STAR FORMATION HISTORY OF A YOUNG SUPER-STAR CLUSTER IN NGC 4038/39: DIRECT DETECTION OF LOW-MASS PRE-MAIN SEQUENCE STARS

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ABSTRACT

We present an analysis of the near-infrared spectrum of a young massive star cluster in the overlap region of the interacting galaxies NGC 4038/39 using population synthesis models. Our goal is to model the cluster population as well as provide rough constraints on its initial mass function (IMF). The cluster shows signs of youth, such as thermal radio emission and strong hydrogen emission lines in the near-infrared. Late-type absorption lines are also present which are indicative of late-type stars in the cluster. The strength and ratio of these absorption lines cannot be reproduced through either late-type pre-main sequence (PMS) stars or red supergiants alone. Thus, we interpret the spectrum as a superposition of two star clusters of different ages, which is feasible since the 1σ spectrum encompasses a physical region of ≈90 pc and radii of super-star clusters (SSCs) are generally measured to be a few parsecs. One cluster is young (≤3 Myr) and is responsible for part of the late-type absorption features, which are due to PMS stars in the cluster, and the hydrogen emission lines. The second cluster is older (6 Myr–18 Myr) and is needed to reproduce the overall depth of the late-type absorption features in the spectrum. Both are required to accurately reproduce the near-infrared spectrum of the object. Thus, we have directly detected PMS objects in an unresolved SSC for the first time using a combination of population synthesis models and PMS tracks. This analysis serves as a testbed of our technique to constrain the low-mass IMF in young SSCs as well as an exploration of the star formation history of young UCHII regions.

Key words: galaxies: individual (NGC 4038, NGC 4039) – galaxies: interactions – stars: luminosity function, mass function – stars: pre-main sequence

1. INTRODUCTION

The advent of the Hubble Space Telescope (HST) has made it possible to study in detail nearby starburst galaxies with star formation rates orders of magnitude higher than the Milky Way (e.g., M82, Henize 2-10, and NGC 5253) and many are now known to host massive (10^5–10^6 M⊙) young super-star clusters (SSCs). These clusters are thought to mirror a mode of star formation that was ubiquitous in the early universe (Leitherer 2001) as evidenced by the fact that star formation rates of galaxies at high redshift are very similar to those in local starbursts (Steidel et al. 1996).

SSCs represent an extreme form of star formation that cannot be studied in the Milky Way. The closest analog is R136 in the LMC with a mass of 10^{12} M⊙ (Massey & Hunter 1998) though the Galaxy also hosts some clusters with masses greater than 10^5 M⊙ (e.g., Westerlund 1 and NGC 3603). Massive young clusters have been of particular interest in the search for initial mass function (IMF) variations. Since the local stellar IMF (within 1 kpc) appears to be universal (Meyer et al. 2000), we are forced to expand the search for IMF variations to more extreme regions of star formation. SSC often form in the intense radiation environment of nuclear starbursts and interacting galaxies. Thus, they represent ideal objects to search for IMF variations with initial conditions, such as metallicity and formation environment. Many young massive clusters with ages ≤40 Myr have varying mass-to-light ratios (e.g., NGC 1705-1, Smith & Gallagher 2001; NGC 1569-B, Anders et al. 2004), which have often been interpreted as changes in the mass function. The mass-to-light ratios are determined through dynamical mass estimates however, which assume that clusters are in virial equilibrium. Goodwin & Bastian (2006) have shown that this assumption can be faulty in young clusters due to the effects of gas expulsion. The mass-to-light ratio of M82-F however, a massive cluster in the prototypical starburst M82 with an age of 40–60 Myr, remains inconsistent with a Kroupa (2001) IMF (McCrady et al. 2005). Mass-to-light ratios are at best an indirect way to determine the IMF of a young cluster because the whole stellar mass range is represented by one mass bin. A more direct method of detecting stellar populations in unresolved SSC is needed to provide confirmation of the shape of their IMF.

Star clusters are dominated dynamically by their low-mass content. Yet, most of the light in young clusters is seen through their massive stars. To understand whether a young SSC will remain bound or disperse, it is important to get a direct census of low-mass stars. In addition, differences in the IMF of SSCs are most easily detected in low-mass stars, since the characteristic mass in both a Kroupa (2001) and Chabrier (2003) IMF is around 0.5 M⊙. Even small variations in the IMF of a young SSC may make the difference between a bound and an unbound cluster. The difference between a Salpeter (1955) and a Chabrier (2003) IMF accounts for a factor of 2 in the mass of low-mass stars, for example.

