CN Variations in High-Metallicity Globular and Open Clusters

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ABSTRACT. We present a comparison of CN band strength variations in the high-metallicity globular clusters NGC 6356 and NGC 6528 with those measured in the old open clusters NGC 188, NCG 2158 and NGC 7789. Star-to-star abundance variations, of which CN differences are a readily observable sign, are commonplace in moderate-metallicity halo globular clusters but are unseen in the field or in open clusters. We find that the open clusters have narrow, unimodal distributions of CN band strength, as expected from the literature, while the globular clusters have broad, bimodal distributions of CN band strength, similar to moderate-metallicity halo globular clusters. This result has interesting implications for the various mechanisms proposed to explain the origin of globular cluster abundance inhomogeneities, and suggests that the local environment at the epoch of cluster formation plays a vital role in regulating intracluster enrichment processes.

1. INTRODUCTION

Intracluster abundance variations are well-known among globular cluster stars on the red giant branch, subgiant branch, and main sequence (see Gratton et al. 2004 for a thorough review). Within halo globular clusters, at fixed stellar luminosity, some stars are observed to have a typical Population II abundance pattern, while others are depleted in carbon, oxygen, and magnesium, and enriched in nitrogen, sodium, and aluminum. This latter abundance pattern is most easily observed as unusually strong CN absorption in low-resolution spectra, whereby it was first discovered. Consequently such stars are referred to as “CN-strong,” and the entire abundance pattern from carbon through aluminum is implied by that name. The existence of CN-strong stars in globular clusters is presently interpreted as a sign of an early enrichment process whose details are murky (e.g., Cannon et al. 1998; Bekki et al. 2007). This process apparently occurs in all halo globular clusters (Gratton et al. 2004), but not in open clusters (e.g., Norris & Smith 1985; Smith & Norris 1984) or the halo field (Gratton et al. 2000).

There are several possible explanations for the existence of CN-strong stars in globular clusters, including pollution of cluster-forming gas by AGB star winds (e.g., Cottrell & Da Costa 1981), an early generation of stars with a top-heavy mass function (e.g., Cannon et al. 1998), or Wolf-Rayet stars (e.g., Smith 2006). There is also an emerging paradigm that sufficiently massive globular clusters form their stars in multiple generations (e.g., Carretta et al. 2008; D’Ercole et al. 2008). In this picture, cluster mass loss is driven by supernovae, primarily affecting the first generation of stars and accounting for the varying ratios of halo-like to enriched stars and differing horizontal branch morphologies. All of the various models have a few common characteristics: the process must happen quickly, since there is a limited time from the first star formation in a globular cluster until the 0.8 \( M_\odot \) stars that are presently red giants have finished forming. All models rely on intermediate-to high-mass stars as a source for polluting material, both because of their relatively short lifetimes and because the existence of anticorrelated Mg and Al abundances implies high-temperature fusion. All models also require a proto-cluster to have a significant gravitational potential (to retain enriched gas) and a sufficiently rarefied environment (to prevent ram pressure stripping). Given these characteristics, it can be understood qualitatively why old, isolated halo globular clusters would contain CN-strong stars while lower-mass disk objects like open clusters would not.

Disk globular clusters, with their relatively high metallicities, provide an interesting intersection of those two populations, and a convenient testbed for models of the primordial enrichment process. If the process is prohibited by in-disk orbits or high metallicity, then disk globular clusters will have homogeneous abundance patterns similar to those in open clusters. However, if
the high initial mass and relatively deep potential well of a proto-globular cluster is the key to allowing enrichment, disk and bulge globular clusters could also contain a subpopulation of stars with the same CN-strong abundance pattern observed in halo globular clusters (if the yields of the enriching stars scale with metallicity).

