Detailed Chemical Abundances of Extragalactic Globular Clusters

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Abstract. We are developing a technique for measuring the detailed chemical composition of unresolved, extragalactic globular clusters (GCs) from echelle spectra of their integrated light. To do this, we are using a "training set" of spatially resolved clusters. We scan these clusters to obtain integrated light spectra, and also take spectra of individual stars in these clusters to obtain "fiducial" abundances by the usual analysis methods. We briefly describe here the importance of obtaining detailed abundances, the technique we are developing to analyze integrated light spectra, and the accuracies that can be obtained with our technique.

1 The Advantage of Detailed Abundances

Low resolution spectroscopy and photometry of globular clusters (GCs) in other galaxies reveal that GCs form throughout the lifetimes of galaxies and in major star formation episodes. The abundance patterns and dynamics of the Milky Way GCs provided the first strong constraints on the formation of our own galaxy [6, 12]. The fact that extragalactic GC systems are known to be good tracers of the total star formation and host galaxy mass suggests that GC abundance patterns and kinematics provide strong constraints on galaxy formation in general.

In the Milky Way, especially useful formation diagnostics have come from the abundances ratios of key elements. Particularly useful are "α-elements" (e.g. Mg, O, Si, S, Ca, Ti), which come almost exclusively from Type II supernovae with progenitors that evolve on timescales of a few $\times 10^6$ yrs, and iron-peak elements (e.g. Cr, Mn, Fe, Co, Cu Zn), which have a major contribution from Type Ia supernovae with progenitors that evolve on timescales of $\sim 10^9$ yrs. The ratios of these elements, α/Fe, therefore trace the rate and duration of star formation. Unfortunately, high resolution abundances are very difficult to obtain for individual stars beyond the Milky Way and are just recently becoming available in the nearest dwarf satellite galaxies with 8-m class telescopes. A few luminous supergiants can be observed with Keck beyond the LMC, reaching to M31 (e.g. [16]); however, these massive, young stars only probe the current gas composition. Only red giant stars can provide the fossil evidence of a galaxy's enrichment history, and these are too faint to observe individually at the required spectral resolutions beyond distances of ∼100 kpc.

It is possible, however, to obtain high resolution, high signal to noise spectra of GCs as far away as 4 Mpc with *current* telescopes given the low (roughly 5–25 km/s) velocity dispersion of GCs. It is important to note that the formation constraints available from detailed abundance ratios of GCs will never be obtainable from photometry or low-resolution line indices such as the Lick system for at least two reasons. First, abundances inferred from line indices depend strongly on the abundance ratios of the spectra used to calibrate the line system (e.g. [15, 14]). Second, and more fundamentally, self-enrichment in GC stars can cause the Mg/Fe ratio to deviate from that with which the stars formed and from the abundance ratio of α-elements not affected by self-enrichment; unfortunately, estimates of the α/Fe abundance in the Lick system come mostly from strong Mg lines.

While the Milky Way clusters appear to be exclusively old and metal poor, there are examples of GC systems which appear to cover a range of ages and abundance patterns even within the Local Group. In addition to the young ($<$ 5 Gyr) LMC clusters, some GCs in the disk of M31 also appear to be young, although their ages are difficult to determine (see [5] and references therein). Moreover, a range of GC ages may be common in galaxies with complex merger histories [13]. Note that for young GCs with unusual abundance ratios, the interpretation of Lick indices would depend on uncertain theoretical calibrations (e.g. [11]).

2 Abundance Analysis from Integrated Light

Chemical abundance analysis typically involves comparing the measured equivalent width (EW) of lines in the spectrum of a single star with predicted EWs that are based on spectrum synthesis calculations using model atmospheres. By contrast, abundance analysis of an unresolved GC must be based on measured EWs in the integrated light of the cluster (see Fig. 1). We have developed a technique that will let us interpret measured EWs in IL spectra by incorporating a CMD in the calculation of light-weighted, predicted EWs. To check the reliability of our results we are using a "training set" of Milky Way and LMC GCs, that span the full available range of age, metallicity, and α/Fe-ratios. This method is outlined below (see [1, 2] for details).

Our analysis uses model CMDs, i.e. isochrones derived from stellar evolution tracks combined with a Kroupa IMF [9]. Observed CMDs can also be used to analyze the Milky Way clusters in the training set, but that does not present an interesting test-analysis for extragalactic, unresolved clusters. We treat these isochrones as possible CMDs without assuming that the ages or abundances are correct. Our analysis then begins with the Fe I and Fe II lines, of which there are many at a wide range of excitation potentials and wavelengths. For any isochrone, we produce stellar atmospheres for the stars