The Antennae (NGC 4038/9) are the nearest (distance = 19.2 Mpc, 1″ ≈ 93 pc; Whitmore et al. 1999) pair of merging spiral galaxies. They contain up to a thousand young star clusters. These clusters have been the target of a multitude of studies at different wavebands (e.g., Whitmore et al. 1999; Neff & Ulvestad 2000; Brandl et al. 2005). Whitmore & Schweizer (1995) identified a large population of SSC in the optical using HST WFPC2 images. The faintest and reddest of these sources are revealed to be bright near-infrared and mid-infrared emitters and contain the youngest clusters (Snijders et al. 2006; Wang et al. 2004; Brandl et al. 2005). Radio images by Neff...
Galactic background contamination. After sky subtraction, the
background had no identifiable shape and the noise in the
background was dominated by instrumental noise. We did not
see detectable CO absorption outside of our cluster in the
spectrum which would have affected our analysis. Calibration
data were obtained including a flat field and appropriate dark
frame as well as neon and argon arc lamp spectra to use for
wavelength calibration. To correct for telluric absorption, we
used a G2V star in the H band and an A0V star in the K band.
To ensure the best telluric correction, we observed the standard
stars within 0.05 air mass of the target. Flat fielding and cosmic
ray removal were performed on each spectrum using standard
IDL procedures.

NIRSPEC spectra have spatial and spectral distortions that
must be removed during the reduction process. The spatial
distortion corrections were calculated by measuring the position
of the brightest calibrator spectra at multiple positions in the
slit. The traces of these sources were fit with polynomials to
determine the spatial distortion correction. This routine was
modified from the REDSPEC4 package written by Lisa Prato.
For wavelength calibration, we used an argon arc lamp in the
H band and a neon arc lamp in the K band. The reduction of
the calibrator stars was carried out in the same manner.
To determine the atmospheric calibration, we applied template
spectra using Meyer et al. (1998) in the H band and Wallace
& Hinkle (1997) in the K band smoothed to the resolution of
our spectra (R ⊘ 1100–1500). The calibrator stars were largely
featureless, except for Brγ absorption in the K band, which was
not well matched by the template and removed independently.
 Stellar absorption centers were measured in both the template
and the calibrator spectrum to remove any spectral offset.
The H-band template spectra covered the entire wavelength
range of the H-band atmospheric calibrator observations; for
the K band, the template spectra ended at 2.4 μm, while
our observations extended redward to 2.47 μm. We assumed
a featureless blackbody for the template spectra from 2.4 to
2.47 μm. We examined the final telluric spectrum to ensure that
there were no mismatches between the G2V standard and the
solar spectrum particularly around the Mg absorption line at 1.71
μm which could have affected our analysis. The atmospheric
calibration was calculated by dividing the calibrator spectrum by
the shifted template spectrum and normalizing the result at the
center of the band. Any spectral offset between the atmospheric
correction and the source spectra were measured by comparing
the location of atmospheric absorption features and applying
an offset to the atmospheric correction if necessary. Typical
offsets were less than 0.1 pixels. The atmospheric correction
removes both the effects of the atmosphere and variations in
NIRSPEC system throughput as a function of wavelength. The
final spectrum was extracted from the atmospherically calibrated
composite exposure with an aperture size of 5× the seeing.

& Ulvestad (2000), which detect sources with purely thermal
nebular emission (i.e., α_{4cm–6cm} ⩾ −0.4) due to massive stars
in the clusters, provide additional evidence for the youth of these
objects. Sources with non-thermal radio emission likely contain
supernova remnants and are thus older.

This paper expands on a method introduced in Meyer &
Greissl (2005) to constrain the low-mass stellar content in young
SSC using late-type absorption features in the near-infrared. For
young clusters, most low-mass objects are still on the pre-main
sequence (PMS) and are thus orders of magnitude brighter than
their main sequence counterparts. Thus, they can be detected in
high signal-to-noise ratio (S/N) spectra of young SSC. We focus
our analysis on one massive young cluster in the Antennae.

Cluster 89/90 (designation of Whitmore & Schweizer1995),
the cluster targeted in this study, was first surveyed by Whitmore
& Schweizer (1995) using WFPC2 on the HST. It is the brightest
near-infrared cluster in NGC 4038/9 as well as the second
brightest thermal radio source at 4 and 6 cm. In addition,
Snijders et al. (2006) observed the cluster in the mid-infrared
and found strong Ne ii 12.8 and Ne iii 15.5 μm emission as well as
polycyclic aromatic hydrocarbon emission at 11.25 μm. These
features are an indication of the presence of hot stars (Mirabel
et al. 1998). See Table 1 for a list of broadband magnitudes for
cluster 89/90 obtained from archival data.