It is in this context that we consider our data set, which is comprised of Keck/LRIS blue spectra of 24 upper red giant branch stars in the high-metallicity disk globular cluster NGC 6356 and 11 similar stars in NGC 6528. NGC 6356 is in a location consistent with being a disk globular cluster (e.g., Zinn 1985): 2.7 kpc above the Galactic plane, on the far side of the Galactic center (Bica et al. 1994). Its metallicity is [Fe/H] = −0.50 according to the 2003 revision of the Harris (1996) catalog. NGC 6528 is located in Baade’s window, 0.6 kpc from the Galactic center and 0.6 kpc below the plane. As such, it is considered a bulge globular cluster (Minniti 1995), with Zoccali et al. (2004) and Origlia et al. (2005) finding metallicities of [Fe/H] = −0.1 and −0.2 dex from optical and infrared spectroscopy, respectively. We compare these spectra to Lick/Kast blue spectra of 22 red giants in the old open clusters NGC 188 ([Fe/H] = −0.06, Carraro & Chiosi 1994), NGC 2158 ([Fe/H] = −0.60, Carraro et al. 2002), and NGC 7789 ([Fe/H] = −0.04, Tautvaišienė et al. 2005). These are all northern clusters, with estimated ages ranging from 1.3 Gyr for NGC 7789 to 7.5 Gyr for NGC 188 (both age estimates from Carraro & Chiosi 1994). We measure the strength of the CN absorption band at 4215 Å with the index $S(4142)$, defined by Norris & Freeman (1979) as

$$S(4142) = -2.5 \log \frac{\int_{4200}^{4290} I_\lambda d\lambda}{\int_{4210}^{4216} I_\lambda d\lambda}.$$  

This quantity, like most spectral indices, measures the magnitude difference between the integrated flux inside the absorption feature in question and in a nearby continuum region. By considering CN band strength variation as a proxy for the full enriched abundance pattern, we hope to explore whether NGC 6356 and NGC 6528 exhibit CN bimodality like their low-metallicity halo counterparts do, or whether their similarity to open clusters includes a homogeneous abundance distribution along with near-Solar metallicities and disk orbits.

2. THE DATA SET

Spectra in NGC 6356 were acquired on two nights in 2002 June, using the Low Resolution Imaging Spectrometer (LRIS, Oke et al. 1995) at the Keck I Telescope on Mauna Kea. Spectra in NGC 6528 were taken on two nights in 2003 June with the same instrumental setup. Using a mirror in place of a dichroic, all light was directed to the mosaic of two 2 K × 4 K Marconi CCDs in the blue camera. The 400/3400 grism and a slit width of 1″ (8.7″ for flux standard stars) resulted in a pixel spacing of 1.1 Å and a resolution of 8 Å. Typical exposure times of 1200–1500 seconds produced a signal-to-noise ratio (S/N) per pixel of roughly 60 at 4320 Å, just redward of the G band.

The open cluster stars were observed with the Shane 3 m telescope at Lick Observatory on two nights in 2005 February, three nights in 2005 September, and three nights in 2006 August. In each case a mirror was used to direct all light to the blue side of the Kast double spectrograph. The 600/4310 grism and a slit width between 1″ and 2″, depending on weather (9″ for flux standard stars), produced a pixel spacing of 1.8 Å and a resolution of 5.4 Å. Exposure times varied widely because of a range of two magnitudes in distance modulus, and the typical S/N at 4320 Å is 150. Table 1 lists identifying information, photometry, exposure time, and the CN band strength index $S(4142)$ for each globular cluster giant observed. Analogous information for the open cluster giants, and membership probabilities where available, are given in Table 2.

