QUANTITATIVE SPECTROSCOPIC J–BAND STUDY OF RED SUPERGIANTS IN PERSEUS OB-1

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ABSTRACT

We demonstrate how the metallicities of red supergiant (RSG) stars can be measured from quantitative spectroscopy down to resolutions of ≈3000 in the J-band. We have obtained high resolution spectra on a sample of the RSG population of h and χ Persei, a double cluster in the solar neighborhood. We show that careful application of the MARCS model atmospheres returns [Fe/H] measurements consistent with solar metallicity. Using two grids of synthetic spectra—one in pure LTE and one with NLTE calculations for the most important diagnostic lines—we measure [Fe/H] = +0.04 ± 0.10 (LTE) and [Fe/H] = −0.04 ± 0.08 (NLTE) for the sample of eleven RSGs in the cluster. We degrade the spectral resolution of our observations and find that those values remain consistent down to resolutions of less than λ/δλ of 3000. Using measurements of effective temperatures we compare our results with stellar evolution theory and find good agreement. We construct a synthetic cluster spectrum and find that analyzing this composite spectrum with single-star RSG models returns an accurate metallicity. We conclude that the RSGs make ideal targets in the near infrared for measuring the metallicities of star forming galaxies out to 7-10 Mpc and up to ten times farther by observing the integrated light of unresolved super star clusters.

Subject headings: Red 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 (Prantzos & Boissier 2000; Garnett 2004; Colavitti et al. 2008; Yin et al. 2009; Sánchez-Blázquez et al. 2009; De Lucia et al. 2004; de Rossi et al. 2007; Finlator & Davé 2008; Brooks et al. 2007; Köppen et al. 2007; Wiersma et al. 2009).

The pursuit of these scientific goals has been undermined by the difficulty of obtaining reliable metallicities. Investigations tend to rely on spectroscopy of the emission lines of H\textsc{ii} regions. The observationally efficient “strong line” analysis methods use the fluxes of the strongest forbidden lines relative to H\textbeta. These methods require empirical calibration and choosing different commonly used calibrations yields varying and sometimes conflicting results from the same set of observations. Both the slope and absolute scaling of metallicity are susceptible to choice of calibration: the mass-metallicity gradient across all galaxies and the radial gradients within individual galaxies can change from steep to flat while the overall metallicity can shift by a factor of up to four (Kewley & Ellison 2008; Kudritzki et al. 2008; Bresolin et al. 2009). Even the more physical “Tc-based method” (which utilizes auroral lines to remove the need for “strong line” calibrations) is potentially subject to biases—especially in the metal rich regime characteristic of the disks of all massive spiral galaxies (Bergemann et al. 2014; Stasińska 2005; Bresolin et al. 2005; Ercolano et al. 2010; Zurita & Bresolin 2012).

One technique which avoids the uncertain calibrations of the “strong line” H\textsc{ii} region method is the quantitative spectroscopy of supergiant stars. Blue supergiants have become a powerful tool for measuring metallicities, gradients, and distances to galaxies in and beyond the Local Group (WLM – Bresolin et al. 2006; Urbaneja et al. 2008; NGC 3109 – Evans et al. 2007; IC1613 – Bresolin et al. 2007; M33 – U et al. 2009; MS1 – Kudritzki et al. 2012). This technique, while extremely promising, may also be subject to systematic uncertainties and needs to be checked by independent methods. Moreover, it requires optical spectroscopy. However, next generation telescopes such as the TMT and E–ELT will be optimized for observations at infrared wavelengths, using adaptive optics supported multi object spectrographs. Thus, we need bright abundance tracers which radiate strongly in the IR. Such stars—including red giants, the asymptotic giant branch, and red supergiants—will have a clear advantage in the future.

The extremely luminous red supergiant stars
Fig. 1.— Spectral library of RSGs observed at high resolution with IRCS on Subaru. The main diagnostic atomic lines are labeled. Best fitting NLTE models are over plotted in red. The Mg i line is not included in the fit because it is calculated in LTE but subject to strong NLTE effects. NLTE calculations for Mg i will be implemented soon. Plots are arranged by spectral type (see Table 1).
(RSGs)—which emit $10^5$ to $10^6$ 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, extended 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) (henceforth DFK10) has demonstrated that quantitative, medium resolution spectroscopy (R $\lambda/\Delta \lambda \sim 2000$) in the J–band can determine metallicities accurate to $\sim 0.15$ dex for a single RSG. While a principal limitation of the quantitative spectroscopy of stars is distance, these supergiant studies using 8-meter class telescopes have the potential to be extended to $\sim 10$ Mpc (Evans et al. 2011).

