02 mag in reddening resulted in $T_{\text{eff}}$ errors of 20 K. Had we adopted the Alonso et al. (1999) $T_{\text{eff}}$ : color : [Fe/H] calibration for giant stars, our values for $T_{\text{eff}}$ would be 93 K ($\sigma = 29$ K) hotter and $\log g$ would be 0.07 dex ($\sigma = 0.05$ dex) higher. We note that the Schlegel et al. (1998) dust maps give a reddening $E(B - V) = 0.39$ and that Paltrinieri et al. (2001) find a very low value of $E(B - V) = 0.33$. Had we adopted the lowest published value $E(B - V) = 0.33$, our $T_{\text{eff}}$ would be 108 K ($\sigma = 20$ K) cooler and $\log g$ would be 0.03 dex ($\sigma = 0.04$ dex) lower. We estimate that internal uncertainties in the stellar parameters are $T_{\text{eff}} \pm 50$ K, $\log g \pm 0.2$ dex, and $\xi_t \pm 0.2$ km s$^{-1}$. While the zero point of our derived abundances would shift, the amplitude of the star-to-star abundance variation for C, N, O, F, and Na would

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![Fig. 1.— Spectra of V21 for the two wavelength regions. Lines used in the abundance analysis are indicated.](image-url)
TABLE 3
RADIAL VELOCITIES (km s⁻¹)

| Star   | 15550 Å HJD | 15550 Å Vrad | 15550 Å σ | 23330 Å HJD | 23330 Å Vrad | 23330 Å σ | Mean Vrad |
|--------|-------------|--------------|-----------|-------------|--------------|-----------|-----------|
| V10... | 2454308.7893 | −104.8       | 0.8       | 2454341.5200 | −109.8       | 0.8       | −107.3    |
| V8..... | 2454330.5523 | −106.5       | 2.0       | 2454341.5398 | −107.4       | 1.3       | −106.9    |
| V21.... | 2454330.5807 | −106.7       | 0.9       | 2454341.5577 | −108.2       | 0.4       | −107.4    |
| LM5..... | 2454330.6036 | −112.6       | 1.2       | 2454341.5753 | −117.2       | 0.6       | −114.9    |
| LM8..... | 2454330.6243 | −114.2       | 0.7       | 2454341.6055 | −115.4       | 0.5       | −114.8    |
| LM10.... | 2454330.6487 | −101.4       | 1.1       | 2454341.6389 | −103.3       | 0.5       | −102.3    |

Notes.—For the radial velocity standards, we adopted HD 203344 Vrad = −88.8 km s⁻¹ and HD 206642 Vrad = −58.0 km s⁻¹ (Barbier-Brossat & Figon 2000).

3. RESULTS

Based on optical (V vs. B − V) and infrared (K vs. J − K) color-magnitude diagrams, V8 is a likely asymptotic giant branch (AGB) star. The radial velocity and line strengths are consistent with cluster membership, as expected given the proper-motion selection criterion. For this star, the lines are considerably broader than in the rest of the sample. To match the observed spectra, the synthetic spectra for V8 were convolved with a Gaussian of width 16 km s⁻¹, which represents the combined effect of the instrumental profile (6 km s⁻¹), atmospheric turbulence, and stellar rotation. For the remaining stars, the synthetic spectra were convolved with a Gaussian of typical width 10 km s⁻¹ to match the observed spectra.

For the elements C, N, O, Na, and F, we find large star-to-star abundance variations (~0.6 dex) even within our small sample. For these elements, the amplitude of the abundance variation far exceeds the measurement uncertainties. In this respect, NGC 6712 behaves like all other well-studied Galactic globular clusters. We also find that the Fe abundance does not show any star-to-star abundance variation, although we note that the number of Fe lines available in our wavelength regions is very small. The dispersion in Fe abundances within our sample (σ = 0.04 dex) can be attributed entirely to the measurement uncertainties.

In Figure 5, we plot the abundances of N, O, F, Na, and Fe against C, as well as O vs. Na. As seen in all globular clusters, the abundances of C and N are anticorrelated and the abundances of C and O are correlated. In this figure, we fit a straight line to the data, taking into account both the x and y errors. We show the formal slope of the fitted line as well as the 1σ uncertainty in the slope. The C-N anticorrelation is significant at the 3σ level and within the grid provides accurate results. Although we are extrapolating beyond the grid, we regard the steps in surface gravity as small, Δ log g ≤ 0.26, and so we anticipate that our results should be reliable. The abundance dependences on the stellar parameters are shown in Table 5.
the C-O correlation is significant at the 4σ level. We also find that the Na abundances are anticorrelated with C at the 6σ level and that Na is anticorrelated with O at the 4σ level.

