2 Observational Data Reduction

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1 Introduction

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near-infrared spectroscopy of super star clusters.

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Fig. 1. NIRSPEC $K$-band image of NGC 1569 in $0.7\arcsec$ seeing. Clusters for which spectra were obtained are labeled

Date were reduced in the usual fashion, and the optimally extracted $K$-band spectra are shown in Fig. 2a. The strongest features in $K$ band are the CO first overtone bands longward of 2.295 $\mu$m. These saturated bands are found in the cool atmospheres of supergiants and giants. Their presence implies that the clusters contain stars that are at least 6 or 7 Myr old, since that much time is required before the most massive stars evolve off of the main sequence.

Stellar evolution models for a simple stellar population predict that the hot blue stars capable of driving nebular emission will have completely evolved off of the main sequence by the time red supergiants appear. Thus the conjunction of strong CO bands together with weak $Br\gamma$ and H$\alpha$ emission in the spectra of Clusters A and C1 suggests that they are not instantaneous bursts. In the case of cluster C1 we believe that the weak emission lines are explained by contamination from a nearby HII region [18]. The weak nebular emission from SSC A (a double cluster [2]) is likely due to the Wolf-Rayet stars known to be present there [3].

Thus the spectrum of SSC A cannot be explained with a single simple stellar population according to current population synthesis models. Cluster C2, on the other hand, shows both $Br\gamma$ and H$\alpha$ in absorption, which may be due to a much older population dominated by A stars and red giants.

Optimally extracted $H$-band spectra of SSCs A and B are shown in Fig. 2b, together with the spectrum of a K 1.5 Ib supergiant from the KPNO stellar atlases [17,12]. A comparison of the star and cluster spectra reveals that most of the features in the cluster spectra are real, not noise, and that $H$-band photospheric spectra are remarkably rich in strong metallic and molecular features. Only the CO bands stand out in the $K$-band spectra, while many metal features in $H$ band are as strong as the second overtone CO bands. Most of the features in $H$ band are blends of lines from CO, OH, and metals such as Fe, Si, Al, and Mg.
3 The Cluster Integrated Light

The most massive, evolved members of a single-aged stellar population tend to dominate its integrated light. Thus the simplest approach to interpreting the integrated light may be to ask, what is the dominant spectral type of the cluster? We attempt to characterize a cluster by an effective spectral type by fitting its $H$- and $K$-band spectra to a grid of NextGen model atmospheres [5], in order to determine an effective temperature, surface gravity, and metallicity for each object. The NextGen atmospheres were available for spherically symmetric giant stars with a range in $T_{\text{eff}}$ of 3000 K to 6800 K, a range in $\log g$ of 0.0 to 3.5, and metallicities of $[\text{Fe}/\text{H}] = 0.0$ (solar), $-0.3$, $-0.5$, and $-0.7$.

We first test the utility of this procedure by fitting the model atmospheres to an empirical spectrum of a star of known spectral type to evaluate the precision and accuracy with which it selects the atmospheric parameters. Fig. 3a shows the resulting $\chi^2$ contours for a fit to a solar-metallicity K1.5 Ib spectrum. The resulting parameters, $T_{\text{eff}} = 4400 \pm 100$ K and $\log g = 0.0 \pm 0.5$, are a good match to those of the star. Both $H$- and $K$-band spectra were required in order to remove degeneracies in the fits.

Next we fit the NextGen atmospheres at metallicity $[\text{Fe}/\text{H}] = -0.5$ (which is closest to that of NGC 1569, $[\text{Fe}/\text{H}] = -0.6$ to $-0.7$ [3, 9]) to the $H + K$ spectra
Fig. 3. $\chi^2$ contours for fit of NextGen models for: (a) spectrum of a K1.5 Ib star; (b) SSC B; (c) SSC A. White filled contour indicates 1 sigma confidence level, and line contours represent 90, 95, and 99\% confidence limits. Best-fit parameters for SSC B imply an effective spectral type for the cluster light of K0 supergiant. Best-fit parameters for SSC A imply an effective spectral type for the cluster light of G5 supergiant with log g = 1.3 ± 1.3. The temperature and range of log g are consistent with a mixed population of stars, either two short bursts or an extended epoch of star formation

of the brightest K-band cluster, SSC B. The resulting $\chi^2$ contours in Fig. 3b have the same shape as those found for the star in Fig. 3a, indicating that the light of cluster B is heavily dominated by stars with a very narrow range in spectral type. The effective spectral type for SSC B is that of a K0 supergiant, with $T_{\text{eff}} = 4400 \pm 100$ K and log g = 0.5 ± 0.5.