In the following sections, we present a K- and H-band
spectral of cluster 89/90 and model its underlying population.
Section 2 details the observations and data reduction. Section 3
gives an overview of the method used to model the spectrum of
the cluster. The analysis of the spectrum, which constrains the
population of the cluster, is presented in Section 4. Section 5
contains the results of the analysis, as well as its limitations.
Section 6 places our analysis in the context of previous work.
Section 7 details our conclusions.

2. OBSERVATIONS AND DATA REDUCTION

H- and K-band spectra of cluster 89/90 were obtained with
NIRSPEC (McLean et al. 1998) on Keck in 2003 February
using the 42′′ slit with a scale of 0.144 pixel−1. The spectrum
was observed as part of a larger data set of Antennae clusters
which are described in detail in Christopher (2008). For the
H-band spectra, we used the N5 filter, covering 1.54–1.83 μm.
The K-band spectrum was obtained with the N7 filter covering
2.05–2.47 μm. The K band seeing during the observations was
≈0.5 and stable throughout the night; accordingly, the 0.57 wide
slit was used in both bands. The spectra were obtained with a
total integration time of 900 s (3×300 s) in both the H- and the
K-band at an air mass of ≈ 1.3. The object was offset along the
slit in successive frames to allow for sky subtraction. Since SSC
can often have a wealth of small-scale structure, we were careful
to make sure the sky-subtracted images contained no significant
galactic background contamination. After sky subtraction, the

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Table 1
Archival Data of Cluster 89/90

| R.A. (J2000.0) | Decl. (J2000.0) | F_{4\text{cm}} (\mu\text{m}) | F_{6\text{cm}} (\mu\text{m}) | m_{V} | m_{B} | m_{R} | m_{I} | m_{Y} | m_{H} | m_{K} |
|---------------|---------------|-----------------|-----------------|------|------|------|------|------|------|------|
| 12:01:54.58   | −18:53:03.42  | 1957            | 2316            | 19.07| 18.40| 15.05| 14.71| 14.27|

Notes.

a From Neff & Ulvestad 2000.
b From Whitmore & Zhang 2002.
c From Brandl et al. 2005 in the Two Micron All Sky Survey (2MASS) system.
d From 2MASS.

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See http://www2.keck.hawaii.edu/inst/nirspec/redspec/index.html
Figure 1 shows the final extracted $H$- and $K$-band spectrum of cluster 89/90.

3. MODELING THE NEAR-INFRARED SPECTRUM OF UNRESOLVED STAR CLUSTERS

We model the spectra of young SSCs in the near-infrared incorporating the fact that at young ages low-mass stars are still on the PMS. For objects on the PMS, we use our own synthesis code combined with a set of PMS tracks (Siess et al. 2000). For any objects not on the PMS, we use the STARBURST99 (S99) population synthesis models (Leitherer et al. 1999) which are designed to accurately reproduce spectrophotometric properties of starbursts and SSC but do not incorporate any PMS tracks. For our S99 models, we used the included Padova tracks with AGB stars and the atmospheres used were Pauldrach/Hillier (Vazquez & Leitherer 2005). The final model has two separate components, one stellar component as well as a nebular component due to thermal free–free and free–bound emission from hot stars in the cluster. In Section 3.1, we describe the inputs and parameters of the stellar model, while Section 3.2 details the constraints we can place on the nebular emission in clusters empirically.

3.1. Stellar Component

The stellar spectrum of our clusters is modeled in the following way (see also Meyer & Greissl 2005). To determine the most massive star still on the PMS at a given age, we use the tracks of Siess et al. (2000). At ages of 1 and 3 Myr, this corresponds to 7 $M_{\odot}$ and 5 $M_{\odot}$, respectively. An appropriate PMS mass–luminosity relationship for this age is then assumed (Siess et al. 2000). Stars above this limiting mass are modeled through S99. This includes the main sequence as well as the post-main sequence. We use instantaneous burst models assuming a Salpeter (1955) IMF above the PMS cutoff combined with the evolutionary models of the Padova group. The mass of the PMS and S99 components are scaled according to the IMF used and the total mass of our simulated clusters is $10^6 M_{\odot}$. We adopt a lower mass cutoff of 0.08 $M_{\odot}$ and an upper mass cutoff of $100 M_{\odot}$. We have adopted solar metallicity for our analysis in the Antennae in accordance with metallicity measurements (Mengel 2001; Christopher 2008).