The F abundance shows a large star-to-star variation. In Figure 5, the F abundances are correlated with C at the 3σ level. Therefore, F is also correlated with O and anticorrelated with N and Na. The amplitude of the F abundance variation [$\Delta A(F) = 0.80$ dex] exceeds the amplitude of the O variation [$\Delta A(O) = 0.64$ dex]. [Given the measurement uncertainties $\sigma A(O) = 0.11$ dex and $\sigma A(F) = 0.14$ dex, O and F may have comparable abundances.]

Indeed, of the elements measured in our sample, F exhibits the largest amplitude abundance variation.

We find that the sum of C+N+O is constant in NGC 6712 within the measurement uncertainties (C+N+O is not correlated with the C abundance). Finally, we note that the Fe abundances are not correlated with C. Adopting a solar abundance $A(Fe)_0 = 7.48$, we find a mean cluster abundance $[Fe/H] = -0.96 \pm 0.02$ ($\sigma = 0.04$), which is in good agreement with previous estimates for this cluster by Zinn & West (1984), [Fe/H] = −1.01, and Jasniwicz et al. (2004), [Fe/H] = −1.2.

4. DISCUSSION

4.1. Abundance Comparison between NGC 6712 and M4

M4 is an ideal globular cluster with which to compare the chemical abundances in NGC 6712. M4 is the only other cluster in which F abundances have been measured in more than two stars (Smith et al. 2005), it has a comparable metallicity ([Fe/H]$_{M4}$ = −1.20 and [Fe/H]$_{NGC6712}$ = −1.01; Harris 1996), and the orbital parameters are very similar ($R_{apocentric}^{M4} = 5.9 \pm 0.3$ kpc, $R_{periocentric}^{M4} = 6.0 \pm 0.1$ kpc, and $Z_{apocentric}^{M4} = 1.5 \pm 0.4$ kpc and $R_{NGC6712}^{NGC6712} = 6.2 \pm 0.3$ kpc, $Z_{periocentric}^{NGC6712} = 0.9 \pm 0.1$ kpc, and $Z_{apocentric}^{NGC6712} = 0.9 \pm 0.2$ kpc; Dinescu et al. 1999). (In the globular cluster $\omega$ Cen, F has been

![Diagram](image1)

**Fig. 2.—** Observed spectra (circles) and synthetic spectra for C (top), N (middle), and O (bottom) in LM8. The synthetic spectra show the best fit (thick black line) and unsatisfactory fits (thin red and blue lines), $A(C) = 0.15$ dex, $A(N) = 0.20$ dex, and $A(O) = 0.15$ dex. [See the electronic edition of the Journal for a color version of this figure.]

![Diagram](image2)

**Fig. 3.—** Observed spectra (circles) and synthetic spectra for LM10. The lines show syntheses with different C and Na abundances. The positions of CO and Na lines are shown. [See the electronic edition of the Journal for a color version of this figure.]

![Diagram](image3)

**Fig. 4.—** Observed spectra (circles) and synthetic spectra for F in LM10 (top) and V10 (bottom). In the bottom panel, two sets of syntheses are plotted corresponding to $\log g = +0.22$ (dashed line) and 0.00 (solid line). The lines are indistinguishable, and for this element in this star the extrapolated abundance for $\log g = -0.22$ is $A(F) = 2.65$. [See the electronic edition of the Journal for a color version of this figure.]

**TABLE 5**

| Species | $T_{eff} + 50$ | $\log g + 0.2$ | $\xi + 0.2$ | Total $^a$ |
|---------|--------------|----------------|-------------|------------|
| $A(C)$ | 0.04         | 0.05           | 0.03        | 0.07       |
| $A(N)$ | 0.04         | 0.08           | 0.03        | 0.09       |
| $A(O)$ | 0.09         | −0.05          | −0.03       | 0.11       |
| $A(F)$ | 0.13         | −0.05          | 0.01        | 0.14       |
| $A(Na)$| 0.05         | −0.02          | −0.03       | 0.06       |
| $A(Fe)$| −0.03        | 0.02           | −0.02       | 0.04       |

$^a$ The total value is the quadrature sum of the three individual abundance dependences.
measured in one star and an upper limit measured in another star [Cunha et al. 2003]. However, we note that M4 may be uniquely enriched in s-process elements among the Galactic globular clusters (Ivans et al. 1999; Pritzl et al. 2005; Yong et al. 2008b), with the usual exception of ω Cen (Norris & Da Costa 1995; Smith et al. 2000).

