A NEW METHOD FOR MEASURING METALLICITIES OF YOUNG SUPER STAR CLUSTERS

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ABSTRACT

We demonstrate how the metallicities of young super star clusters can be measured using novel spectroscopic techniques in the J–band. The near-infrared flux of super star clusters older than ∼6 Myr is dominated by tens of hundreds of red supergiant stars. Our technique is designed to harness the integrated light of that population and produces accurate metallicities for new observations in galaxies above (M83) and below (NGC 6946) solar metallicity. In M83 we find [Fe/H] = +0.28 ± 0.14 dex using a moderate resolution of R∼3500 J–band spectrum and in NGC 6496 we report [Fe/H] = −0.32 ± 0.20 dex from a low resolution spectrum of R∼1800. These measurements correspond to iron abundances of 1.9× solar and 0.5× solar, respectively—results supported by literature studies of the disks of M83 and NGC 6496. Recently commissioned low resolution multiplexed spectrographs on the VLT (KMOS) and Keck (MOSFIRE) will allow accurate measurements of super star cluster metallicities across the disks of distant star-forming galaxies with single night observation campaigns using the method presented in this letter.

Subject headings: galaxies: abundances, galaxies: star clusters, stars: supergiants

1. INTRODUCTION

Measuring metallicities in star-forming galaxies is a ubiquitous goal across the field of extragalactic astronomy. The evolutionary state of a galaxy is imprinted in the central metallicity and radial abundance gradient of iron- and α-group elements. Observed trends in these measurements across ranges of galactic mass, redshift, and environment constrain the theory of galaxy formation and chemical evolution. Central metallicity is dictated by galactic mass, a relationship encoded by the initial properties and evolution of these objects (Lequeux et al. 1979; Tremonti et al. 2004; Maiolino et al. 2008). Radial metallicity gradients provide a wealth of information needed to describe the complex dynamics of galaxy evolution including clustering, merging, infall, galactic winds, star formation history, and initial mass function evolution including clustering, merging, infall, galactic winds, star formation history, and initial mass function. The evolutionary state of a galaxy is imprinted on the VLT (KMOS) and Keck (MOSFIRE) will allow accurate measurements of super star cluster metallicities across the disks of distant star-forming galaxies with single night observation campaigns using the method presented in this letter.

Subject headings: galaxies: abundances, galaxies: star clusters, stars: supergiants

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tracers with their flux-maximum in the IR will have a clear advantage. The extremely luminous red supergiant stars (RSGs)—which emit $10^4$ to $\sim10^6$ L/$L_\odot$ largely in the infrared (Humphreys & Davidson 1979)—thus become ideal targets for measuring extragalactic cosmic abundances. Complications due to the densely packed spectral features synonymous with the cool, inflated atmospheres of RSGs are minimized in the J-band. Here the dominant features are isolated atomic lines of iron, titanium, silicon, and magnesium. Molecular lines of OH, H$_2$O, CN, and CO manifest weakly or not at all in this bandpass. A new technique proposed by Davies et al. (2010) has demonstrated that quantitative, medium-resolution spectroscopy in the J-band can determine metallicities accurate to $0.15$ dex for a single RSG, and continued work has increased this accuracy to $\sim0.1$ dex. Still, a principle limitation of the quantitative spectroscopy of stars is distance, and for the 8-meter class telescopes, supergiant studies are limited to $\sim10$ Mpc (Evans et al. 2011).

Stellar techniques can be extended by exploiting the integrated light of coeval ensembles of stars. In star-forming galaxies, such populations exist as super star clusters (SSCs), the result of single bursts of star formation creating a population with a stellar mass of $10^4$-$10^6$ M$_\odot$ in a tight association (Portegies Zwart et al. 2010). Roughly 6 Myr after formation the first massive stars evolve into RSGs, and by 7 Myr the population of tens to hundreds of RSGs dominate the near-IR light (Gazak et al. 2013). With $\geq 90\%$ of the J-band flux due to RSG members, these objects can be used for quantitative spectroscopy at far greater distances than for single supergiants.

In this letter we demonstrate a new method for the measurement of metallicities of young super star clusters—and thus the disks of star-forming galaxies—within $\sim35$ Mpc and across a wide range of galactic metallicity. To this end we have collected J-band spectra of two SSCs, one in the disk of the super-solar metallicity galaxy NGC5236 (M83) at 4.8 Mpc and one in the sub-solar metallicity galaxy NGC 6946 at $\sim6$ Mpc. This represents the pioneering first step towards studying the disks of star-forming galaxies with stellar spectroscopy over distances extending well beyond the limitations of single-supergiant techniques. To accomplish this we observed M83–f–117 (referred to as NGC5236-805 in Larsen & Richtler 2004), a $m_J=16.1$ SSC at an age of $\sim20$ Myr and mass of $2\times10^5$ M$_\odot$ in the nearby spiral galaxy M83. For the sub-solar case we targeted NGC 6946-1447, a $m_J \sim13$ SSC at an age of $\sim10$-15 Myr with a mass of $\sim10^5$ M$_\odot$.