Assuming an IMF and an age, all stars below the PMS cutoff in the simulated cluster are assigned a standard star spectrum (Meyer et al. 1998; Wallace & Hinkle 1997) depending on their temperature, with an appropriate luminosity. The standards used are field dwarfs that cover a spectral range between B2 and M6. The spectra are scaled with the appropriate luminosity, co-added and weighted by the main sequence and post-main sequence contribution from S99.

3.2. Nebular Emission

In addition to stellar light, the near-infrared spectrum also contains nebular free–free and free–bound emission due to ionizing radiation emitted by the massive stars present in high-mass clusters. S99 predicts that at very young ages up to 90% of the near-infrared luminosity of young SSC should be emitted in nebular mission. However, the free–free and free–bound components can be constrained directly through thermal radio data. Cluster 89/90 was observed by Neff & Ulvestad (2000) at 4 and 6 cm (Table 1). Using the 4 cm flux, which is less susceptible to non-thermal contamination, we can estimate the Lyman continuum flux being emitted by the cluster in the $H$ and $K$ band in the following way. The number of Lyman continuum photons is related to the radio flux by the following formula (Condon 1992):

$$Q_{\text{Lyc}} \geq 6.3 \times 10^{52} \left(\frac{T_e}{10^4 \text{ K}}\right)^{-0.45} \left(\frac{\nu}{\text{GHz}}\right)^{0.1} \times \left(\frac{F_{\text{nebular}}}{10^{27} \text{ erg s}^{-1} \text{ Hz}^{-1}}\right),$$

(1)

where $T_e$ is the electron temperature. We assumed a value of 7500 K for $T_e$ which is a “typical” temperature assumed for Galactic UC H II regions and the same temperature assumed by Neff & Ulvestad (2000). For cluster 89/90, this results in $Q_{\text{Lyc}} \geq 8.46 \times 10^{52} \text{ s}^{-1}$ which corresponds to the equivalent of $\geq 2300$ O5 stars powering the free–free and free–bound emission of the cluster. We then convert this to a nebular flux in the $H$ and $K$ band following:

$$F_{\text{nebular}} = \left(\frac{C}{L}\right) \times \left(\frac{Q_{\text{total}}}{\alpha_B}\right) \times Q_{\text{Lyc}},$$

(2)

where $\alpha_B$ refers to the case B recombination coefficient and $Q_{\text{total}}$ is the continuous emission coefficient. The values used were adopted from Ferland (1980). With the assumption of
a distance for the Antennae, this value can then be directly compared to the measured near-infrared flux for cluster 89/90 in the $H$ and the $K$ band (see Table 1). This results in $F_{\text{nebH}} = 2.78 \times 10^{-13}$ and $F_{\text{nebK}} = 1.98 \times 10^{-13}$ erg s$^{-1}$ $\mu$m$^{-1}$ cm$^{-2}$ in cluster 89/90. This corresponds to 19.1% and 23.5% of the total $H$- and $K$-band flux from the cluster. This is the value we will use for the rest of the analysis as the nebular percentage contributing to the near-infrared emission in cluster 89/90. The slope of the free–free and free–bound emission in the near-infrared is $f_{\text{ff}} \propto \lambda^{-2}$. S99 assumes that every Lyman continuum photon emitted in the cluster is absorbed and reradiated into free–free or free–bound emission (case B). This assumption seems to overestimate the measured nebular emission in young SSC. We attribute this to the fact that the dust surrounding the hot stars in young clusters is likely clumpy. Indebetouw et al. (2006) have found that the near-infrared spectral energy distributions of high-mass stars can vary by orders of magnitude depending on the clumpiness of the circumstellar material.

### 4. APPLICATION TO CLUSTER 89/90 IN THE ANTENNAE

We now model the spectrum of cluster 89/90 comparing the NIRSPEC spectrum to the results of the modeling routine described above. Figure 1 shows the $H$- and $K$-band spectrum of the cluster with emission lines marked. The absorption lines are barely visible at this scale. Emission lines are not included in our model or our analysis. To model the spectrum of cluster 89/90, we first assume that the cluster represents one co-eval burst of star formation (see Section 4.1) and explore the IMF required to reproduce the spectrum. We also consider two separate bursts as the underlying population of the spectrum (see Section 4.2), since (1) the spatial scale covered by our spectrum is quite large with $\approx 50\%$ of the clusters in the sample of Christopher et al. (2008) revealed as multiple clusters in HST imaging and (2) the IMF required by a single coeval burst exceeds the Salpeter slope. Table 2 lists the best-fit model parameters for the two approaches.