In Figure 6 we show the abundance ranges for C, N, and O for our six stars in NGC 6712 and the seven stars in M4 (Smith et al. 2005). In both clusters, the targets are located near the tip of the red giant branch. Within the small samples, NGC 6712 may have slightly larger abundance amplitudes for C, O, and C+N+O; the abundance amplitude for C+N is very similar for these clusters, and M4 has a larger abundance amplitude for N. The mean cluster abundances are very similar for O. However, NGC 6712 may have higher mean abundances of N, C+N, and C+N+O, along with a lower mean C abundance than M4. The higher N abundances and lower C abundances in NGC 6712 relative to M4 suggests that the extent of CN cycling may have been greater in NGC 6712. However, NGC 6712 was formed from gas with higher amounts of C+N and C+N+O than M4.

In Figure 7 we show the abundance ranges for F, Na, and the ratio [O/Na] for NGC 6712 and M4. Within the small samples, NGC 6712 may have larger abundance amplitudes for F, Na, and [O/Na] than M4. The mean cluster abundances of F are in agreement; however, NGC 6712 has a higher mean Na abundance and a slightly lower [O/Na] ratio than M4, which is consistent with a higher degree of hydrogen burning via \((p,\alpha)\) reactions. Larger samples are required to fully appreciate the abundance differences between these two clusters whose orbital parameters are very similar.

4.2. F Destruction and Constraints on AGB Nucleosynthesis

The general behavior of the abundances of F with respect to C, N, O, and Na in NGC 6712 is identical to that seen in M4 (Smith et al. 2005). We reiterate that in both NGC 6712 and M4, the amplitude of the F abundance variation is comparable...
to, or exceeds, the amplitude of the $O$ variation. Therefore, any scenario invoked to explain the light element abundance variations in globular clusters must account for these large $F$ variations.

In sufficiently massive AGB stars, the base of the convective envelope can reach temperatures that permit hydrogen burning, a process called hot-bottom burning (HBB; Scalo et al. 1975). HBB can qualitatively produce the required $C$, $N$, $O$, $Na$, $Mg$, and $Al$ abundance patterns observed in globular clusters, and intermediate-mass AGB stars have long been suspected of producing the light element abundance variations (Cottrell & Da Costa 1981), although AGB models have thus far failed to match the observations (Fenner et al. 2004; Karakas et al. 2006a). An additional signature of HBB is $F$ destruction via $^{19}F(p,\alpha)^{16}O$ (Mowlavi et al. 1996; Lugaro et al. 2004; Smith et al. 2005). In contrast, low-mass AGB stars produce $F$ (Jorissen et al. 1992; Forestini et al. 1992).

If AGB stars are solely responsible for the $F$ and $O$ abundance variations in NGC 6712, theoretical yields (Karakas & Lattanzio 2003, 2007; Karakas et al. 2008) offer insight into the range of possible masses of these stars. These models indicate that $F$ may be destroyed by up to 1 dex while $O$ is destroyed by up to 0.5 dex during HBB in 5 and 6 $M_{\odot}$, $Z = 0.004$ AGB stars, in general agreement with the observations. However, $F$ destruction ceases and indeed $F$ production begins to occur again when HBB is terminated, and it is during this phase when much of the mass loss occurs. Therefore, even for the most massive stars, the AGB winds contain material with $O$ and $F$ depleted by similar amounts. The main uncertainties in these models are convection and mass loss. Convection determines the efficiency of HBB, as well as the HBB lifetime (Ventura & D’Antona 2005a, 2005b). The mass-loss rate determines when the mass is lost from the star. For example, a stronger mass-loss rate may result in more mass lost when the star was $O$- and $F$-poor but with a larger degree of $F$ depletion. From $5 M_{\odot}$ models of $[Fe/H] \sim -2.3$ computed for Karakas et al. (2006b), we estimate that the fluorine yields can vary by up to a factor of $\sim 3$ by changing the mass-loss rate. If massive metal-poor AGB stars are responsible for the $F$ and $O$ variations in NGC 6712 and M4, and if the $F$ variation exceeds that of $O$, then the models would require both stronger mass loss and more efficient convection.