The J–band technique is thus poised to study a substantial volume of the local universe, one containing groups and clusters of galaxies. The determination of accurate abundances for the RSG populations of star forming galaxies in this volume will provide an unparalleled observational constraint for models of galaxy formation and evolution. An increased utilization of supergiant stars may also aid in the proper development of the observationally efficient H$_2$-region methods while providing independent alternate measurement technique to the blue supergiants.

Still, DFK10 is a pilot study of the J–band technique and the analysis methods to best study these stars requires careful development and testing. Studies of RSGs have classically required high resolutions (R $\sim 20,000$) in the H–band in order to separate and study the dense forest of atomic and molecular features present throughout their spectra. Part of this requirement is driven by the scientific desire to study stellar evolution, for which abundances of C, N, and O are important. The J–band technique returns no information specific to CNO processing and in exchange avoids the high observational overheads inherent to such studies. This repurposing for extracting global chemical enrichment at modest resolution is novel.

Multiple facets of ongoing research investigate the limitations and systematic uncertainties of the technique in great detail. Davies et al. (2013) provide a thorough investigation of the temperature scale of RSGs in the LMC and SMC and conclude that previous work at optical wavelengths measure effective temperatures which are too cool for these RSGs. The temperature gradients of the MARCS 1D stellar evolution models become overly steep in the outer atmosphere. This results in lower local temperatures at the formation radii of TiO bands and the models then predict stronger TiO bands than are observed. This discrepancy manifest in low measurements of effective temperature and is a problem greatly reduced at near-IR wavelengths which correspond to deeper atmospheric layers. Additional research is assessing the significance—and observational effects—of the local thermodynamic equilibrium (LTE) calculations for synthetic spectra produced from the MARCS models. Departures from LTE have been calculated for iron and titanium (Bergemann et al. 2012) and silicon lines (Bergemann et al. 2013) in the J–band. Due to the low density environments in the extended atmospheres of RSGs, NLTE effects are noticeable and can be significant. For this work we have access to synthetic spectra calculated in both LTE (TURBOSPECTRUM — Alvarez & Plez 1998; Plez 2012) and with iron, titanium, and silicon lines in NLTE using the results from Bergemann et al. (2012, 2013).

The aim of this paper is to carefully study the proposed methods of DFK10 and develop a proper understanding of the strengths, limitations, and systematics of the technique. The ideal target for such a study is a nearby coeval population of RSGs in the Galaxy, such that we may study the stars as individual objects and test the potential of utilizing distant super star clusters (SSCs) in which the stellar population becomes an unresolved point source. Theoretical predictions by Gazak et al. (2013) show that in young SSCs the RSG population dominates the near-infrared flux. In this case the metallicity of the cluster could be extracted by studying the entire cluster as a single RSG. In order to accomplish these goals we target a galactic population of RSGs in the h and $\chi$ Persei double cluster (henceforth Perseus OB-1) by performing quantitative spectroscopy on high resolution, high precision spectra collected using the Subaru Telescope atop Mauna Kea. The presence of a large population of supergiant stars limits the age of Perseus OB-1 to tens of millions of years, and offers a laboratory for the full range of stellar astrophysics—from IMF to post-main sequence stellar evolution. Currie et al. (2010) present a careful photometric and spectroscopic study of the double cluster and refine the physical parameters of this system. They find an age of $14 \pm 1$ Myr and estimate a minimum total stellar mass of 20,000 $M_\odot$. Ages are determined using three methods which return results in good agreement: main sequence turnoff fitting, the luminosities of red supergiants in the clusters, and pre main sequence isochrone fitting. Solar metallicity is a sensible assumption for such a young population in the Milky Way, and studies of the B and A population of supergiant and giant stars—while incomplete—find solar or slightly sub-solar abundances. Our high resolution spectra of eleven RSGs in Perseus OB-1 provide an ideal dataset for testing multiple aspects of this project.

This paper is organized as follows. In §2 we discuss the observation and reduction of our spectral database. §3 contains a description of our atmosphere models and synthetic spectra as well as an outline of the analysis method we have developed. We discuss the results of our fitting in §4 We discuss and summarize the results of this work in §5.

2. OBSERVATIONS

On the nights of UT October 4 and 5 2011 we observed 11 of the 21 RSGs in the Perseus OB-1 cluster using the InfraRed Camera and Spectrograph (IRCS — Kobayashi et al. 2000) mounted on the Subaru telescope atop Mauna Kea. The observations took place in non-photometric weather with variable partial cloud cover. We operated to achieve maximum spectral resolution, using the 0″.14 longslit in echelle mode with natural guide star adaptive optics.

Spectra of targets and telluric standards were bias corrected, flat fielded, extracted and calibrated using standard packages in IRAF. Due to the variable cloud cover
3. ANALYSIS

3.1. Atmospheric Models and Synthetic Spectra

For the analysis of RSGs in our sample we utilize two grids of synthetic spectra calculated using LTE and NLTE radiative transfer. Both grids of model spectra are calculated using as input an underlying grid of MARCS model atmospheres (Gustafsson et al. 2008). These atmospheric models are calculated in 1D LTE and, while not sharing the complexity of state of the art 3D models, are well suited for this work. Notably, the MARCS model atmospheres have been well tested in the literature and converge quickly such that large grids are possible.

