*Star Clusters: From the Milky Way to the Early Universe*
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# Integrated spectroscopy of extragalactic Globular Clusters

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**Abstract.** Integrated light (IL) spectroscopy enables studies of stellar populations beyond the Milky Way and its nearest satellites. In this paper, I will review how IL spectroscopy reveals essential information about globular clusters and the assembly histories of their host galaxies, concentrating particularly on the metallicities and detailed chemical abundances of the GCs in M31. I will also briefly mention the effects of multiple populations on IL spectra, and how observations of distant globular clusters help constrain the source(s) of light-element abundance variations. I will end with future perspectives, emphasizing how IL spectroscopy can bridge the gap between Galactic and extragalactic astronomy.

**Keywords.** Globular clusters, chemical abundances, chemical evolution.

## 1. Introduction

The chemical abundances, ages, and velocities of globular clusters (GCs) provide essential information about their host galaxies, particularly for distant galaxies whose individual stars are too faint to observe. A GC's metallicity and abundance ratios (including [$\alpha$/Fe]) are set by the mass and star formation history of its original host galaxy. Massive galaxies, for example, can produce more metal-rich stars and GCs than lower-mass galaxies. Similarly, the [$\alpha$/Fe] ratios (represented here by [Ca/Fe]) indicate the relative contributions from massive and low-mass stars, specifically the contributions from Type II core-collapse supernovae relative to the Type Ia supernovae that are due to the detonation of a white dwarf. The combination of [Fe/H] and [Ca/Fe] can be a powerful diagnostic for revealing the mass of a GC's host galaxy (e.g., Tolstoy *et al.* 2009). In a large galaxy with hundreds of GCs, this information provides insight into the low-mass systems that have built up the larger galaxy's halo over cosmic time.

For distant GCs, abundances, ages, and velocities can all be obtained from integrated light (IL) spectroscopy, where a single spectrum is obtained for an entire cluster. IL spectroscopy is necessarily more complicated that analyses of individual stars, as it requires some assumptions about the underlying stellar populations. However, IL spectroscopic techniques have been tested extensively and validated with IL observations of Milky Way GCs (e.g., Schiavon *et al.* 2002a,b, 2004; McWilliam & Bernstein 2008; Sakari *et al.* 2013, 2014; Colucci *et al.* 2017; Larsen *et al.* 2017). The spectral resolution dictates the quantities that can be derived from an IL spectrum. At low-resolution spectral lines are blended together, making it harder to determine individual abundances for most elements; at high-resolution, individual lines can be resolved, yielding high-precision abundances of individual elements. Lower-resolution spectra can provide ages, metallicities, velocities, and some abundances, depending on wavelength coverage, the metallicity of the target,

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and the quality of the spectra; lower resolution IL spectroscopy requires less observing time than high-resolution spectroscopy, and can therefore be applied to many targets. Alternatively, high-resolution spectra provide detailed abundances of a wide variety of individual elements, particularly from weaker lines that can be very difficult to obtain at lower resolution (e.g., Na or Eu) or that become prohibitively weak at low metallicity, but only for the brightest targets. The choice of spectral resolution is therefore motivated by the science goals.

IL spectroscopy at various resolutions has been applied to many extragalactic systems over the last few decades. This paper focuses on the GCs in M31, the Andromeda Galaxy. As the closest large spiral galaxy to the Milky Way, M31 is an ideal place to begin discussions of IL spectroscopy. Its proximity means that its brightest individual stars can be resolved, though they are still generally too faint for spectroscopy. These observations of GCs in the inner and outer regions will provide insight into M31's assembly history; these observations also probe GCs that are unlike those in the Milky Way, providing insight into the formation of multiple populations in GCs.

## 2. The Globular Cluster System of M31

There have been many spectroscopic observations of M31 GCs, dating all the way back to 1932, when Hubble (1932) reported the radial velocity of a single cluster. Since then, several groups have conducted homogeneous analyses of large sample of GCs or detailed studies of individual GCs. Many GCs have been studied in the inner regions (with projected distances from the center of M31 of $R_{\rm proj} < 25$ kpc), where GCs are found in the disk, the bulge, and the inner halo. Studies of large samples of GCs have found that M31 contains many more GCs than the Milky Way, including a population of more massive GCs (Strader *et al.* 2011), a population of younger GCs (Caldwell *et al.* 2009, 2011), an excess of metal-rich GCs (Caldwell *et al.* 2011), and a significant fraction of GCs that rotate with the galaxy (Caldwell & Romanowsky 2016). The presence of so many GCs, especially so many that are unlike Milky Way GCs, hints that M31's star formation and accretion history has been more intense than the Milky Way's. However, the chemical abundances of many of these inner GCs, particularly the [Ca/Fe] ratios (Schiavon *et al.* 2013; Colucci *et al.* 2009, 2014; Sakari *et al.* 2016; see Figure 1) reveal a GC population that is chemically similar to the Milky Way. The vast majority of the inner GCs are consistent with *in situ* formation in M31 or accretion from a fairly massive dwarf galaxy.