#### 4.1. Single-age Burst

To constrain the IMF required in cluster 89/90 if the late-type absorption features are due to a single-age burst, we model clusters at ages of 0.3, 1.3, and 5 Myr. Above 6 Myr, red supergiants appear in clusters, and our single-burst model would no longer be appropriate due to the observed ratios of near-infrared absorption lines in our spectrum (as explained in more detail in the Section 4.2). We found that the 5 Myr models could not accurately reproduce the observed spectrum because of the rapid dimming of the PMS stars and these models are not included in the two-burst model for that reason. We use a single variable power law for the IMF with a break point at $1 M_\odot$ with a variable slope below the break point and a Salpeter (1955) slope ($\alpha = 2.35$ in linear units) above. We vary the slope below $1 M_\odot$ by 0.5 dex between 0.0 and 4.0. To determine which models best fit the cluster spectrum, we performed a $\chi^2$ analysis comparing the model spectrum convolved to the resolution of the data and the data spectrum, which has been shifted to rest-frame wavelengths and normalized by fitting a fifth-order polynomial to the continuum. The nebular emission in the cluster is calculated as given above from the radio data of Neff & Ulvestad (2000) and is independent of these assumptions. We included five spectral regions in our fit, which are marked in Figure 2. These five regions include late-type absorption lines that are seen in red supergiants as well as PMS stars. In the $H$ band, there are numerous $^{12}$CO transitions that are surface gravity sensitive and strong in red supergiants but weak in main sequence and PMS objects. Of these, we include the transitions at 1.62 $\mu$m and 1.71 $\mu$m in our fit. The CO(2–0) 2.29 $\mu$m transition in the $K$ band is also surface gravity sensitive but is a prominent feature in all late-type objects. The Ca triplet (2.261, 2.263, and 2.117 $\mu$m) and the Na doublet (2.206 and 2.208 $\mu$m) in the $K$ band are strongest in stars below 3500 K ($\approx 0.5 M_\odot$). In addition, we included the Mg i 1.71 $\mu$m feature which is blended with one of the $^{12}$CO features at 1.71 $\mu$m and is strongest in stars between 0.5 and 1.5 $M_\odot$ (3500–7000 K). The presence of the Mg (solar-type stars) line in combination with the Ca, Na, and CO (cooler stars) features is what allows us to place constraints on the IMF (Meyer & Greissl 2005). We then minimize $\chi^2$ of the difference between the model spectrum and the data. Here, the goodness of the fit is given by $\chi^2 = \sum_{i=0}^{\text{data}} (d_i - m_i)/\sigma_i^2$, where $d_i$ refers to the $i$th data pixel and $m_i$ refers to the corresponding model point and $\sigma^2$ is the S/N value at the $i$th pixel. $\chi^2$ is reduced in the standard way by diving by the number of pixels in our absorption bands minus the degrees of freedom in our analysis. This process is described in more detail in the following section.

The best-fit model is plotted in Figure 2; and the model parameters are listed in Table 2. This single-age model does not match the depth of the surface gravity sensitive CO features well and the spectrum which best matches the data has $dN/dM \propto m^{-3.0}$ or steeper. As this seems extraordinary, we consider an alternate hypothesis of two separate bursts of star formation at different ages.

#### 4.2. Two Separate Bursts

We now attempt to reproduce the spectrum given two underlying bursts of star formation. Given that our $1^\prime$ slit represents a physical scale of $\approx 90$ pc at the distance of the Antennae, this approach seems warranted. We model the spectrum as one young population containing PMS stars (hereafter, Population ‘A’) in addition to an older population containing red supergiants (hereafter, Population ‘B’). We model these populations separately and then combine the two. Incorporating an older
Figure 2. Best-fit single-age model overlaid over a normalized scaled spectrum of cluster 89/90. The bands used in our analysis are marked. The emission lines as well as large parts of the continuum were not included in the modeling. The best-fit reduced $\chi^2 = 1.40$.

The presence of a young component is also supported by the emission lines seen in the spectrum of cluster 89/90. The red supergiants have stronger late-type absorption lines but cannot match the observed surface gravity sensitive equivalent width ratios. A combination of red supergiants and late-type dwarfs however can reproduce both the surface gravity index as well as the overall depth of the absorption features. In our best-fit model, A and B have a flux ratio of $\approx 7$ to 1, which is well reproduced by the location of Cluster 89/90 in Figure 3.

There are three variables we consider for each burst: mass, age, and IMF. The nebular emission in the cluster is again estimated from the radio data of Neff & Ulvestad (2000). The spectrum of B is modeled using S99, with appropriate standard spectra (Meyer et al. 1998; Wallace & Hinkle 1997) used for the red supergiants in the spectrum similar to A. The output of S99 includes the number of stars of each spectral type. For each supergiant of a given spectral type and temperature, we then use an appropriate spectral standard. The temperature scale used was adapted from the cool supergiant temperature scale by Levesque et al. (2005).