Data reduction was accomplished for both the Keck and Lick data sets using the XIDL “low-redux” programs. The instrument-specific programs handle bias subtraction, flat-fielding, cosmic ray removal, object identification and extraction, sky subtraction, flexure correction, wavelength calibration, atmospheric correction, coadding, and flux calibration. The standard stars Feige 34, Feige 110, BD +28 4211, and BD +33 4211 were used for flux calibration, with “true” spectra taken from the CALSPEC database (Bohlin 1996). The upper panel of Figure 1 shows a typical flux-calibrated spectrum from each of the Kast (open cluster) and LRIS (globular cluster) data sets, with the science band (4120 Å to 4216 Å) and comparison band (4216 Å to 4290 Å) of $S(4142)$ shown as regions with closely spaced shading and widely spaced shading respectively. The Kast spectrum (upper spectrum, shorter wavelength coverage) is of NGC 7789 star 614 ($M_V = −1.3$), and the LRIS spectrum is of NGC 6356 star 111 ($M_V = −1.1$). The lower panel of Figure 1 shows a close-up of the 4215 Å CN band region of spectra from NGC 6356 111 (drawn with a thick line) and NGC 6356 113 (thin line), with the S(4142) bandpasses marked by vertical dashed lines. The two stars have similar V magnitudes and temperatures but the 4215 Å CN band is stronger in 113 than in 111, implying larger [N/Fe] abundance.

2.1. Cluster Membership

Because all of the star clusters observed for this study orbit within the disk or bulge, the line of sight to each of them contains more foreground stars than the line of sight to a typical halo globular cluster. Because of the near-solar metallicities of the cluster stars and the typically low systemic radial velocities of the clusters relative to the Sun, two of the most straightforward methods for identifying foreground stars in low-metallicity globular cluster fields are ineffective with the present
data set. Three of our five target lists (for NGC 6356, NGC 6528, and NGC 2158) were constructed from photographic studies without the astrometric or spectroscopic information necessary to identify foreground late-K and M dwarfs.

We use a combination of visual spectrum inspection, photometry, and spectral indices focused on gravity-sensitive features to identify foreground dwarfs and other non-useful stars in our data set and remove them from further analysis. We reject NGC 6356 17 because of TiO bands not seen in any of the other NGC 6356 stars, and NGC 6356 51 because it is significantly bluer and has a distinctly smaller Ca K index (Morrison et al. 2003) than all other stars observed in NGC 6356. We also drop NGC 6528 II-29 from the sample because its 3α883 CN band, measured by the index S(3839) (Briley et al. 1990), is abnormally small. In NGC 188, though the stars are all confirmed as cluster members by proper motion (Stetson et al. 2004) and radial velocity (Geller et al. 2008), star 1001 is thought to be a postcoalescence FK Comae star (Harris & McClure 1985) and star 3018 is significantly brighter than the rest of the sample. We are therefore unsure whether 3018 is an AGB star, and we remove it from the analysis. NGC 7789 also has proper-motion–based membership probabilities in the literature (Gim et al. 1998). We do not see any outliers in the photometry or measured indices in NGC 7789, and include all of the NGC 7789 stars listed in Table 2 in the analysis. In all, we exclude 5 of the 62 stars initially observed from the final sample, leaving 24 stars in NGC 6356, 11 in NGC 6528, 6 in NGC 188, 6 in NGC 2158, and 10 in NGC 7789.

### 3. CN Band Strength Distribution

We measure the CN band strength index $S(4142)$ from each of our flux-calibrated spectra. Because it is defined as the magnitude difference between the integrated flux inside the 4215 Å CN band and a nearby CN-free region, larger values of $S(4142)$ reflect stronger CN absorption. We determine the error on the index measurement on a cluster-by-cluster basis. We define a pseudoidex $S_p(4142)$, with the same comparison band as the original $S(4142)$ and the science band shifted to 4027 Å through 4077 Å, a CN-free region of the spectrum. The scatter in $S_p(4142)$ at a given absolute magnitude will then be independent of CN band strength, and will be representative of the scale of the random errors in $S(4142)$. Figure 2 shows $S(4142)$ (upper panel) and $S_p(4142)$ (lower panel) versus $M_V$ for our NGC 7789 stars. As expected from previous abundance-inhomogeneity studies of open clusters, the stars stay within a fairly small range in $S(4142)$. In NGC 7789 the scatter in $S_p(4142)$, which is 0.05, is comparable to that in $S(4142)$, implying that there is very little CN abundance variation among the stars. It is also worth noting that $S_p(4142)$ rises with brightening $M_V$ in Figure 2, while $S(4142)$ does not. This could be a result of the larger wavelength range spanned by the bandpasses of $S_p(4142)$, which makes it more sensitive to changes in stellar temperature.