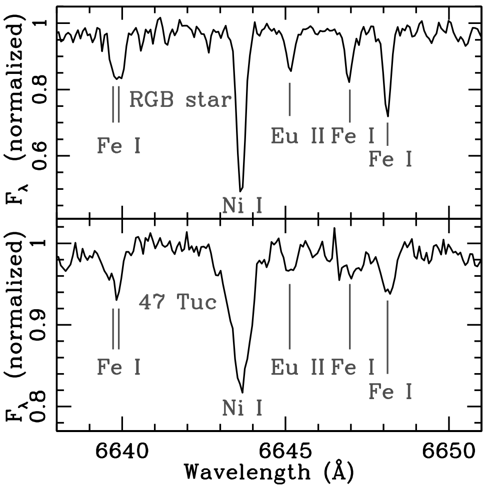

Fig. 1. A sample region of the integrated light spectrum of 47 Tuc compared with the spectrum of an RGB star in that cluster. Note that the lines marked in the RGB star can be readily detected in the integrated light of 47 Tuc, albeit broadened by the ~13 km sec^{-1} σ_v of the GC and weakened by the contribution of light from hotter stars. The isolated Eu II line at 6645 Å has an equivalent width of ~ 15 mÅ in the integrated light.

in the model CMD and synthesize each Fe line for those stars. We then vary [Fe/H] in the line synthesis until the light-weighted, combined EW for each Fe line matches the observed EW. This gives us the inferred value of [Fe/H] for each line. We average these together to obtain [Fe/H] for each isochrone.

As an example of this analysis, we show the inferred value of [Fe/H] for 47 Tuc from the observed Fe I and Fe II lines in its integrated light spectrum (see Fig. 2). By requiring that the [Fe/H] solution for all Fe I lines be independent of excitation potential, we can narrow the range of acceptable isochrones to those older than 5 Gyr. For those acceptable isochrones, the Fe I and Fe II lines give a unique solution at a small range of [Fe/H] around −0.65 dex. We use $\log gf$ values calibrated to Arcturus to reduce systematic errors. We then adjust the best-fit isochrone (10 Gyr, [A/H]=−0.63) for mass segregation in the core of the cluster and repeat the analysis. This changes the [Fe/H] abundance by only −0.05 dex. Using this adjusted isochrone, we then derive abundances by the same procedure for 18 other elements for which we can measure lines in the integrated light. We are able to obtain abundances for iron-peak elements (Sc, V, Cr, Mn, Fe, Ni), α-elements (Si, Ca, Ti), light elements (Na, Mg, Al), and neutron capture elements (Y, Zr, Ba, La, Nd, Eu) [2]. Our results are very similar to those obtained from standard analysis of single stars in 47 Tuc [4,3,8,10]. In addition, we detect significant (~ 0.2 dex) enrichment in Na and depletion of Mg relative Fe compared to the relative abundances of other α elements ([α/Fe]≈ 0.3 dex). This is consistent with

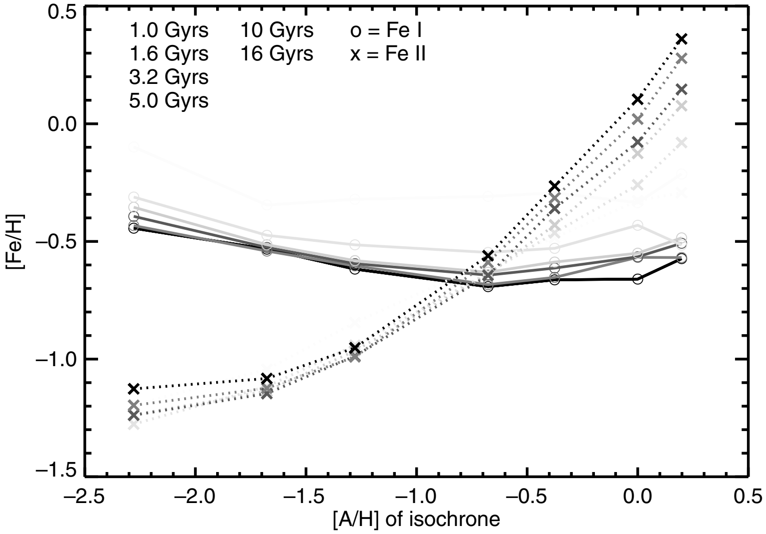

Fig. 2. [Fe/H] from the integrated light analysis of 47 Tuc. The x-axis shows the abundances of the Padova isochrones; the y-axis shows the inferred value of [Fe/H] from Fe I (*dots*) or Fe II (*boxes*) lines. The age (indicated by the *line color*) and [A/H] of the isochrone are not important for the analysis, but are used here to label the respective isochrones.

the known variation of Na and Mg from star to star in this and other Milky Way clusters due to self-enrichment within the cluster (see [7] and references therein).

Additional constraints on the isochrones will come from the Hα, Hβ, Hγ, and Hδ line profiles, which are sensitive to horizontal branch morphology; most of these lines cannot be accurately measured at low resolution. We can use these profiles to adjust the morphology of the horizontal branch in the isochrones in the cases where the presence of a blue horizontal branch is clearly indicated by the spectra.

This method will allow us to constrain the detailed chemical enrichment histories of stellar populations in normal galaxies within 4 Mpc for the first time. Moreover, each GC we observe and analyze at high resolution becomes an empirical calibrator for the line index systems, will always be applicable at larger distances than can be observed at echelle resolutions.

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