4.2.1. Model Parameters

According to S99, the first supergiants in a star cluster appear around 6 Myr though a significant population does not appear before 7 Myr. Late-type supergiants disappear at an age of $\approx 30$ Myr. Thus, we can roughly constrain the age of B to between 7 and 30 Myr. In the $H$ band, cool stars possess a $^{12}$CO absorption line which blends with the 1.71 $\mu$m Mg line in the $H$ band (see Figure 2). This feature is strongly surface gravity sensitive and very weak in dwarfs. This blend is observed in Cluster 89/90 giving additional credence to the fact that red supergiant features are present in our spectrum. We considered models in 3 Myr steps.

5 The values measured for Cluster 89/90 for the equivalent widths in Figure 3 are CO(2–0) = 14.84 ± 3.29 Å, Ca = 3.30 ± 0.48 Å, and Na = 4.19 ± 0.63 Å. The Ca triplet and Na doublet bandpasses were chosen in accordance with Kleinmann & Hall (1986) while the CO(2–0) bandpass was 2.293–2.318 $\mu$m with the continuum between 2.2887 and 2.2915 $\mu$m.
For A, the goal was not to constrain the age accurately but to assure that the best fit was consistent across different ages. Changing results with age would have limited the usefulness of our analysis method, since we do not have an independent constraint on the age of A except for an upper limit on the age of \( \lesssim 5 \) Myr. We considered models of 0.3, 1, and 3 Myr.

We vary the mass ratio of the two populations between zero and one in steps of 0.01 below \( M_{\text{old}}/M_{\text{young}} = 0.2 \) and in steps of 0.1 above 0.2. We cannot directly constrain the total mass of the cluster, because the overall flux of the spectral model depends on the mass ratio of the best-fit model. After we have determined the best spectral model fit, it is possible to constrain the mass through broadband magnitudes. There is no way to directly constrain the IMF of B since we only trace a very small mass range of stars in the population in our spectrum, the red supergiants. Thus, the IMF of B is assumed to be the same as that of A except for the lowest masses.

We now discuss the implications of the ranges of parameters constrained by our modeling (see Table 2). The three plots in Figure 5 show the probability distribution of the age of the old population, mass ratio of the two bursts, as well as the slope of the IMF below \( 1 \, M_\odot \). Each plot shows the probability distribution at the three different ages of A to make sure that the results are consistent over a range of ages. Panel 1 shows that the older population has a most probable age of 12 Myr. Within 90% confidence limits, the models are consistent with an age between 6 and 18 Myr for the old population. It should be noted that a population containing no supergiants is ruled out as can be seen by the fact that an age of 1 Myr and 3 Myr for B have zero probability. This coarse age constraint is not surprising since very little differentiates spectra of red supergiants in the near-infrared besides the overall strength of late-type absorption lines.

The plot of mass ratios shows the cumulative probability with respect to \( M_{\text{old/young}} \). The mass ratio strongly favors A dominating in mass by a factor of \( \gtrsim 5 \) over B. The best-fit model comparison of the K-band flux with the K-band broadband flux of the cluster yields a total mass of \( 1.4 \times 10^7 \, M_\odot \) down to the hydrogen burning limit. If we assume that the total mass is \( 1.4 \times 10^7 \, M_\odot \), then the total mass of A is \( \gtrsim 1.2 \times 10^7 \, M_\odot \), while...
the mass for B is $\lesssim 2 \times 10^6 M_\odot$. The best fit indicates a mass of B of $5 \times 10^5 M_\odot$ and a ratio of $M_{\text{old}}/M_{\text{young}} = 0.04$. The total mass estimate agrees well with that calculated by Gilbert et al. (2000; $1.6 \times 10^7 M_\odot$) using the Lyman continuum flux of cluster 89/90. Thus, the young component of cluster 89/90 likely is one of the most massive young star clusters which formed in the Antennae galaxies. The 90% confidence limit for the mass ratio is roughly 0.02–0.12 though this value changes slightly between different ages of A. Thus, we have clearly detected the PMS in the cluster. A mass ratio of 0 and therefore $M_{\text{old}} = 0$ is ruled out as well as a mass ratio $\geq 0.12$ and thus no PMS contribution.

