*Star Clusters: From the Milky Way to the Early Universe*
*Proceedings IAU Symposium No. 351, 2019*
*A. Bragaglia, M. Davies, A. Sills & E. Vesperini, eds.*

doi:10.1017/S1743921319006859

# Light element discontinuities in the globular cluster NGC 6402 (M14)

**Christian I. Johnson**

Center for Astrophysics | Harvard & Smithsonian, 60 Garden Street, Cambridge, MA, USA 02138
email: cjohnson@cfa.harvard.edu

**Abstract.** NGC 6402 is one of the most massive globular clusters in the Galaxy but until recently little was known about its detailed chemical composition. Interestingly, recent results have shown that NGC 6402 exhibits a paucity of intermediate composition stars that may be indicative of an early termination of star formation. As a result, NGC 6402 may be important for understanding cluster formation and the order in which various stellar populations are born.

**Keywords.** Globular Clusters

## 1. Introduction

Globular clusters are ancient relics from the early Universe and offer a unique window into the first epochs of intense star formation and nucleosynthesis. These clusters serve as chronometers that trace specific formation events in galaxy histories (e.g., Brodie & Strader 2006), and their collective properties, such as specific frequency and metallicity, are well-correlated with fundamental host galaxy characteristics. Globular clusters are among the most luminous stellar populations within galaxies, and serve as crucial tracer elements that enable observations out to $>$ 100 Mpc. However, an accurate interpretation of extragalactic properties depends critically on a deep understanding of the Milky Way globular cluster system.

Recent work has shown that globular clusters fall into three broad categories: (1) low mass clusters that may consist of only one stellar population (e.g., Dotter *et al.* 2018); (2) intermediate and/or massive clusters hosting 2-3 distinct stellar populations with different light element abundances (e.g., Carretta *et al.* 2009); and (3) massive "iron-complex" clusters hosting several generations of stars with distinct light and heavy element abundance patterns, including clear metallicity spreads (e.g., Marino *et al.* 2019). Interestingly, a significant fraction of the most massive Galactic globular clusters belong to the latter group, and some evidence suggests these objects may be the former cores of dwarf galaxies that have been captured and tidally destroyed by the Milky Way (e.g., Da Costa 2016).

These observations have motivated a search for additional clusters that exhibit clear metallicity spreads, and a particular emphasis has been placed on clusters with $M_V < -8$. As a consequence, Johnson *et al.* (2019) investigated the chemical composition of NGC 6402 (M14), which is both massive and exhibits some ancillary evidence that it may have an extragalactic origin (e.g., peculiar RR Lyrae properties and the existence of a CH star).

## 2. Overview

The chemical composition of NGC 6402 was investigated using high resolution spectra obtained with the Michigan-Magellan Fiber System (M2FS; Mateo *et al.* 2012)

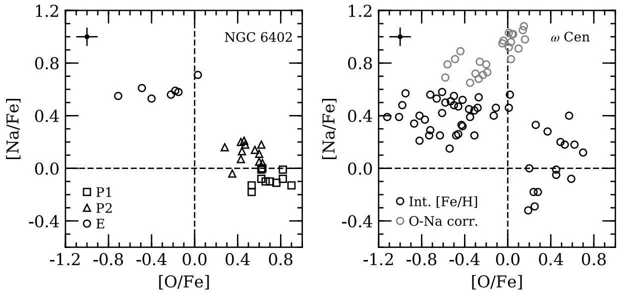


**Figure 1.** *Left:* the O-Na anti-correlation for NGC 6402 is shown with the P1, P2, and E populations designated as open squares, triangles, and circles, respectively. A peculiar composition gap is observed between the P2 and E populations. *Right:* a similar O-Na anti-correlation is shown for the intermediate metallicity ([Fe/H] $\sim -1$) stars in $\omega$ Cen based on data from Johnson & Pilachowski (2010). Note that the similar metallicity stars in both clusters exhibit a common paucity of stars near [O/Fe] $\sim +0.1$ dex. For completeness, the peculiar intermediate metallicity $\omega$ Cen stars that exhibit an O-Na correlation are shown as light grey circles.

instrument on the Magellan-Clay 6.5m telescope. The observations targeted ~40 bright red giant branch (RGB) stars within a radius of ~3.5 arc minutes from the cluster core. In general, the R $\sim$ 27,000 spectra were of high quality with signal-to-noise ratios of $\sim$ 100 per reduced pixel. The data ranged in wavelength from ~6140-6700 Angstroms in order to target key absorption lines of light, $\alpha$, Fe-peak, and neutron-capture lines ranging from oxygen to europium.