Results presented by Izzard et al. (2007), which use updated NeNa and MgAl hydrogen-burning rates, gave fluorine abundances increased by a factor of 72. This last result is net production of $^{19}F$ as opposed to destruction by HBB in the former models, and serves to illustrate just how uncertain the AGB models are to variations in the input physics and to the nuclear uncertainties, especially at the range of temperatures found in the H- and He-burning shells of AGB stars. (We refer the reader to the discussions in Lugaro et al. [2004, 2008] and Izzard et al. [2007] and references therein for an overview of the current uncertainties regarding AGB model yields for fluorine and other light elements.) Additional observations of $F$ in AGB stars, such as those presented by Uttenthaler et al. (2008), as well as measurements in higher mass AGB stars are critical to constrain the AGB models.

In addition to HBB in intermediate-mass AGB stars, another possible source of these abundance anomalies is massive stars (Prantzos & Charbonnel 2006; Smith 2006; Decressin et al. 2007). While massive stars will also destroy $F$ (Prantzos et al. 2007), quantitative yields for $F$ and $O$ would be of interest to constrain all currently proposed sources of the globular cluster abundance variations. At present, the star-to-star $F$ abundance variations in NGC 6712 and M4 could be explained by pollution from either a generation of massive stars or intermediate-mass AGB stars that underwent HBB.

### 4.3. A Comparison of $[O/Fe]$ in NGC 6712 with the General Bulge Trend

The $O$ abundances vary from star to star in globular clusters (e.g., Kraft 1994). Stars with high $O$ abundances also show high
Mg abundances along with low Na and Al. We refer to these stars as “normal” because comparisons have shown that the abundance patterns of these cluster stars are in accord with field stars at the same metallicity. At the opposite end of the abundance distribution in globular clusters lie the O-poor, Mg-poor, Na-rich, and Al-rich stars which we refer to as “polluted.” No field stars have been observed with compositions matching these “polluted” cluster stars. In globular clusters such as NGC 6752 (Yong et al. 2003a) and M13 (Sneden et al. 2004), the “normal” stars with the highest O abundances have [O/Fe] ratios in agreement with field stars at the same metallicity.

Following Meléndez et al. (2008), we adopt solar abundances of $\frac{\text{O}}{\text{Fe}} = 8.72$ and $\frac{\text{Fe}}{\text{O}} = 7.48$, which are similar to the Asplund et al. (2005) values based on three-dimensional hydrodynamical model atmospheres. For NGC 6712, our highest relative abundance is $\frac{\text{O}}{\text{Fe}} = 0.59$. We assume that this star is “normal” and that this O abundance is representative of the initial cluster value prior to the processes which produced starto-star variations in the light element abundances. Within the measurement uncertainties, the O abundance for NGC 6712 is comparable to the values recently measured in bulge giants by Meléndez et al. (2008), who showed through a homogeneous differential analysis that the thick disk and bulge (and halo) had $\frac{\text{O}}{\text{Fe}}$ ratios in agreement at a given $[\text{Fe}/\text{H}]$. Therefore, we tentatively conclude that the $[\text{O}/\text{Fe}]$ ratio in “normal” giants in NGC 6712 is in agreement with the general bulge trend (and halo stars at the same metallicity).

4.4. A Comparison of Fluorine in NGC 6712 with Other Galactic Populations

The fluorine abundances measured in NGC 6712 are now compared to those from other samples of Galactic stars, which include field stars (Cunha et al. 2003; Cunha & Smith 2005), along with bulge red giants (Cunha et al. 2008), as well as the measurements for the globular clusters M4 (Smith et al. 2005) and $\omega$ Cen (Cunha et al. 2003). As is the case for oxygen, the assumption is made that the highest fluorine abundances in NGC 6712 (as well as for M4) represent the initial cluster value prior to the processes which produced the globular cluster star-to-star abundance variations. In Figure 8 are plotted the abundances of $\frac{\text{F}}{\text{O}}$ versus $\frac{\text{O}}{\text{Fe}}$ (top panel) and $\log \frac{\text{N}(\text{F})}{\text{N}(\text{O})}$ versus $\frac{\text{O}}{\text{Fe}}$ (bottom panel) for all stars from the various studies. As a first point of comparison, it is found that the most F-rich stars in NGC 6712 (and in M4) are underabundant in fluorine when compared to most of the bulge and field stars that have comparable values of $\frac{\text{O}}{\text{Fe}} \sim 8.2-8.4$ (here oxygen is used as a proxy for metallicity). Most of the field stars and bulge stars fall along a similar distribution in the $\frac{\text{F}}{\text{O}}$ versus $\frac{\text{O}}{\text{Fe}}$ diagram, while the globular cluster stars seem to define a different trend.