The probability for the IMF of A rises strongly toward steeper slopes with the probability being highest for a Salpeter slope below $1 M_\odot$. However, the spectrum is formally consistent with a slope down to a power-law slope of 1.5 within a 90% confidence limit. This result is consistent across all ages of the young population. A top-heavy IMF weighted more heavily toward high-mass stars than a Kroupa (2001) IMF has often been cited as expected for SSC clusters, and the best remaining evidence of an unusual IMF in an SSC (M82-F) indicates a top-heavy IMF. Our result is consistent with a normal Galactic IMF (Covey et al. 2008) as well as a Salpeter IMF. A low-mass cutoff in this cluster is ruled out since PMS objects in the young burst below $1.0 M_\odot$ are required to produce the observed spectrum. We did not include any slopes above Salpeter as the goal of this study was not to make claims of extraordinary IMF results within the limited data this cluster offers. In addition, the best-fit model for the two-burst model at a Salpeter slope shown in Figure 4 is a very good fit to the data whereas for the single burst even a Salpeter slope did not fit the data well. This is independent of the probability curve shown, which was shown to illustrate the overall trends of the models rather than the quality of the overall fits. Thus, we feel, it is reasonable to set the cutoff at the Salpeter slope even though the IMF probability is still rising.

5.2. Caveats

Our model has many components and therefore degeneracies exist between its different subsets. One such degeneracy exists between the assumed age of the PMS objects and the IMF slope. Since PMS objects grow fainter as they age, one might erroneously assign an IMF that is too flat to a 1 Myr cluster that is really 3 Myr old. However, Figure 5 shows that our IMF results are very similar at different assumed ages for the young burst, and thus we do not expect this to be a problem. Another concern is that the calculated nebular emission is wrong and this might affect the results of our models. We varied the input nebular continuum by 50% in both directions which did not change our results substantially. In addition, there are limits to the inputs of our models. Our standards are field dwarfs with high surface gravity, while PMS objects are young and have lower surface gravity than dwarfs. The surface gravity of PMS objects is generally between $\log g = 3.0$ and 4.2 (Gorlova et al. 2003), while dwarfs are generally have $\log g = 5.0$–5.5. This would increase the depth of the CO absorption features in our spectrum. Obtaining spectral standards of young PMS objects is difficult because the largest nearby sample is found in relatively distant young clusters, making it observationally expensive to obtain a complete high S/N sample in the near-infrared. Since we used spectral standards to model our spectra rather than synthetic spectra, our coverage of individual spectral types is not complete. This might cause errors in the depth of the absorption features of our model spectra due to binning the stars into spectral types for which spectral coverage exists. However, this effect is likely small compared to the error introduced by the usage of dwarf rather than PMS standards. Since synthetic spectra struggle to accurately model low-mass young PMS stars (Doppmann et al. 2003).
dwarf standards currently remain the best option to accurately model the near-infrared spectra of SSC. However, PMS stars generally lie closer to field dwarfs than supergiants in surface gravity (Gorlova et al. 2003); and it is thus likely that even including PMS standards would not remove the need of having a supergiant component in our models. The presence of veiling due to disks around young stars can dilute the absorption features in near-infrared spectra. We do not have an independent method of quantifying the affect veiling has on our data since we are modeling a whole star cluster, but we expect the effect to be minimized by the use of line ratios. Finally, in some very young objects, CO features can be seen in emission due to the presence of a disk (e.g., Blum & McGregor 2008). We do not observe evidence for this in our spectrum.

6. DISCUSSION

6.1. Previous Work

We have shown that it is possible to directly detect PMS stars in unresolved SSC as well as place some constraints on the underlying IMF and age of the cluster. Substantial work has been done studying the IMF of SSC through measurements of mass-to-light ratios, including in the Antennae. Mengel et al. (2002) measured mass-to-light ratios in the $K$ band for a number of clusters in NGC 4038/9 and found variations indicative of IMF variations in the clusters. To measure mass-to-light ratios in clusters younger than $\approx 30$ Myr requires the ability to constrain velocity dispersions through strong CO absorption bands that exist in clusters dominated by red supergiants. Bastian et al. (2006) used UV spectra of clusters in two merger remnants with ages of more than 300 Myr to measure their mass-to-light ratios and found them to be consistent with a Kroupa IMF. Similarly, Larsen et al. (2004) and Larsen & Richtler (2004) measured mass-to-light ratios in older clusters through optical spectroscopy and found them to be consistent with a Kroupa IMF. This dichotomy: young clusters with varying mass-to-light ratios and older cluster with mass-to-light ratios consistent with normal IMFs provide evidence that something other than IMF variations are the cause of varying mass-to-light ratios in young SSC or that perhaps SSC with unusual IMFs get disrupted preferentially. This work shows an avenue for providing more concrete measurements of IMFs in SSC than mass-to-light measurements can deliver though this data set is not the ideal application of our method.