Images of M31's outer halo ($R_{\rm proj} > 25$ kpc) from the Pan-Andromeda Archaeological Survey (PAndAS; McConnachie *et al.* 2009) reveal a number of stellar streams, which are debris from dwarf satellite galaxies that are being accreted into M31. There are 92 GCs known in the outer halo of M31 (Mackey *et al.* 2019), many of which were discovered in PAndAS and proceeding surveys. On average, the outer halo GC population is generally more metal-poor than the innermost GCs, as expected from the overall metallicity gradient in the field stars (Gilbert *et al.* 2014; Ibata *et al.* 2014). However, there are several fairly metal-rich GCs at large projected distances from the center (Colucci *et al.* 2014; Sakari *et al.* 2015; Wang *et al.* 2019), which may have been accreted. Mackey *et al.* (2019) also found that 35−60% of the outer halo GCs are likely to be associated with bright stellar streams, based on their locations and kinematics (also see Veljanoski *et al.* 2014). These streams and GCs were therefore likely accreted within the last few Gyr. The [Fe/H] and [Ca/Fe] ratios of several of these GCs place constraints on the masses of the dwarf galaxies that have created these streams (see Sakari *et al.* 2015). For example, the high [Ca/Fe] abundance of the GC H10, at [Fe/H] $\sim -1.4$ (Sakari *et al.* 2015), suggests that it formed in a fairly massive dwarf galaxy; H10 might also be a member of the

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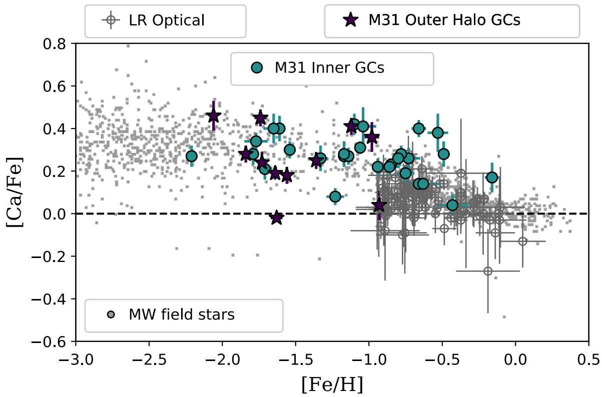


**Figure 1.** [Ca/Fe] ratios as a function of [Fe/H] in Milky Way field stars (grey points; from Venn *et al.* 2004; Reddy *et al.* 2006; Sakari *et al.* 2018) and M31 GCs. The open grey circles show low-resolution IL measurements from Schiavon *et al.* (2013); the sample is limited to metal-rich clusters ([Fe/H] $> -0.95$) because of difficulties modeling the horizontal branch in lower metallicity clusters. The cyan circles and purple stars show high-resolution IL ratios for clusters in the inner ($R_{\rm proj} < 25$ kpc) and outer halo, respectively, from Colucci *et al.* (2014) and Sakari *et al.* (2015, 2016).

SW Cloud, a bright feature to the southwest of M31 (Mackey *et al.* 2019). The chemical abundances of H10 therefore suggest that the progenitor galaxy of the SW Cloud was more massive than the current stream indicates, in agreement with other papers (e.g., McMonigal *et al.* 2016).

Several GCs that are not associated with any substructure look to have similar chemical abundances as dwarf galaxy stars. PA-17 has [Fe/H] $\sim -0.9$ and [Ca/Fe] $\sim 0$, a signature of metal-rich stars in the a galaxy with a similar mass as the Large Magellanic Cloud (Sakari *et al.* 2015). Given its high metallicity, it is possible that PA-17 originated in the Giant Stellar Stream (GSS), the feature that contains the majority of the metal-rich stars in the outer halo (Ibata *et al.* 2014). Although PA-17 does not currently lie on the GSS, models suggest that the GSS has multiple wraps around the galaxy (e.g., Fardal *et al.* 2013)—in this case, PA-17 could have been stripped from the GSS during an earlier encounter. Colucci *et al.* (2014) also found the more metal-poor GC, G002, to have [Fe/H] $\sim -1.6$ and [Ca/Fe] $\sim 0$, similar to the metal-rich GC in the Fornax dwarf spheroidal galaxy (Hendricks *et al.* 2016). The lack of substructure surrounding these two GCs indicates that they were unlikely to have been accreted very recently.

Ultimately, radial velocities, ages, metallicities, and detailed abundances of individual elements can all be derived from IL spectra of extragalactic GCs, providing valuable constraints on the birth sites of the GCs. Future observations will continue to shed light on M31's assembly history.