The MARCS grid used in this work covers a four dimensional parameter space including Effective Temperature, log gravity, metallicity, and microturbulence ($T_{\text{eff}}$, log $g$, [Fe/H], $\xi$). The dimensions of this grid can be found in Table 2.

The grids of synthetic model spectra used in the analysis of this paper are calculated in first in LTE using turbospectrum (Alvarez & Plez 1998; Plez 2012), and second with NLTE diagnostic lines (iron, titanium, and silicon) using the codes developed in Bergemann et al. (2012, 2013). See Figure 6 for a visualization of the effects of the NLTE corrections.

3.2. Continuum Fitting

At high resolutions it is straightforward to scale a model to the continuum level of the data. This is accomplished by selecting the flat regions of the spectrum, performing a polynomial fit to the ratio of those points to the matching observed flux as a function of wavelength, and then dividing the full wavelength range of the model by this derived fit. At lower resolutions the effort to correct the continuum increases in complexity as the dense forest of weak molecular lines blur together to form a “pseudo-continuum” such that the entire observation technically lies below continuum level. It is not possible to know a priori how to then properly correct for the continuum as the depth below the natural continuum is a function of the stellar parameters themselves, especially metallicity, the primary target of our work. Instead we fit the pseudo continuum of both data and model. While this does not represent the true continuum, the consistent approach provides a proper way to match data to model.

We do this by selecting the ten percent of data points in any given model with normalized flux nearest to unity, assume this is the continuum, then fit and correct the same way as before with a low order polynomial.

3.3. Matching Model Spectra to Data Resolution and Macroturbulence
We extract the best fit parameters. The methodology involves adopting the model with the lowest overall $\chi^2$ value. Upon completion, we have a set of local minimum values for each parameter the zone of $\pm 1\sigma$ is contained between the 15.9 and 84.1 percentile levels. This technique accounts for the noise level in our data as well as any effects based on the spacing in our model grid. We adopt a minimum $\sigma$ value of 20% of the grid spacing for each parameter as we consider a fit more precise than that to be unrealistic given the possibility of nonlinear behavior between grid points. In general, our measured significance in metallicity lies above this minimum $\sigma$ value such that we may confidently trust that our grid is fine enough in metallicity space for this work. In this work, we find that lines of Mg I are never well fit. While the cause is under investigation, for this analysis, we mask out lines of Mg I before calculating $\chi^2$.

### 3.4. Determination of Stellar Parameters and Errors

After calculating a full four-dimensional grid of $\chi^2$ values, we extract the best fit parameters. The methodology is as follows. We begin by selecting the “best” model—the model with the lowest $\chi^2$ value. We use the parameters of this model to inform the selection of six two-dimensional $\chi^2$ planes (see Figure 2). Functionally, two parameters are locked at the “best values” for each plane and the remaining two parameters are varied against each other. We interpolate the $\chi^2$ grid of each plane onto a parameter grid four times as dense and take the minimum of the dense grid as the best fit values for the two free parameters. After completing this procedure for each of the six planes, we have three measured best values for each parameter. We average these values to arrive at a final fit for each parameter.

We assess the significance of our parameter fits with a Monte Carlo simulation. We begin by constructing a spectrum at the exact extracted parameters by linearly interpolating between points in the model grid. For each of 1000 trials, we add random Gaussian noise of strength characteristic of the signal to noise of the measured spectrum. We fit each noisy interpolated model as described in this section. For each trial, we determine the fit parameters and, after completing the computations, analyze the distributions of fitted values for each parameter. In each parameter, the zone of $\pm 1\sigma$ is contained between the 15.9 and 84.1 percentile levels. This technique accounts for the noise level in our data as well as any effects based on the spacing in our model grid. We adopt a minimum $\sigma$ value of 20% of the grid spacing for each parameter as we consider a fit more precise than that to be unrealistic given the possibility of nonlinear behavior between grid points. In general, our measured significance in metallicity lies above this minimum $\sigma$ value such that we may confidently trust that our grid is fine enough in metallicity space for this work. In this work, we find that lines of Mg I are never well fit. While the cause is under investigation, for this analysis, we mask out lines of Mg I before calculating $\chi^2$.

### 4. RESULTS

#### 4.1. The RSG population of h and χ Persei

Initial fits of the spectral database observed for this work measure a slightly sub-solar population metallicity for the Perseus OB-1 RSGs. We measure $[\text{Fe/H}] = +0.04 \pm 0.10$ (LTE) and $[\text{Fe/H}] = -0.04 \pm 0.08$ (NLTE), where...
the ±σ values denote the standard deviation of the sample. Estimates of the global metallicity of the cluster are more precise, as the error in the mean scales the reported σ’s by N−0.5 = 0.3 for our population of eleven stars.