Work on modeling the integrated spectra of young clusters has up until now been done mostly in the UV and optical (e.g., Tremonti et al. 2001) because of the strong signatures of massive stars at these wavelengths. The near-infrared is ideally suited to detect the low-mass stellar content of the clusters as well as evolved giants and supergiants. Recently, Lançon et al. (2008) have attempted to use simple stellar population models to constrain ages of star clusters in M82 in the near-infrared. Brandl et al. (2005) attempted to use near-infrared colors of clusters in the Antennae in combination with thermal radio images to constrain their properties and found them to be uncorrelated. However, Antennae clusters are not ideal objects to study young clusters in detail. They are distant enough that multiple stellar populations of different ages may be treated as unresolved point sources. We have shown that it is possible to constrain the properties of young star clusters through near-infrared spectroscopy. Varying nebular emission due to the ionizing radiation emitted by hot stars provides an additional complication in the understanding of the youngest clusters. The total amount of free–free and free–bound emission in young clusters is easiest to constrain empirically, because it should depend strongly on the formation environment of the cluster. More work is needed studying nearby SSC in the near-infrared to understand whether near-infrared images and spectroscopy can accurately predict the ages and masses of these clusters.

6.2. Scales of Star Formation

What can cluster 89/90 tell us about the scales of star formation in the Antennae galaxies as well as locally? The spectrum of our cluster likely contains two separate underlying populations with an age spread between 6 and 18 Myr and a mass ratio $M_{\text{old}}/M_{\text{young}} \leq 0.2$. At the distance of the Antennae, our 1" slit covers a region of 93 pc. This region likely contains two massive clusters, one with a mass of order $10^7 M_\odot$ and the other $10^6 M_\odot$. It is possible that the older cluster started out at a higher mass and lost a large fraction of its mass due to dispersion into the field. How does this compare to sites of massive star formation we can study in detail?

No young $10^6 M_\odot$ clusters exist in local group galaxies. However, massive sites of star formation (up to roughly $10^7 M_\odot$) are accessible in both the Milky Way and the LMC. Grebel & Chu (1999) present detailed observations of Hodge 301, a cluster in the 30 Doradus star-forming complex. Hodge 301 is between 20 and 25 Myr old and lies at a distance of 3'$ (\approx 44$ pc) from the young center of 30 Doradus, R136. It is estimated to have been relatively massive with an initial mass of up to 6000 $M_\odot$ though less massive than R136 (\approx 30,000 $M_\odot$). In the Galaxy, NGC 3603 and the Arches cluster, two of the most massive star-forming regions in the Milky Way do not appear to have similar older star formation complexes in their proximity, though both have isolated red supergiants in their environments. Melo et al. (2005) found the typical separation of young SSCs in M82 to be $\approx 12$ pc though the equivalent age spread of the clusters is not given. Christopher (2008) found that half of their Antennae NIRSPEC cluster sample with 1" resolution contained more than one star cluster which would indicate a larger typical star cluster separation than in M82. Christopher (2008) also found some sources in their Antennae sample with no obvious cluster superposition which contained emission lines as well as CO band heads simultaneously. This raises the question whether some SSCs have non-instantaneous bursts of star formation over the size of the cluster and about the magnitude of this age spread.

Cluster 89/90 illustrates the need to study massive star-forming regions in detail at a distance where the individual cluster complexes can be resolved from each other. Neff & Ulvestad (2000) found radii of $\approx 3$ pc for the thermal radio sources in NGC 4038/9. This distance corresponds to 0.03 in the Antennae. If we assume a typical star cluster separation of 12 pc, the distance at which a 1" spectrum can resolve this distance is $\approx 2.5$ Mpc. More distant galaxies make ideal targets for observations with adaptive optics (AO) equipped with integral field unit (IFU) spectrographs.

7. SUMMARY AND CONCLUSIONS

We have modeled the integrated properties of a massive young cluster in the Antennae through its $H$- and $K$-band spectrum. Our models use a combination of Starburst99, PMS tracks, and field dwarf spectral standards. We find that the integrated spectrum likely represents two separate star clusters with an age spread of 6–18 Myr with a mass ratio of $M_{\text{old}}/M_{\text{young}} \leq 0.2$ and a total mass of $\approx 10^7 M_\odot$. The IMF in the young cluster is best fit by a...
Salpeter (1955) slope down to the hydrogen burning limit though the cluster IMF is formally consistent with a Chabrier (2003) IMF. We find no evidence of a low-mass cutoff in the cluster. Thus, we have for the first time directly detected low-mass PMS stars in a young extragalactic SSC.

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