2. OBSERVATIONS

Observations of M83–f–117 ($\alpha=13^h37^m02^s$, $\delta=-29^o52'13''$) were obtained using ISAAC/VLT (Moorwood et al. 1998) on the night of 2012 March 13 under the ESO programme 089.D-0750(A) (P.I. Bastian, N). We employed the 1$''$.0 slit width with a central wavelength of 1.17 $\mu$m and integrated on source for two hours using an ABA nod pattern. We observed a B-type star with a similar airmass as a telluric standard. The spectra were reduced following the methodology outlined in Davies et al. (2012). Briefly, this reduction consists of the subtraction of nod pairs, flat-fielding, rectification to correct for distortion in the spatial and dispersion directions, sky subtraction, and cosmic-ray removal.

NGC6946-1447 ($\alpha=20^h34^m52^s$, $\delta=60^o08'14''$) was observed on 2011 August 3 and 2011 October 12 with the near-IR medium resolution SpeX spectrograph mounted on the 3-meter NASA InfraRed Telescope Facility (IRTF) on the summit of Mauna Kea (Rayner et al. 2003). SpeX was set up in short wavelength cross-dispersed mode with a 0$''$.3 slit. The data were reduced and telluric-corrected using the IDL spectral extraction package Spextool (Vacca et al. 2003; Cushing et al. 2004). The observed spectra are plotted in Figure 1.

3. ANALYSIS

We fit the observed spectra using synthetic spectra calculated from a grid of MARCS model atmospheres (Gustafsson et al. 2008). The models are calculated in LTE and are one-dimensional, spherically extended, and in hydrostatic equilibrium. The coverage of the MARCS grid can be found in Table 1. Synthetic model spectra are
calculated in NLTE for iron, titanium and silicon using the atomic models and codes described by Bergemann et al. (2012, 2013). These atoms provide the strong lines crucial for the analysis in the J–band. The contributions by all other atoms and molecules are included in LTE. We assume solar values for the ratios of alpha elements to iron (α/Fe).

We begin by iteratively fitting the spectral resolution of our data by finding the best model and resolution pair by minimizing the χ² statistic. Spectral broadening due to cluster dynamics is inseparable from resolution effects. We find a resolution of R_{eff}=3500 for the M83 ISAAC spectrum and R_{eff}=1800 for the NGC6946 object with SpeX. These values are consistent with the expected capability of the instruments. The measured R_{eff} is applied to the entire grid of synthetic spectra and a four-dimensional χ² grid is calculated using the strong isolated diagnostic features of Fe i, Si i, and Ti i across the spectral window.

Best fit parameters are extracted from the χ² grid as follows. We construct six two-dimensional slices around the best fit model such that each χ² slice is locked to two “best model” parameters and varies over the remaining. Each slice is interpolated onto a new grid at 10× the parameter resolution. The interpolated χ² minimum provides a measurement of the two “free” parameters for each slice: over six slices we accumulate three measurements of each parameter. The best fit values which we tabulate in Table 1 are the average of those three measurements.

Standard χ² statistics requires that the deviations between data and model in each wavelength bin be gaussian in nature. Gaussian deviates cannot be assumed for the following reasons: the input spectrum is contaminated by other spectral types at the ≈5% level, the models are likely to contain systematic errors, and residual features due to imperfect telluric corrections are not randomly normal across the spectrum. Instead we employ a monte carlo test to assess the 1σ uncertainties in our parameter extractions. This test begins by interpolating a model to the extracted fit parameters. We produce 1000 noise spectra as follows: generate a random gaussian deviate for each pixel such that the global standard deviation of the noise spectrum is characteristic of the signal-to-noise ratio of the observed spectrum. We iterate over the noise spectra, adding each to the interpolated model and feeding the resulting spectrum through our fitting procedure. Each noisy model produces a set of best fit parameters, of which the central 68% represents a classic 1σ region of uncertainty without assuming gaussian error processes.

We experiment with the effect of ∼5-10% contaminative flux from the remaining stellar flux of the SSC (Gazak et al. 2013). This is accomplished by assuming a flat spectral dilution and removing 5% and 10% of the median flux of our observed spectra. The effect is to deepen the absorption features—it is in the depths of strong lines that the flat spectrum contributes the largest percent flux. We repeat our fitting procedure after scaling out 5 and 10% of the median flux. These adjusted spectra yield consistent measurements of [Fe/H]; measurement uncertainties dominate the shift in metallicity due to deeper absorption features.