The LTE model grid measures higher metallicities for cluster stars than the NLTE grid. This is to be expected; the cores of our strongest diagnostic lines (FeI, TiI, and SiI) are deeper in the NLTE case (see Figure 6). For any given observed spectrum, a NLTE fit will provide a lower measurement of metallicity. We find that using a fully LTE grid of MARCS models induces, on average, a shift in [Fe/H] of +0.07 dex for RSGs near solar metallicity.

4.2. Parameter Stability vs. Spectral Resolution

The power of the methodology presented in DFK10 is the need for only moderate resolution spectral data. Our high resolution spectral catalogue allows for the first systematic tests of the resolution limits of the J-band technique. In the following tests we degrade the resolution of our observed spectra and those spectra become the inputs to our fitting procedure. To achieve this degradation we convolve the high resolution observed spectrum with a gaussian with characteristic width of FWHM = √((λ/λ′)² − (λ/λdata)²), where λ represents the output resolution of the “new” spectra.

We then follow identically the techniques presented in §3, treating each degraded spectra as an independent observation using nothing learned from the actual observations. We iterate from R of 10,000 to 2,000 in steps of 1,000. At each resolution we calculate the average and standard deviation of measured metallicity for the eleven objects. These values have been plotted in Figure 3. We find that the fitted average metallicity remains stable for both LTE and NLTE grids from spectral resolutions of 12,000 through 2,000. Furthermore, the standard deviation in the individual metallicity measurements holds stable at ~0.12 dex down to R=3000. At this point individual atomic spectral features become too blended and diluted; the parameter fits of individual objects begin to diverge from high resolution fit values.

We conclude from these tests that the J-band technique can be utilized on RSGs down to spectral resolutions of 3000. To study large populations of RSGs at extragalactic distances, then, one needs a multi object spectrograph operating at R≥3000 on a telescope with enough collecting area south that the limiting magnitude is fainter than the target RSGs. Two such instruments exist: MOSFIRE on Keck operates at R~3200 and KMOS on the VLT operates at R~3400. These ideal instruments for the study of extragalactic populations of

### TABLE 3
PERSEUS OB-1 RED SUPERGIANTS NLTE

<table>
<thead>
<tr>
<th>Target</th>
<th>T eff [K]</th>
<th>log g</th>
<th>Z [dex]</th>
<th>ξ [dex]</th>
<th>$\lambda_\text{\footnotesize{eff}}$</th>
<th>M/M⊙</th>
<th>Ev. log g</th>
<th>Lit. T effb</th>
</tr>
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<tbody>
<tr>
<td>BD+59 372</td>
<td>3920 ± 25</td>
<td>+0.5 ± 0.3</td>
<td>−0.07 ± 0.09</td>
<td>3.2 ± 0.2</td>
<td>13600</td>
<td>9.86</td>
<td>+0.72</td>
<td>3825</td>
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<tr>
<td>BD+56 395</td>
<td>4060 ± 25</td>
<td>+0.2 ± 0.7</td>
<td>−0.15 ± 0.13</td>
<td>4.0 ± 0.2</td>
<td>11900</td>
<td>13.2</td>
<td>+0.43</td>
<td>3800</td>
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<tr>
<td>HD 14404</td>
<td>4010 ± 25</td>
<td>+0.2 ± 0.4</td>
<td>−0.07 ± 0.10</td>
<td>3.9 ± 0.2</td>
<td>11100</td>
<td>15.4</td>
<td>+0.24</td>
<td>3625</td>
</tr>
<tr>
<td>HD 14826</td>
<td>3930 ± 26</td>
<td>+0.1 ± 0.2</td>
<td>−0.08 ± 0.07</td>
<td>3.7 ± 0.4</td>
<td>11200</td>
<td>15.7</td>
<td>+0.18</td>
<td>3625</td>
</tr>
<tr>
<td>HD 236979</td>
<td>4080 ± 25</td>
<td>−0.6 ± 0.3</td>
<td>−0.09 ± 0.09</td>
<td>3.1 ± 0.2</td>
<td>11700</td>
<td>16.5</td>
<td>+0.18</td>
<td>3700</td>
</tr>
<tr>
<td>HD 13136</td>
<td>4030 ± 25</td>
<td>+0.2 ± 0.4</td>
<td>−0.10 ± 0.08</td>
<td>4.1 ± 0.2</td>
<td>12300</td>
<td>17.7</td>
<td>+0.08</td>
<td>3700</td>
</tr>
<tr>
<td>HD 14270</td>
<td>3900 ± 25</td>
<td>+0.3 ± 0.3</td>
<td>−0.04 ± 0.09</td>
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<td>+0.14</td>
<td>3625</td>
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<tr>
<td>HD+56 724</td>
<td>3840 ± 25</td>
<td>−0.4 ± 0.5</td>
<td>+0.08 ± 0.09</td>
<td>3.0 ± 0.2</td>
<td>10900</td>
<td>16.6</td>
<td>−0.05</td>
<td>3575</td>
</tr>
<tr>
<td>HD 14469</td>
<td>3820 ± 25</td>
<td>−0.1 ± 0.4</td>
<td>−0.03 ± 0.12</td>
<td>4.0 ± 0.2</td>
<td>10200</td>
<td>17.6</td>
<td>−0.17</td>
<td>3575</td>
</tr>
<tr>
<td>BD+56 512</td>
<td>4090 ± 35</td>
<td>+0.4 ± 0.3</td>
<td>+0.01 ± 0.12</td>
<td>4.1 ± 0.2</td>
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<td>10590</td>
<td>16.8</td>
<td>−0.07</td>
<td>3550</td>
</tr>
</tbody>
</table>