This pseudoidex error, calculated as the RMS of $S_p(4142)$ about a best-fit line in the $S_p(4142)–M_V$ plane, is calculated for each of the clusters in our sample individually. For NGC 6356 the scatter in $S_p(4142)$ is 0.048 and for NGC 6528 the scatter is 0.082; a representative value of ±0.05 mag is adopted as the error in all measured values of $S(4142)$. After inspecting some

### TABLE 1

| Cluster ID | Star ID | $M_V$ | $B - V$ | $t(\text{s})$ | $S(4142)$ |
|------------|---------|-------|--------|--------------|------------|
| NGC 6356   | 14      | −0.81 | 1.51   | 2400         | −0.119     |
|            | 17      | −1.33 | 2.11   | 1800         | −0.123     |
|            | 18      | −0.59 | 1.42   | 1200         | 0.019      |
|            | 20      | −1.15 | 1.63   | 1200         | 0.078      |
|            | 21      | −0.93 | 1.42   | 1200         | −0.034     |
|            | 61      | −0.89 | 1.69   | 1200         | 0.081      |
|            | 69      | −0.42 | 1.42   | 1500         | −0.140     |
|            | 70      | −0.85 | 1.62   | 1200         | −0.102     |
|            | 71      | −0.67 | 1.52   | 1200         | 0.052      |
|            | 73      | −1.18 | 1.7    | 1500         | −0.099     |
|            | 74      | −0.43 | 1.55   | 1500         | −0.136     |
|            | 77      | −0.87 | 1.7    | 1500         | 0.127      |
|            | 93      | −0.75 | 1.49   | 1500         | −0.191     |
|            | 9       | −0.65 | 1.52   | 1200         | 0.141      |
|            | 104     | −0.45 | 1.65   | 1200         | −0.149     |
|            | 107     | 0.07  | 1.39   | 1500         | 0.081      |
|            | 111     | −1.1  | 1.76   | 1500         | −0.053     |
|            | 113     | −1.0  | 1.66   | 1500         | 0.082      |
|            | 116     | −0.01 | 1.26   | 1500         | 0.002      |
|            | 154     | −0.55 | 1.64   | 1500         | −0.148     |
|            | 157     | −0.89 | 1.49   | 1200         | −0.157     |
|            | 164     | −0.68 | 1.71   | 1500         | −0.052     |
|            | 166     | −0.55 | 1.69   | 1200         | −0.115     |
|            | 53      | −0.44 | 1.36   | 1500         | 0.119      |
|            | 81      | −0.24 | 1.46   | 1500         | 0.081      |
| NGC 6528   | 0–16    | −0.031| 1.57   | 2100         | −0.067     |
|            | II-19   | 0.027 | 1.73   | 2100         | −0.027     |
|            | II-22   | −0.012| 1.70   | 2100         | 0.118      |
|            | II-51   | 0.125 | 1.78   | 1800         | −0.069     |
|            | II-7    | −0.409| 1.88   | 3000         | −0.037     |
|            | II-8    | −0.345| 1.89   | 1800         | 0.083      |
|            | II-12   | −0.279| 1.65   | 1800         | −0.094     |
|            | II-27   | 0.206 | 1.66   | 2100         | 0.027      |
|            | II-39   | −0.15 | 1.85   | 1800         | 0.083      |
|            | II-3    | −0.157| 1.74   | 1800         | −0.059     |
|            | II-4    | 0.101 | 1.53   | 2100         | −0.052     |
|            | II-70   | −0.179| 1.88   | 3900         | −0.045     |

$^a$NGC 6356: Star identifiers and photometry are taken from Sandage & Wallerstein (1960).