Johnson *et al.* (2019) found that NGC 6402 is a moderately metal-poor cluster with $\langle$[Fe/H]$\rangle = -1.13$ dex. However, the [Fe/H] dispersion is only 0.05 dex, which indicates that although NGC 6402 is among the most massive clusters in the Galaxy it does not possess an intrinsic metallicity spread. As a result, NGC 6402 is not likely to be a former galaxy nucleus, but does share a similar mass and metallicity with the peculiar globular cluster NGC 2808.

Although NGC 6402 is a more typical monometallic cluster, Johnson *et al.* (2019) found a surprising result when investigating the cluster's light element abundance pattern. As summarized in Figure 1, NGC 6402 exhibits the usual O-Na anti-correlation that is prevalent in nearly all old globular clusters. However, NGC 6402 possesses a clear gap in its O-Na distribution and appears to be missing the normally prevalent intermediate composition stars. Similar gaps are present for Mg, Al, and Si as well. With a sample size of >30 stars for all element combinations, the probability that the observed composition gaps are due to random sampling is $<$ 0.06 per cent. Figure 2 further emphasizes that the measured composition gaps are real and not an artifact of the analysis. For example, the differences in line strengths for O, Na, and Al are relatively small when comparing stars belonging to the "P1" and "P2" groups, but the "E" spectra clearly have much stronger Na, Al, and Si features along with much weaker O lines (and stronger CN). Transitions for heavier elements, such as Ni and Fe, are identical in strength for all three populations.

A comparison between the second parameter pair clusters NGC 6402 and NGC 2808 by Johnson *et al.* (2019) indicated that the pollution sources between the two clusters were likely similar, but that NGC 2808 experienced pollution from stars that reached temperatures at least 5-10 MK higher than for NGC 6402. Although NGC 6402 is unique in that it is the only monometallic cluster to exhibit such a clear paucity of intermediate composition stars, Figure 1 shows that the [Fe/H] $\sim -1$ stars in $\omega$ Cen exhibit a similar composition gap. NGC 2419 may also exhibit a strongly bimodal light

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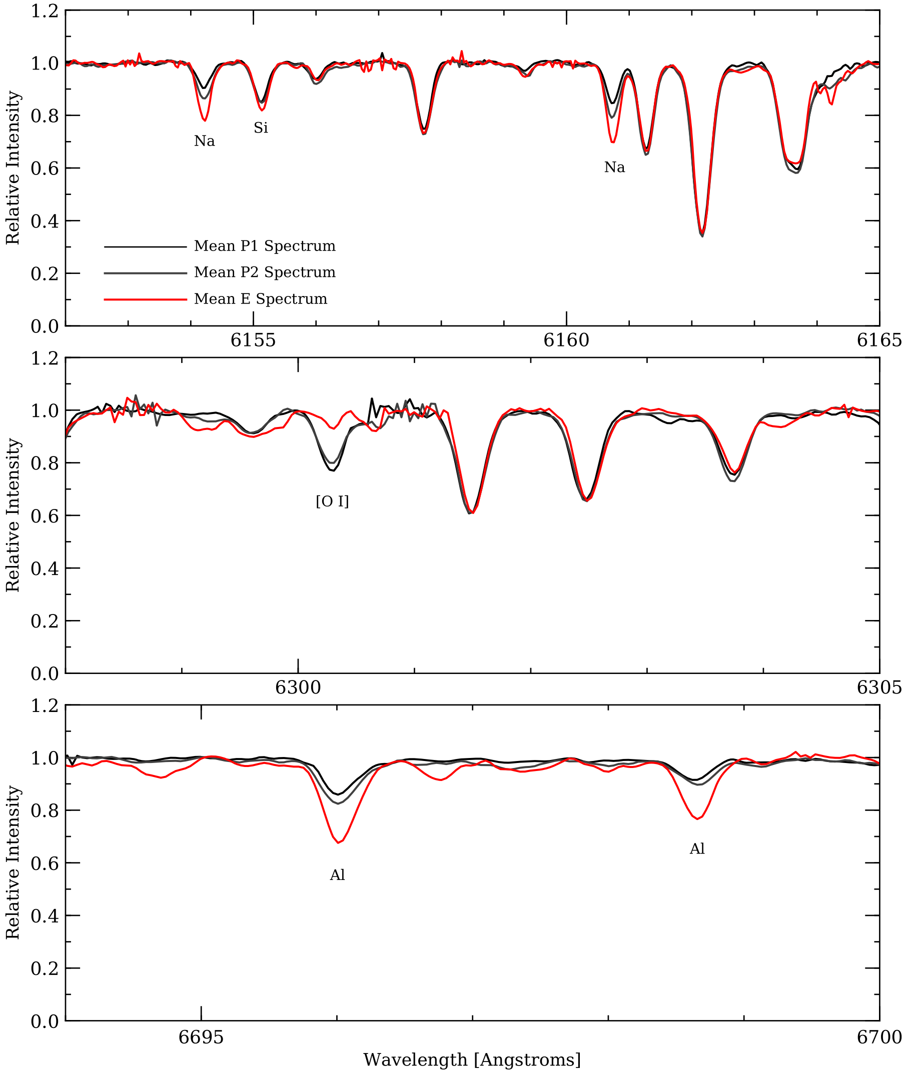