**Note.** — Parameter fits to observed RSGs using the grid of synthetic spectra with NLTE corrections to FeI, TiI, and SiI lines (Bergemann et al. 2013, 2012). Masses and Evolutionary log g are calculated using the Geneva stellar evolution tracks which include effects of rotation (Meynet & Maeder 2000).

- a Spectral resolution is measured to ± 100.
- b Temperatures from Levesque et al. (2005) where target lists overlap.

### TABLE 4
PERSEUS OB-1 RED SUPERGIANTS LTE

<table>
<thead>
<tr>
<th>Target</th>
<th>T eff [K]</th>
<th>log g</th>
<th>Z [dex]</th>
<th>ξ [dex]</th>
<th>$\lambda_\text{\footnotesize{eff}}$</th>
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</thead>
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<td>3930 ± 90</td>
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<td>−0.10 ± 0.06</td>
<td>3.4 ± 0.2</td>
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<td>BD+56 395</td>
<td>3970 ± 25</td>
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<td>4.1 ± 0.2</td>
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</tr>
<tr>
<td>HD 14404</td>
<td>3950 ± 40</td>
<td>+0.2 ± 0.1</td>
<td>+0.06 ± 0.09</td>
<td>4.1 ± 0.2</td>
<td>11500</td>
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<tr>
<td>HD 14826</td>
<td>3870 ± 25</td>
<td>+0.3 ± 0.2</td>
<td>+0.04 ± 0.10</td>
<td>3.6 ± 0.2</td>
<td>12600</td>
</tr>
<tr>
<td>HD 236979</td>
<td>4040 ± 30</td>
<td>−0.5 ± 0.1</td>
<td>+0.01 ± 0.06</td>
<td>3.1 ± 0.2</td>
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<td>HD 13136</td>
<td>4030 ± 40</td>
<td>+0.4 ± 0.2</td>
<td>−0.11 ± 0.09</td>
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<tr>
<td>HD 14270</td>
<td>3890 ± 25</td>
<td>+0.2 ± 0.3</td>
<td>+0.06 ± 0.12</td>
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<td>HD+56 724</td>
<td>3740 ± 25</td>
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<td>HD 14469</td>
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<td>+0.17 ± 0.08</td>
<td>3.2 ± 0.2</td>
<td>11700</td>
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</table>

**Note.** — Parameter fits to observed RSGs using the TURBOSPECTRUM grid of synthetic spectra calculated in LTE (Plez 2012; Alvarez & Plez 1998).
Fig. 3.— Evolution of the average measured metallicity for our sample of Perseus OB-1 stars as a function of spectral resolution. Error bars mark the standard deviation of the individual eleven measurements at each step. The horizontal gray region shows ±1σ of the average metallicity between 12000 ≤ R ≤ 3000, demonstrating the stability of the technique down to resolutions of R=3000. Vertical lines mark the spectral resolutions of key J–band spectrographs, KMOS on VLT in dash-dotted blue and MOSFIRE on Keck in dashed red. A horizontal dotted line marks solar metallicity. We plot results from the LTE model grid (left panel) and NLTE grid (right panel). See §3.1 and §4.2.

Fig. 4.— Signal to noise ratio needed to achieve target precision for measurement of [Fe/H] as a function of spectral resolution. Each point is the average and standard deviation of the necessary S/N for the set of eleven RSG spectra. Vertical lines mark the spectral resolutions of key J–band spectrographs, KMOS on VLT in dash-dotted blue and MOSFIRE on Keck in dashed red. For a description of the technique, see §4.3.

RSGs operate near but safely above the resolution limits of our technique.

4.3. Parameter Stability vs. Signal to Noise

In our tests for parameter stability as a function of spectral resolution we assume that at each resolution step we have the same signal to noise ratio (S/N) as in the original, high resolution spectrum. This value of S/N is ≈ 100-150 per object. By reducing the spectral resolution we functionally increase the S/N per resolution element.