$^b$NGC 6528: Star identifiers and photometry are from van den Bergh & Younger (1979).
of the spectra, we feel that large-scale variations in continuum shape are most likely to be responsible for the variations in $S_p(4142)$. These may be a result of atmospheric diffraction causing the scattering of blue light preferentially out of the slit, particularly in NGC 6356 and NGC 6528, which are fairly southerly for observation from the Keck I telescope. Since the bandpasses of $S_p(4142)$ are more widely separated in wavelength than those of $S(4142)$, and extend further into the violet, the former index will be more sensitive to observational effects such as differential light loss at the spectrograph slit, and errors in flux calibration. As such, our approach may overestimate the observational error in $S(4142)$ for the globular cluster observations.

The left panel of Figure 3 shows the CN band strength index $S(4142)$ versus absolute visual magnitude for NGC 6356. There is clearly a vertical range in $S(4142)$ at each $M_V$, which is also seen in every other CN-bimodal globular cluster. Adapting the analysis method of the Norris et al. (1981) study of CN variations in NGC 6752, we fit a line to the lower collection of points and measure the quantity $\delta S(4142)$, the vertical distance from each point to the line. In this study we set the slope of the baseline to zero, in keeping with previous studies on 4215 Å CN band strength in high-metallicity globular clusters (e.g., Briley 1997). The right panel of Figure 3 shows a generalized histogram of $\delta S(4142)$ values measured from the left panel. This curve is produced by representing each $\delta S(4142)$ point as a Gaussian with a width $\sigma$ equal to the measurement error, which in this case is 0.05. The sum of those individual Gaussians is then a realistically smoothed histogram. Figure 4 shows the analogous data in NGC 6528, with a generalized histogram calculated in the same way. With fewer data points and a smaller gap in $S(4142)$ between relatively CN-weaker and CN-stronger groups, the generalized histogram for NGC 6528 looks less bimodal than the generalized histogram for NGC 6356. The dashed curve in the right panel of Figure 4 shows the generalized histogram that results if $\sigma$ is set to 0.08, the measured standard deviation in $S_p(4142)$ in NGC 6528. Increasing $\sigma$ smooths the curve dramatically, reducing what appears in the solid curve to be a distinct CN-stronger group to a broad, asymmetric distribution.

### Table 2

| Cluster ID | Star ID | $M_V$ | $B - V$ | $t$ (s) | $S(4142)$ | $P_{pm}$ (%) | $P_{rev}$ (%) |
|------------|---------|-------|---------|--------|-----------|--------------|--------------|
| NGC 188\(a\) | II-76   | 0.64  | 1.23    | 2700   | 0.145     | 84           | 98           |
|            | I-69    | 0.47  | 1.34    | 2700   | 0.020     | 86           | 96           |
|            | I-105   | 0.56  | 1.25    | 2700   | 0.052     | 85           | 98           |
|            | II-72   | 0.62  | 1.33    | 2700   | 0.074     | 85           | 98           |
|            | III-18  | -0.44 | 1.51    | 1080   | -0.054    | 82           | 98           |
|            | I-1     | 0.12  | 1.18    | 2400   | 0.031     | 82           | 98           |
|            | II-51   | 1.14  | 1.18    | 2700   | -0.037    | 81           | 98           |
| NGC 2158\(b\) | S1 R1 16 | -1.43 | 1.85    | 5400   | 0.015     | ............. | ............. |
|            | S3 R1 32 | -1.72 | 1.79    | 5400   | -0.037    | ............. | ............. |
|            | S4 R1 8 | -1.54 | 1.63    | 5400   | -0.084    | ............. | ............. |
|            | S2 R4 c | -1.47 | 1.62    | 7200   | -0.035    | ............. | ............. |
|            | S3 R2 55 | -1.51 | 1.73    | 5400   | 0.018     | ............. | ............. |
|            | S4 R5 12 | -1.01 | 1.74    | 8100   | -0.056    | ............. | ............. |
| NGC 7789\(c\) | 491     | -0.27 | 1.47    | 2400   | -0.046    | ............. | 97           |
|            | 589     | -1.42 | 1.65    | 1500   | -0.009    | ............. | 97           |
|            | 614     | -1.3  | 1.71    | 3600   | -0.063    | ............. | 97           |
|            | 732     | -1.06 | 1.63    | 2400   | -0.004    | ............. | 98           |
|            | 583     | -1.25 | 1.66    | 720    | -0.006    | ............. | 97           |
|            | 654     | -0.23 | 1.44    | 720    | 0.012     | ............. | 84           |
|            | 671     | -0.45 | 1.48    | 1800   | -0.005    | ............. | 98           |
|            | 933     | -0.7  | 1.55    | 1200   | -0.002    | ............. | 98           |
|            | 990     | -0.6  | 1.51    | 1200   | -0.009    | ............. | 98           |
|            | 1074    | -0.67 | 1.56    | 1200   | -0.011    | ............. | 98           |