**Figure 2.** The black, grey, and red lines illustrate the co-added spectra for all stars with similar model atmosphere parameters that belong to the P1, P2, and E populations, respectively. The absorption lines for O, Na, Al, and Si are identified. Note in particular the large change in line strength for O between the P1/P2 and E populations, and that the light element abundance variations extend up to at least Si. Unidentified lines are predominantly a mixture of Ca, Fe, Ti, Ni, and CN.

element composition pattern (Di Criscienzo *et al.* 2015; Mucciarelli *et al.* 2015), but this observation needs to be confirmed with a larger sample.

## 3. Implications

One of the most interesting aspects about the missing intermediate composition stars in NGC 6402 is that it may shed light on the order in which various populations in monometallic globular clusters form. Most models predict that the primordial composition stars form first and that the intermediate and extreme stars are formed as a result of mixing polluted (from asymptotic giant branch stars?) gas with pristine cluster gas. The mixing process is thought to occur over $> 40$ Myr (e.g., D'Antona *et al.* 2016) and

https://doi.org/10.1017/S1743921319006859 Published online by Cambridge University Press

largely take place after the initial epoch of core collapse supernova (SN) explosions. Using the notation from Carretta (2015), the order of formation for clusters may proceed from P1→E→I2→I1→P2 (e.g., D'Antona *et al.* 2016) or P1→P2→I1→I2→E (e.g., Kim & Lee 2018). However, since Figure 1 shows that NGC 6402 contains both P2 and E stars but no I1/I2 stars, it is difficult to reconcile current models with the cluster's observed composition pattern.

Therefore, Johnson *et al.* (2019) proposed a modified version of previous models and suggested that the P1 and E populations form within the first few Myr while the P2/I1/I2 stars form via pollution and mixing after the SN era. In order to match observations in other clusters, this model would require that a high temperature burning source produced E composition gas within a small region around the cluster core. The presence of a supermassive ($>$ 1000 solar mass) star forming via runaway collisions in a cluster's core is one possible solution (e.g., Gieles *et al.* 2018), and could provide a natural explanation for E composition stars existing almost exclusively in the most massive clusters. After the SN epoch, the commonly adopted dilution and mixing models would still be required for describing the formation of intermediate composition stars. Interestingly, the paucity of I1/I2 stars in NGC 6402 (see Figure 1) suggests that these may be the last stars to form in a cluster, and as a result NGC 6402 may have prematurely halted star formation.

The observed paucity of intermediate composition stars in NGC 6402, $\omega$ Cen, and possibly NGC 2419 poses interesting challenges to current globular cluster formation scenarios and several outstanding questions remain. For example, is the composition gap observed in NGC 6402 real? A sample of $\sim$35 stars is usually sufficient to fully examine a cluster's composition pattern, but confirmation with more spectra and/or chromosome maps (e.g., Milone *et al.* 2017) would be desirable. If the gap is real, why do so few clusters exhibit this pattern? Furthermore, does the gap represent a specific mode of star formation or is it primarily driven by environment? Did the [Fe/H] $\sim -1$ stars in $\omega$ Cen form within the cluster or did the $\omega$ Cen progenitor ingest an object like NGC 6402? Finally, if supermassive stars are a viable solution to the formation of clusters like NGC 6402, can we detect their presence in high redshift environments? The "supernebula" region of NGC 5253 may be useful for examining star formation in an environment that at least somewhat resembles early globular clusters (e.g., Turner *et al.* 2015).

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