We measure the S/N of our spectra as follows. After measuring the stellar parameters as described in §3, we construct a model at those parameters by linear interpolation from grid points in our models. This “perfect model” represents an infinite S/N version of our observation. We add a gaussian noise spectrum consistent with a S/N of 1000 to the perfect model and measure its χ^2 relative to the best fitting model in our grid. We iteratively increase the strength of the added noise spectrum until the χ^2 becomes consistent with the χ^2 between the observed spectrum and best fitting model. We adopt this S/N as the functional S/N of our data.

To adjust the S/N of our data for the following tests we note that the target S/N is just a quadrature sum of the S/N and the additional noise spectrum that we need to add such that the strength of that gaussian noise, σ_scale is

$$\sigma_{\text{scale}} = \sqrt{(S/N)_{\text{target}}^{-2} - (S/N)_{\text{meas}}^{-2}}$$

At this point, adding random gaussian noise scaled by σ_scale to our observed spectrum degrades it to S/N_target. Since we have now prepared a spectrum for which we know the S/N, we assign an error spectrum which is simply the ratio of the flux spectrum and S/N_target. To understand the S/N necessary to reach our target precision of σ[Fe/H] ≈ 0.10 we use the above method starting with a modest S/N_target = 5 and iteratively increase that value until the σ[Fe/H] we extract are consistent with those measured for the original spectrum, i.e., any additional S/N provides no increase in fit precision given the data and model grid. The results of this test are plotted in Figure 4, and indicate that for instruments operating at resolutions of ~3000, a S/N of ~ 100 per resolution element is an ideal target for observational programs.

5. DISCUSSION

5.1. Metallicity

The average metallicity of [Fe/H] = −0.04 ± 0.08 obtained for the Perseus OB-1 RSGs in this work agrees well with the metallicity of young massive stars in the solar neighborhood. Nieva & Przybilla (2012) studied a large sample early B dwarfs and giants using strongly improved detailed nLTE line diagnostics. They obtained surprisingly narrow (σ ≈ 0.05) abundance distributions for the elements C, N, O, Ne, Mg, Si, Fe with average values very close to the sun (Asplund et al. 2009). This implies that there is little scatter in metallicity of the young massive star population around the sun and also practically no chemical evolution over the last 5 Gyrs. The fact that we also obtain a metallicity very close to the solar value is, thus, a strong indication that the spectroscopic J–band method leads to reliable results.

Unfortunately, the study by Nieva & Przybilla (2012)
Normalized Flux + offset

Fig. 5.— For the analysis in this work we degrade the observed spectrum by convolving those spectra with a gaussian function. The plot shows the effects of spectral degradation on the spectrum of BD+56 595, and each is over plotted in red with the best model spectrum for that data.

Fig. 6.— The effects of NLTE corrections on diagnostic lines. Left panel shows a model at [Fe/H] = +0.25, right panel [Fe/H] = −0.25 does not include objects in Perseus OB-1. However, Firnstein & Przybilla (2012) have recently analyzed A supergiant stars in the solar neighborhood including some objects in Perseus OB-1. While this work does focus on the determination of stellar parameters and does not provide a detailed abundance study, it provides magnesium abundances for three objects with an average value -0.10 dex below the Nieva & Przybilla (2012) average of B stars in the solar neighborhood (the uncertainty for each individual A supergiant is ≈ ±0.07 dex). We take this as a confirmation that the metallicity of Perseus OB-1 is close to solar.

5.2. Effective Temperatures

We measure higher T\textsubscript{eff} for all stars which overlap the target list of Levesque et al. (2005) (see Table 3). The average difference in temperatures is 270 ± 130 [K], a significant discrepancy. There are a number of differences between this work and that of Levesque et al. (2005), including the new NLTE corrections we use when computing synthetic spectra, the fact that we fit for [Fe/H], micro turbulence, and spectral resolution, and the near IR spectral window of this work. The latter is the most likely candidate for the large difference in measured T\textsubscript{eff} values. While we work in the J-band, Levesque et al. (2005) use optical spectra, concentrating on the strength of molecular bands of TiO to derive temperatures. Davies et al. (2013) have showed that the derivation of RSG temperatures using quantitative spectroscopy in optical bandpasses returns lower values than are measured using methods which are less dependent on model atmospheres (the flux integration method). In addition, Davies et al. (2013) show that optical temperatures over predict the IR flux of RSGs when full spectral energy distributions are available and under predict reddening as compared to nearby stars. Temperatures derived from near IR spectroscopy alone are closer to those values from the flux integration method.

New work with 3D models of RSGs will likely do much to resolve the issue of temperature derivation for RSGs, but these models are still in their infancy (see, for example, Chiavassa et al. 2011).