\(a\)NGC 188: Star identifiers and photometry are taken from Sandage (1962); proper motion-based membership probabilities are from Stetson et al. (2004), radial velocity-based membership probabilities are from Geller et al. (2008).

\(b\)NGC 2158: star identifiers and photometry are taken from Arp & Cuffey (1962).

\(c\)NGC 7789: Star identifiers and photometry are taken from McNamara & Solomon (1981), radial velocity-based membership probabilities are from Gim et al. (1998).
Figure 5 shows generalized histograms of $\delta S(4142)$ for the open clusters NGC 188, NGC 2158, and NGC 7789, all calculated in the same way as for the globular clusters, with flat baselines and $\sigma$ set to 0.05. The curves are all normalized at the peak for easier intercomparability, and the generalized histogram for NGC 6356 is overplotted in each panel as a dotted curve. It is clear that the distribution of CN band strength in the three open clusters is single-peaked, and that there are two groups in CN
band strength in NGC 6356, but NGC 6528 is more difficult to categorize. It is possible that the difference in [N/Fe] between CN-enhanced and CN-normal stars is smaller in Solar-metallicity globular clusters, since the total mass in nitrogen required to produce an abundance gap of up to 1 dex is far larger than in low-metallicity globular clusters. The broad but not clearly bimodal distribution of CN band strengths in NGC 6528 could be a sign that there is an upper limit on the amount of nitrogen that can be injected into feedback material in high-metallicity globular clusters.

![Figure 3](image1.png)

**Fig. 3.**—Measured values of the CN index $S(4142)$ in NGC 6356 (*left panel*) and a generalized histogram of the offset $\delta S(4142)$ between the data points and the horizontal baseline (*right panel*).

![Figure 4](image2.png)

**Fig. 4.**—Measured values of the CN index $S(4142)$ in NGC 6528 (*left panel*) and a generalized histogram of the offset $\delta S(4142)$ between the data points and the horizontal baseline (*right panel*). The presence of a smaller gap between relatively CN-stronger and CN-weaker groups than in NGC 6356, and the smaller number of CN-stronger stars, create a less bimodal-looking generalized histogram than in Figure 3. The *dashed curve* shows the generalized histogram calculated with $\sigma$ set to 0.08.
4. RESULTS

The homogeneity of CN band strengths in the open clusters surveyed is an expected result: Norris & Smith (1985), Smith & Norris (1984), and Tautvaišienė et al. (2005) have all demonstrated small ranges in band strengths or abundances in these clusters. However, the disk/bulge globular clusters NGC 6356 and NGC 6528 have distributions of CN band strength that clearly resemble those observed in halo globular clusters like NGC 6752 and M3, and that is surprising. We interpret the presence of CN-strong stars in NGC 6356 and NGC 6528 to mean that the same primordial enrichment process took place in disk and bulge globular clusters as in halo globular clusters. Higher resolution spectroscopy is needed to determine whether the full “enhanced” abundance pattern from carbon through aluminum is present in the CN-strong stars. On a related note, Origlia et al. (2008) have found evidence of a Mg-Al abundance anticorrelation, such as often accompanies CN variations in globular clusters, in the bulge globular NGC 6441 ([Fe/H] = −0.5).