## 3. Multiple Populations in M31 GCs

Light element abundance variations, commonly referred to as "multiple populations," are a ubiquitous feature in all classical GCs in the Milky Way and its nearby satellites (see Bastian & Lardo 2018). IL spectroscopy provides the opportunity to assess the presence of multiple populations in distant GCs. Since IL spectra provide only a single abundance for an entire GC, star-to-star spreads cannot be directly detected, though they can be inferred. Several papers have demonstrated that M31 GCs show high IL [N/Fe], [Na/Fe], or [Al/Fe], indicating the presence of multiple populations (Colucci *et al.* 2009, 2014;

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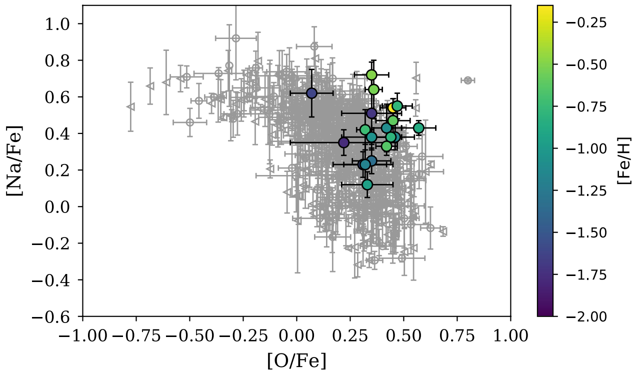


**Figure 2.** IL [Na/Fe] vs. [O/Fe] ratios for a sample of M31 GCs, color-coded by [Fe/H]. The [Na/Fe] ratios come from the high-resolution, optical observations of Colucci *et al.* (2014) and Sakari *et al.* (2016), while the [O/Fe] ratios are from the analysis of *H*-band spectra by Sakari *et al.* (2016). The grey open circles show individual stars from Carretta *et al.* (2009), while the sideways triangles show upper limits in [O/Fe].

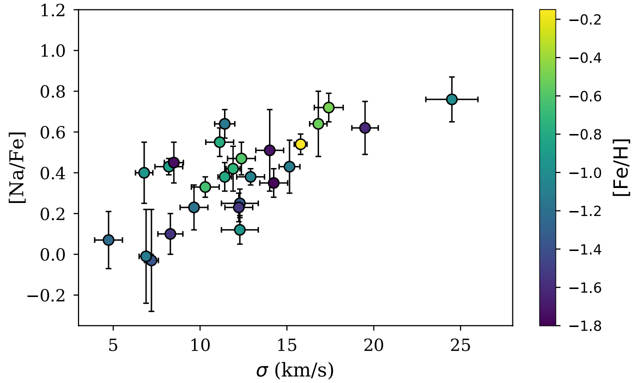


**Figure 3.** IL [Na/Fe] (from Colucci *et al.* 2014, Sakari *et al.* 2016, and Sakari *et al. in prep.*) versus cluster velocity dispersion. The points are color-coded by [Fe/H].

Schiavon *et al.* 2013; Sakari *et al.* 2015, 2016; Larsen *et al.* 2018). Figure 2 shows IL [Na/Fe] vs. [O/Fe] ratios for a sample of M31 GCs, color-coded by [Fe/H]. Many of these GCs fall into the "intermediate" region defined by Carretta *et al.* (2009), which falls between the "primordial" region (where stars have similar Na and O as field stars) and the "extreme" region (where stars are highly enhanced in Na and deficient in O, characteristic of hot H-burning). The location of the M31 GCs in this plot suggests that they host a significant population of Na-enhanced stars.

Clusters with a greater proportion of "intermediate" or "extreme" stars should have higher IL [Na/Fe] ratios. The IL abundances therefore provide an opportunity to investigate trends with cluster properties, such as mass. Schiavon *et al.* (2013) found a significant increasing trend in the IL [N/Fe] ratios with cluster mass. A similar trend is also evident in IL [Na/Fe] with cluster velocity dispersion (Figure 3), one that extends to the massive cluster G1 (Sakari *et al.in prep.*). Similar trends in [Na/Fe] were also found by Colucci *et al.* (2014) and Sakari *et al.* (2016); note that both papers also found hints of similar trends in Mg and Al, but only for some clusters. Altogether, the IL abundance ratios suggest that more massive clusters are able to produce relatively more "intermediate"

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or "extreme" stars, in agreement with results from Milky Way GCs (e.g., Carretta *et al.* 2010). Future observations of more clusters and more elements will enable trends to be investigated as a function of other cluster parameters.

## 4. The Power of IL Spectroscopy

IL spectroscopy of GCs has provided valuable constraints on the assembly of M31's halo, particularly its accretion history. These observations have yielded complementary information to resolved photometry and spectroscopy of M31's brightest individual stars. Future observations will expand the sample of clusters with known metallicities, ages, and detailed chemical abundances, so that the properties of their birth environments can be investigated more thoroughly. For observations beyond the Local Group, it is currently very difficult to observe individual stars, and IL spectroscopy is therefore the best option for probing the kinematics, chemical abundances, and ages of distant systems (e.g., Colucci *et al.* 2013). The advent of extremely large telescopes will allow individual stars in distant systems to be observed and IL spectroscopy to push to fainter targets. New developments in large spectroscopic surveys (e.g., the Maunakea Spectroscopic Explorer; The MSE Science Team *et al.* 2019) will enable large numbers of GCs to be studied simultaneously, providing more holistic characterizations of entire GC systems. Ultimately, advances in technology will enable distant galaxies to be studied at the same level of detail that M31 can be studied today.

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