5.3. Stellar Evolution

To compare our results with stellar evolution models we first construct an observational Hertzsprung-Russel diagram (HRD). We calculate bolometric luminosities for program stars using archival K band 2MASS photometry (Table 1, Skrutskie et al. 2006), the bolometric correction recipes of Davies et al. (2013) and Levesque et al. (2005), and distance modulus of Currie et al. (2010). We applied the Cardelli et al. (1989) extinction law using measurements of the reddening to Perseus OB-1 (Currie et al. 2010). These luminosities are plotted against the effective temperatures from our spectral fit in the HRD of Figure 9. We then over plot evolutionary tracks adopting the Geneva database of stellar evolutionary models including the effects of rotation (Meynet & Maeder 2000). All stars except one align along the evolutionary tracks with an original zero age main sequence (ZAMS) masses of 15-20 M\textsubscript{\odot}. This result is in good agreement with the age of Perseus OB-1 of 14±1 Myr (Currie et al. 2010). Only the 15 M\textsubscript{\odot} track agrees with this time frame. At the age of Perseus OB-1, 20 M\textsubscript{\odot} have already evolved from the RSG phase while 12 M\textsubscript{\odot} stars are still on the main sequence.

The first object of Table 2 and 4, BD+59 372, is a clear outlier with a luminosity corresponding to a mass only slightly higher than 9 M\textsubscript{\odot}. At this point we have no explanation for this object.

An independent way to compare our spectroscopic results with stellar evolution is the comparison of gravities log g obtained from the spectroscopy and from evolutionary tracks. For the latter, we obtain a stellar mass from the observed luminosities by interpolating evolutionary track masses and luminosities at the effective temperature observed. This mass is then used in conjunction with the observed luminosity and effective temperature to calculate evolutionary gravities. Fig. 8 compares evolutionary gravities obtained in this way with spectroscopic gravities. Besides one outlier (HD236979) we
find general agreement and no indication of a systematic discrepancy. We also note that the outlier in Fig. 7, BD+59 372, as the object with the highest gravities agrees within the uncertainties of the error bars.

The general agreement between spectroscopic and evolutionary gravities can be used to discuss the influence of convective turbulence pressure on the model atmosphere stratification. The 3D-hydrodynamic convection simulations by Chiavassa et al. (2011) include effects of pressure caused by the convective motion on the atmospheric density stratification. On the other hand, the 1D MARCS models used in our analysis do not account for convective pressure. It is straightforward to show (see, for instance, Chiavassa et al. 2011, eq. (8)) that as the result of convective pressure the stellar gravity is reduced to an effective gravity which can be approximated by

$$
\log g_{\text{eff}} = \log g - \log(1 + \beta v_{\text{turb}}^2/v_{\text{sound}}^2)
$$

where $v_{\text{turb}}$ is the average turbulence speed and $v_{\text{sound}}$ the sound speed. $\beta$ is a parameter close to unity if the turbulent velocity fields is almost isotropic. Chiavassa et al. (2011) concluded from their calculations and a comparison with MARCS models that gravity corrections of 0.25 to 0.3 dex are needed to match the density stratifications of the 1D with the 3D models corresponding to turbulence velocities of the order of the sound speed.

Our comparison of spectroscopic and evolutionary gravities does not indicate a systematic effect of this order. On the other hand, our two objects with the lowest spectroscopic gravities may well be influenced by large effects of turbulence pressure. We note, however, that the models used to calculate our synthetic spectra and those models used for the stellar evolution calculations of (Meynet & Maeder 2000) utilize 1D model atmospheres which may affect stellar evolution and atmosphere predictions in the same way.

### 5.4. Simulation of Super Star Cluster Spectral Analysis

The scientific strength of the low resolution J-band technique derives from the radiative power of RSG stars. In this work we carefully demonstrate that the method is stable and precise well below the spectral resolution of current instrumentation on the largest telescopes available, notably MOSFIRE on Keck and KMOS on the VLT. With these multiplexed instruments we are able to efficiently apply this technique to entire populations of RSGs as individual objects over extragalactic distances.

In Gazak et al. (2013) we presented simulations showing that the near-IR flux of young super star clusters (SSCs) is dominated by their RSG members. These simulations show that the J-band spectrum of a SSC older than 7 Myr will appear very similar to that of a single RSG. This opens the possibility to use the integrated J-band light of SSCs in distant galaxies as a source for spectroscopic determination of galaxy metallicities.