For the double cluster, SSC A, the $\chi^2$ contours are less tightly constrained in the fit parameters than for SSC B. Fig. 3c shows them to be centered at a hotter $T_{\text{eff}} = 4800 \pm 200$ K and larger range of log g = 1.3 ± 1.3, typical for stars of types G5 I and G5 III. It is unlikely, however, that such stars dominate the cluster’s emission, since optical/UV evidence indicates that hot blue Wolf-Rayet stars are present together with the red evolved stars creating the strong infrared CO bands. Thus the inferred effective spectral type determined from the stellar atmospheres may simply result from the superposition of the two distinct populations.

4 IR Spectral Population Synthesis

Since a cluster consists of stars with a range of stellar masses, luminosities, and temperatures, it is more informative to model the integrated population directly than to focus on its effective spectral type. Thus we employ the technique of population synthesis to calculate the distribution of stars in the H-R diagram of a cluster as a function of time. We then calculate the integrated spectrum of the cluster by adding the appropriate numbers of stellar spectra — either empirical spectra or model atmospheres.
Fig. 4. (a) Sequence of model cluster spectra as a function of time, calculated using Starburst99 and KNPO stellar atlases. (b) SSC A and B H-band spectra shown in an age progression between synthetic cluster spectra (at solar metallicity) at ages of 12, 15, and 18 Myr.

4.1 Models

All models in this paper were constructed using the updated evolutionary synthesis code Starburst99 [10]. The code incorporates the most recent stellar evolutionary tracks from the Geneva group at metallicities ranging from very metal-poor, to twice solar metallicity [15,16], and it has been updated to allow the use of isochrone synthesis. Starburst99 is a particular set of synthesis models which are optimized to reproduce properties of galaxies with active star formation, so it puts most of the emphasis on early evolutionary phases. Later phases, like AGB stars or white dwarfs, are covered only crudely or not at all.

Origlia et al. [14] show that low-metallicity tracks do not reproduce the CO 1.62 µm and CO 2.29 µm indices of young LMC clusters. However, if the fraction of time spent as a RSG during the core-helium phase is forced to at least 50%, and if the RSG temperature is maintained to less than 4000 K, the models agree well with the observations. Our modeling technique was modified according to this prescription (Leitherer, private communication, 2000).

In order to generate model cluster spectra, we combine the Starburst99 models with the empirical libraries of stellar spectra obtained at Kitt Peak by Wallace & Hinkle [17] and Meyer et al. [12]. For a given cluster population, we add up the spectra of component stars, and include nebular continuum emission (but not the recombination lines) based on the number of ionizing photons predicted for the cluster. Thus we generate a time series of model cluster spectra such as that shown in Fig. 4a for a $10^6 \ M_\odot$ cluster with Salpeter IMF ranging from 0.1
to 100 M\(_\odot\). For the first few Myr, nebular emission powered by the hottest stars dilutes the photospheric emission from the cluster, but by an age of 6–7 Myr, the most massive stars have evolved off of the main sequence to become red supergiants, whose spectra are marked by [\(^{12}\)CO bands.

Finally, we can place observed cluster spectra in an evolutionary sequence by fitting them to the model sequences. Figure 4b displays the \(H\)-band spectra of SSCs A and B together with the three model cluster spectra (15, 18, and 21 Myr) which most closely resemble the observations. Note the correspondence between features and the decrease in their strength with time. Since the models are for solar metallicity clusters, they presumably have stronger metal features at a given age than expected for a lower-metallicity cluster. Thus the age estimates we derive from these models will be too large during this epoch of the cluster’s evolution.

5 Conclusions

We have presented new high-quality near-infrared spectra of several of the SSCs in the nearby irregular starburst, NGC 1569, and demonstrated the utility of the rich \(H\)-band spectral region for modeling stellar populations. We found that combining \(H\)- and \(K\)-band spectra removed some of the degeneracy in fitting just one band to model spectra.

We used population synthesis models together with model stellar atmospheres and empirical stellar spectra to fit for the effective spectral type of a cluster, and to generate sequences of synthetic cluster spectra to help determine the ages of observed clusters. Since the empirical libraries are only complete for solar metallicity, we are constructing models that use model atmospheres at lower metallicities that are more appropriate for systems like NGC 1569.

References