The straight lines shown in the top panel of Figure 8 represent linear fits to the globular cluster data and, in addition, fits to the field plus bulge star points; extrapolations of these lines do not intersect, which confirms the impression that the globular clusters have a distinct mixture of F and O abundances when compared to the field and bulge stars. This observation is based on the stellar samples studied to date, with a still small metallicity overlap; the behavior of fluorine in the field has not been probed below oxygen abundances $\frac{\text{O}}{\text{Fe}} \sim 8.4$. However, to have a single distribution, or curve, of $\frac{\text{F}}{\text{O}}$ to $\frac{\text{O}}{\text{Fe}}$ fit both sets of data (field and globular clusters) would require a rapid, nearly discontinuous drop of about 0.8 dex in the fluorine abundance near an oxygen abundance of $\frac{\text{O}}{\text{Fe}} \sim 8.2-8.4$. It is also noted that the rather oxygen-rich bulge giant (BMB 78) studied by Cunha et al. (2008), with $\frac{\text{O}}{\text{Fe}} = 9.0$ but a low F abundance of $\frac{\text{F}}{\text{O}} = 4.26$, falls along the line extrapolated from the globular cluster stars.

Another way to compare F and O abundances is shown in the bottom panel of Figure 8, with the ratio of F/O plotted as a function of the oxygen abundance. Here again there appears to be a rather sharp, near discontinuity in the values of F/O in the globular clusters in comparison to the field and bulge stars near $\frac{\text{O}}{\text{Fe}} \sim 8.3$. In the globular clusters, the values of F/O remain nearly constant as the oxygen abundance varies, which is due to the depletion of both $^{16}\text{O}$ and $^{19}\text{F}$ by the H-burning processes that shape the peculiar chemical evolution found in the globular clusters; inspection of the F and O abundances in both M4 and NGC 6712 reveals nearly equal decreases in both $^{19}\text{F}$ and $^{16}\text{O}$ (as expected to occur in only the most massive AGB stars, as discussed above), which results in nearly constant ratios of F/O within the cluster stars. Note that Figure 2 in Cunha et al. (2008) shows predictions for $^{19}\text{F}$ production via neutrino nucleosynthesis in Type II supernovae taken from the Woosley & Weaver (1995) models, as well as the approximate downward revisions to the fluorine yields as suggested by Heger et al. (2005). Neutrino nucleosynthesis predicts values of $\log \frac{\text{N}(\text{F})}{\text{N}(\text{O})} \sim -5.0$ for models with oxygen abundances of about $\frac{\text{O}}{\text{Fe}} = 8.4$, which matches the envelope of values found for the stars in NGC 6712, M4, as well as the two stars studied to date in $\omega$ Cen.
Within the uncertainties in the measurements, along with the models, it is suggested that the $^{19}\text{F}$ observed in the globular clusters could have been created by neutrino nucleosynthesis alone (with the fluorine arising mostly from core-collapse neutrinos spalling $^{20}\text{Ne}$). The increased values of F/O found in the field and bulge stars require additional sources of $^{19}\text{F}$, which have been discussed and modeled by Renda et al. (2004) and discussed in Cunha et al. (2008), and consist of Wolf-Rayet winds (whose yields of fluorine increase substantially with stellar envelope metallicity), along with thermally pulsing AGB stars. Such a picture would suggest that the globular clusters are less polluted by Wolf-Rayet winds and low-mass AGB stars (AGB stars with $M > 2 - 3 M_\odot$ destroy $^{19}\text{F}$) than either the bulge or field stars with metallicities greater than about 1/3 solar. If the globular clusters represent the remnants of systems that formed from gas that was chemically seeded by very metal-poor Type II supernovae, the low values of F/O represent the “chemical memory” of this enrichment.