Our collection of Perseus OB-1 spectra allows us to test this possibility. With a total estimated mass of 20000 $M_\odot$ (Currie et al. 2010) Perseus OB-1 comes close to the observed mass range of extragalactic SSCs. We, therefore, use the addition of the spectra of our observed RSGs weighted by the J-band luminosity to produce a simulated integrated SSC spectrum. The spectrum is shown in Figure 7. We then apply the same analysis technique as in section 3 and obtain a metallicity of $[\text{Fe/H}] = -0.03 \pm 0.12$ (NLTE), very similar to the average metallicity obtained from the analysis of the 11 individual spectra. The effective temperature obtained from the cluster spectrum is $T_{\text{eff}} = 3970 \pm 30$ and the gravity $\log g = +0.1 \pm 0.2$. In agreement with the LTE study of the individual Perseus OB-1 supergiants we measured $[\text{Fe/H}] = +0.08 \pm 0.12$, $T_{\text{eff}} = 3910 \pm 70$, and $\log g = +0.2 \pm 0.1$ when fitting with the full LTE model grid.

Gazak et al. (2013) find that the RSG supergiant population will provide $\sim$95% of the J-band flux in a young SSC. To simulate the effect of the 5% contaminative flux we added a flat spectrum of 5% of the total flux. We then re-fit the spectrum and measured $-0.08 \pm 0.13$ (NLTE) and $+0.06 \pm 0.14$ (LTE). The change in measured metallicity is minimal (with a systematic offset of at most $+0.05$ dex) and in the proper direction—contaminant flux will weaken the deepest lines more strongly and thus a drop in extracted metallicity is to be expected. However, the two results agree statistically and offer strong agreement with the LTE study of the individual Perseus OB-1 supergiants.

![Figure 7](image_url)  
**Fig. 7.** The resulting “cluster spectrum” created when all eleven RSG spectra are summed together as weighted by their J magnitudes. The spectrum is plotted twice, and on the lower spectrum we over plot the best fitting model in red.
Fig. 8.— Evolution of the average measured metallicity for our sample of Perseus OB-1 stars collapsed into a synthetic cluster spectrum as a function of spectral resolution. Error bars mark the standard deviation of the individual eleven measurements at each step. The horizontal gray region shows $\pm 1\sigma$ of the average metallicity between $10000 \leq R \leq 3000$, demonstrating the stability of the technique down to resolutions of $R=3000$. Vertical lines mark the spectral resolutions of key J–band spectrographs, KMOS on VLT in dash-dotted blue and MOSFIRE on Keck in dashed red. A horizontal dotted line marks solar metallicity. We plot results from the LTE model grid (left panel) and NLTE grid (right panel).

Fig. 9.— H-R diagram of program stars. Bolometric corrections are taken from Davies et al. (2013). Overplotted in gray are geneva evolution tracks for solar metallicity including the effects of rotation, labeled with their zero-age main sequence mass. The bold dashed overlay represents the space on the geneva tracks which covers the literature age of Perseus OB-1, $14 \pm 1$ Myr (Currie et al. 2010). Gray squares show luminosities calculated using the bolometric corrections of Levesque et al. (2005), which are systematically higher but within $1\sigma$.

We find that spectroscopy of unresolved young SSCs can become a powerful application of the J–band technique. We find in this case that an unresolved cluster of proper age can be successfully fit with a single RSG template model, a technique which has been used at very high resolution in the H band (Larsen et al. 2006).

We scale the resolution of our synthetic cluster spectrum down to $R=2000$. The results of this work echo that of the individual stars, showing stability in fit parameters down to resolutions around 3000. The NLTE and LTE cases of this test are plotted in Figure 8.

6. CONCLUSIONS

In this paper we have tested the J–band technique for extracting metallicity information from modest resolution spectra of RSGs. Through a careful suite of tests we have demonstrated the precision and accuracy of the technique. We obtain reliable abundances in agreement with high resolution, high signal to noise spectroscopy of young massive B-stars in the solar neighborhood. Using the advantage that all of our RSGs formed within a stellar cluster we test our derived parameters against predictions of stellar evolution theory for a cluster of mass and age of Perseus OB-1. Our results are in good agreement with such theoretical work. We thus confirm the technique presented in DFK10 and show that it remains stable down to resolutions of $R\approx 3000$. This provides a reliable method to determine extragalactic metallicities from individual RSGs to distances of 7-10 Mpc with existing telescopes and instruments. Both Keck (MOSFIRE) and the VLT (KMOS) have multi object spectrographs in the near-IR which operate above resolutions of 3000. With these instruments and the J–band technique, RSGs across the entire disks of star forming galaxies can be observed efficiently.

By utilizing the large populations of RSGs in young, spatially unresolved SSCs we can extend the applicability of the J–band technique out to distances ten times greater with the same instruments. Thus SSCs may allow us to reach beyond the local group and measure the metallicities of star forming galaxies from the stars themselves instead of relying on existing techniques which are
We note that low resolution work is now needed in targets expected to be sub solar and super solar in metallicity. The successful application of the J–band technique in such cases would pose the methods tested in this paper to study the metallicity evolution of star forming galaxies in a large volume of the nearby universe.

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