4. DISCUSSION

4.1 M83

Multiple investigations of M83’s chemical enrichment using both “direct” and “strong line” H II methods have produced abundance gradients across the inner and outer disk of the galaxy (Bresolin & Kennicutt 2002; Bresolin et al. 2005, 2009b). While plagued by the biases and uncertainties discussed in §1, those papers produce lower limits for the [O/H] enrichment in the inner disk of M83 of 1.6× solar and admit that the values require refinement. In particular, Bresolin et al. (2009b) find that two common calibrations of the H II region method on the same dataset return identical slopes for the metallicity gradient but the measurements of the overall metallicity level vary by 0.47 dex—a factor of nearly three. Furthermore, early work on H II regions returned values of 2-10× solar oxygen abundance (Dufour et al. 1980). While current work settles around more modest values of 1.5-2×, it is clear that the calibration of H II metallicities exceeding solar remains problematic.

In Table 2 we tabulate the parameters measured from our spectra corrected for a flat 5% flux contamination. By applying our method for extracting metallicities from the J-band spectra of RSGs we measure a disk metallicity of 1.9× solar ([Fe/H] = +0.28 ± 0.14) for M83. This value is consistent with new, careful H II measurements by Bresolin et al. (2005) who measure a metallicity from H II auroral lines in the inner disk of [O/H] = 1.78× solar.

4.2 NGC 6946

Measurements of the central abundance and gradient of NGC 6946 suffer from the same setbacks of the H II method. Using two empirical calibrations, Moustakas et al. (2010) measure a central metallicity and metallicities at the isophotal radius R_{25} (Z_{⊙}, Z_{R_{25}}) of 3.0× solar and 1.5× solar for one calibration and 0.6× solar and 0.4× solar based on an alternate calibration. Cédrés

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Note. — The parameter space of the MARCS grid of stellar atmospheres used in this work.

\^a [Fe/H]_{⊙} = 0.0

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Note. — Parameter fits to the observed spectra.

\^a [Fe/H]_{⊙} = 0.0


et al. (2012), using the same two calibrations, measure \( Z_0, Z_{\text{RSG}} \) of 3.4 and 1.7× solar for one and of 0.8 and 0.3× solar for the other. In this case three of the four measured gradients are consistent but the offsets in central metallicity between calibrations are factors of four to five (0.63-0.68 dex). We targeted the SSC NGC 6946-1447 because it is the target of a careful, high-resolution analysis: Larsen et al. (2006) use \( R = 25,000 \) H and K spectra and a proprietary spectral synthesis code to measure \( [\text{Fe/H}] = -0.45 \pm 0.08 \) (0.35× solar) and \( \alpha/\text{Fe} = +0.22 \pm 0.11 \).

In NGC 6946 we measure a metallicity of \( \sim 0.5 \times \) solar \( ([\text{Fe/H}] = -0.32 \pm 0.20) \). Our measurement agrees within 1\( \sigma \) to the published value in Larsen et al. (2006), but we note that the resolution of our NGC 6946-1447 spectrum is less than ideal. Even with this observation at modest \( R \approx 1800 \) we can claim that the disk of this galaxy is significantly sub-solar in metallicity, something that \( \text{H\ II} \) region methods cannot do without an arbitrary choice of calibration. Still, the J-band SSC method is better suited to spectral resolutions above \( R \approx 2500 \). It is important to note that Larsen et al. (2006) also find a significant enrichment in \( \alpha \)-elements relative to iron. Our assumption of a solar \( \alpha/\text{Fe} \) will then skew our measured \( [\text{Fe/H}] \) to higher metallicities. Assumming the SSC does have a super-solar \( \alpha/\text{Fe} \), the silicon and titanium lines in our models will be globally too shallow relative to iron. In this case the best global fit to the spectrum using our grid will require a model with higher \( [\text{Fe/H}] \) and may explain the difference between this work and Larsen et al. (2006).

### 4.3. Summary

Independent techniques to measure the metallicities and gradients across the disks of star-forming galaxies are critical to our understanding of galaxy formation and evolution. Such techniques are also poised to help disentangle the biases and poorly understood systematics inherent to “strong line” \( \text{H\ II} \) methods which are routinely applied to massive datasets of galaxies. Those techniques which have proven most successful are based on the quantitative spectroscopy of supergiant stars. In this letter we have introduced a method capable of avoiding the extreme systematic uncertainties inherent to \( \text{H\ II} \) region “strong line” methods. We utilize the reliable quantitative spectroscopic of supergiant stars in a new method which remains observationally efficient with existing telescopes well beyond the Local Group galaxies. This is accomplished by targeting young super star clusters—coeval stellar populations dominated in the near-IR by red supergiant stars. This J-band technique is ideally suited to multi-object \( R \sim 3000 \) J-band spectrographs. Two such instruments have recently been commissioned, KMOS on the VLT and MOSFIRE on Keck, allowing for studies of super star clusters in star-forming galaxies up to conservative distance estimates of 35 Mpc in galaxies across the northern and southern skies. Indeed, an observation campaign is planned to push beyond this pioneering first step and collect spectra of super star clusters across the disk of M83 to provide an independent measurement of central metallicity and the abundance gradient of this star-forming galaxy.

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