Although “normal” globular cluster stars have compositions that are indistinguishable from field stars at the same metallicity, as discussed above, $^{19}\text{F}$ is an exception. Another exception is represented by the minor isotopes of Mg, whose ratios $^{25}\text{Mg}/^{24}\text{Mg}$ and $^{26}\text{Mg}/^{24}\text{Mg}$ in “normal” cluster stars exceed the values found in field stars at the same metallicity (Shetrone 1996; Yong et al. 2003a, 2003b, 2006). While the contribution, or absence, of Wolf-Rayet winds and/or low-mass AGB stars provides a plausible explanation for the F discrepancy as discussed above, the situation for the Mg isotopes is less clear. One explanation is that the entire globular cluster was polluted by intermediate-mass AGB stars, which raised the low abundances of $^{25}\text{Mg}$ and $^{26}\text{Mg}$ provided by supernovae (Fenner et al. 2003) to the high levels observed.

Finally, the bulge star BMB 78, with unusually low F, may be an O-rich star whose F abundance could be attributed solely to neutrino nucleosynthesis (i.e., the F in this star has experienced little or no contribution from Wolf-Rayet or AGB stars). As discussed by Cunha et al. (2008), this star could therefore have important implications for the inhomogeneous chemical evolution of the bulge. An additional, and highly speculative, explanation for the unusual F and O abundances in BMB 78 is that this star was born in a globular cluster but was subsequently stripped away.

### 4.5. Light Element Abundance Variations and Implications for Galactic Formation

Star-to-star abundance variations for the light elements have been found in every well-studied Galactic globular cluster. Such abundance patterns are the signature of hydrogen burning at high temperatures. The currently favored candidates are intermediate-mass AGB stars and massive stars. Our abundance measurements in NGC 6712 provide new and critical information. Specifically, the F abundance is found to vary from star to star with an amplitude comparable to, or possibly exceeding, that of O. Therefore, the two globular clusters in which F has been measured in more than two stars both show large abundance variations.

The fact that NGC 6712 exhibits large star-to-star abundance variations of the light elements has implications for Galactic formation. The current mass in globular clusters is small, but in the past there may have been many more clusters. Some fraction of field stars may have been born in globular clusters that were subsequently destroyed by the Galactic tidal field. However, the abundance signature of globular clusters, O, F, Na, Mg, and Al variations, has never been observed in field stars to date. (C and N variations are found in field halo stars as well as cluster stars [e.g., Gratton et al. 2000] and can be attributed to internal nucleosynthesis and mixing with the observed stars.) Current estimates suggest that globular clusters comprise roughly 2% of the mass of the stellar halo (Freeman & Bland-Hawthorn 2002). If we arbitrarily assume that one globular cluster was destroyed for every surviving cluster (i.e., the initial globular cluster population was double the current population), then for every 50 field halo stars observed, only 1 star would come from a disrupted globular cluster. However, not every star in a given globular cluster has peculiar O, F, Na, Mg, and Al abundances with respect to field stars at the same metallicity (e.g., see the earlier discussion on “normal” stars). If we arbitrarily assume that half the stars in globular clusters have distinct abundances of O to Al relative to field stars at the same metallicity, then 100 field halo stars need to be observed to find one star whose chemical abundances indicate that it was born in a globular cluster. Nevertheless, no field halo stars have been identified that show large Na and Al enhancements along with large O depletions. Gratton et al. (2000) investigated a large sample of 105 stars with $-2 \leq [\text{Fe/H}] \leq -1$, and so the nondetection of the globular cluster abundance anomalies in field stars is not due to a lack of effort (although larger samples may be needed). NGC 6712 and Pal 5 are tidally disrupted globular clusters which have almost certainly contributed stars to the disk and halo. Both clusters show large abundance variations for light elements, which suggests that clusters such as NGC 6712 and Pal5 cannot have provided many field stars and/or field stars did not form in environments with chemical evolution histories like those of NGC 6712 and Pal 5.