The presence of CN-strong stars in disk and bulge globular clusters provides strong constraints on the primordial enrichment process. Since the Galactic orbits of NGC 6356 and NGC 6528 do not allow for long periods of time outside the disk or bulge, the transfer of enriched material from evolved higher-mass stars to still-forming low-mass stars must have been both relatively fast and efficient in order to avoid ram pressure stripping from a primordial environment that was likely much denser than at present. In addition, the absolute amount of nitrogen needed to create a difference of between 0.5 and 2.0 dex in [N/Fe] between CN-weak and CN-strong stars (e.g., Kraft 1994, Cohen et al. 2005, Yong et al. 2008) is significantly larger at near-Solar metallicity than it is at typical halo metallicity. This implies that the material transferred to low-mass stars must have been more enriched in nitrogen in the higher-metallicity globular clusters. Such a requirement may pose a problem for AGB star enrichment scenarios. The 4 and 5 $M_\odot$ AGB models with Reimers mass loss rates of Karakas & Lattanzio (2007) eject a total mass of $14^\text{N}$ of $7.7 \times 10^{-2} M_\odot$ and $3.6 \times 10^{-2} M_\odot$ respectively for $Z = 0.0001$, $2.3 \times 10^{-2} M_\odot$ and $6.3 \times 10^{-2} M_\odot$ respectively for $Z = 0.004$, and $2.2 \times 10^{-3} M_\odot$ and $5.4 \times 10^{-2} M_\odot$ respectively for $Z = 0.008$. There is no indication from these models that early AGB stars in bulge or disk globular clusters would eject a proportionally larger amount of nitrogen than intermediate-mass AGB stars in halo clusters. To obtain comparable enhancements of [N/Fe] in CN-strong giants in both disk and halo globular clusters, it may be necessary to assume that the former were enriched by a larger number of AGB stars per unit cluster mass than halo clusters.

The evidence in this article indicates that disk and bulge globular clusters contain a population of CN-enhanced giants, presumably analogous to those in halo globular clusters, whereas open clusters of similar metallicity do not. This may indicate that open clusters were not massive enough to experience early enrichment of the type evinced by globular clusters. Alternatively, disk and bulge globular clusters may have had a larger than typical number of AGB stars per unit mass. Could this have been a consequence of the environment in which the bulge and disk globulars formed? Conditions in the central parts of the proto-Galaxy may have favored high- and intermediate-mass star formation under starburst conditions. Open clusters, forming further out in the Galactic disk in more quiescent molecular clouds, could have resulted from star formation activity more conducive to lower-mass stars.

Indeed, this consideration of AGB-star yields suggests that self-enrichment of disk and bulge globulars may have been have
associated with more top-heavy stellar mass functions than were present even in halo globular clusters. Many halo globular clusters may have formed within proto-dwarf galaxies or massive clouds of the type suggested by Searle & Zinn (1978), and their chemical evolution would have been set by the environment within such systems. Recent studies of multiple stellar populations in Galactic and extragalactic globular clusters, such as Milone et al. (2008); Piotto et al. (2007); Mackey et al. (2008), make it clear that their star formation took place in a complex and dynamic environment. The sites of disk and bulge cluster formation may have been strongly influenced by conditions within the chaotic and violent inner regions of the proto-Galaxy. Cloud collisions may have been fairly common in the still-forming bulge, resulting in starbursts that were relatively efficient in high- and intermediate-mass star formation, leading to pronounced chemical enrichment that built up not only high overall metallicities, but also high \([\text{N-Na}_\text{Al}/\text{Fe}]\) ratios as well. As such, the study of abundance inhomogeneities in disk and bulge globular clusters could offer the promise of probing some of the most efficient primordial environments for chemical evolution.

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