### 4.6. Constraints on the Initial Cluster Mass from Abundance Variations

Based on the present-day luminosity function, the high-luminosity X-ray source, and the large blue straggler population, it is highly likely that NGC 6712 was initially considerably more massive (de Marchi et al. 1999; Andreuzzi et al. 2001; Paltrineri et al. 2001). Indeed, calculations by Takahashi & Portegies Zwart (2000) suggest that NGC 6712 may have lost 99% of its initial mass such that it might have been one of the most massive clusters that ever formed in the Galaxy, $M_{\text{initial}} \sim 10^7 M_\odot$.

For eight well-studied globular clusters, Carretta (2006) compared the interquartile range (IQR) for $[\text{O/Fe}]$, $[\text{Na/Fe}]$, $[\text{O/Na}]$, and other abundance ratios with various physical parameters and found that the amplitude of the abundance variation shows a dependence on cluster mass, as inferred from the absolute magnitude. Presumably the light element abundance variations in NGC 6712 (and in all clusters) originated early in the life of the cluster. Therefore, the currently observed abundance variations offer an independent estimate of the original mass of NGC 6712.

Our measured values are $\text{IQR}[\text{O/Na}] = 0.85$, $\text{IQR}[\text{O/Fe}] = 0.59$, and $\text{IQR}[\text{Na/Fe}] = 0.55$ (adopting solar values of $A(\text{O})_\odot = 8.72$, $A(\text{Na})_\odot = 6.17$, and $A(\text{Fe})_\odot = 7.48$). Since our sample size is small, we may be underestimating (or overestimating) the true IQRs. We fit a straight line to the Carretta (2006) data and find that the IQRs for $[\text{O/Na}]$, $[\text{O/Fe}]$, and $[\text{Na/Fe}]$ in NGC 6712 correspond to absolute magnitudes of $-9.6$, $-12.7$, and $-11.4$, respectively. While such an analysis is far from robust, inspection of Figures 12 and 13 in Carretta (2006) indicate that NGC 6712 should be a very massive cluster based on the IQRs for $[\text{O/Fe}]$, $[\text{Na/Fe}]$, and $[\text{O/Na}]$. The two most massive globular clusters, ω Cen and M54, have absolute magnitudes $-10.29$ and $-10.01$, respectively, and both clusters are regarded as the nuclei of accreted dwarf galaxies. Despite our small sample size, which may not measure the true IQRs, it is likely that NGC 6712 was initially one of the most massive clusters in our Galaxy, as inferred from the large-amplitude light element abundance variations. Of great interest would be the analysis of a larger number of elements in
a larger sample of stars in NGC 6712 to identify abundance similarities with the massive globular cluster ω Cen. Given the narrow RGB sequence (Cudworth 1988), a star-to-star spread in Fe seems unlikely.

5. CONCLUDING REMARKS

Based on high-resolution infrared spectra, we derive abundances of C, N, O, F, Na, and Fe in six giant stars of the tidally disrupted globular cluster NGC 6712. For the elements C, N, O, F, and Na, we find large star-to-star abundance variations and correlations between these elements, a characteristic that NGC 6712 shares with every well-studied Galactic globular cluster. This is only the second cluster in which F abundances have been measured in useful numbers of stars, and both clusters show F variations whose amplitude is comparable to, or exceeds, that of O. Within the limited data, globular clusters appear to have lower F abundances than field and bulge stars at the same metallicity. Of great interest would be measurements of F in additional stars in ω Cen and other globular clusters, as well as in larger samples of field stars, with both samples overlapping in metallicity. From the amplitude of the O and Na abundance variations, we tentatively confirm that NGC 6712 was once one of the most massive clusters in our Galaxy.

NGC 6712 is a tidally disrupted cluster, as revealed through its highly unusual luminosity function. Pal 5 is another tidally disrupted globular cluster. Both NGC 6712 and Pal 5 have almost certainly contributed stars to the disk and halo. Both clusters exhibit large star-to-star abundance variations for light elements, a characteristic which has yet to be identified in field halo stars. Therefore, the light element abundance variations detected in NGC 6712 indicate that clusters such as NGC 6712 and Pal 5 have not provided many field stars, and/or field stars did not form in environments with chemical enrichment histories like those of NGC 6712 and Pal 5. As pointed out by Smith et al. (2002a), disrupted globular clusters such as Pal 5 have lost CN-strong, O-poor, Na-rich, Al-rich stars to the halo field. But where are these stars? Of great interest would be an abundance analysis of stars within the tidal tails of Pal 5, as well as a large-scale dedicated search for O, Na, and Al abundance anomalies in field halo stars.

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