GEMINI SPECTROSCOPY AND HST IMAGING OF THE STELLAR CLUSTER POPULATION IN REGION B OF M82.1,2

I. S. Konstantopoulos,3 N. Bastian,3 L. J. Smith,3,4 G. Trancho,5,6 M. S. Westmoquette,3 and J. S. Gallagher III7

Received 2007 June 25; accepted 2007 October 2

ABSTRACT

We present new spectroscopic observations of the stellar cluster population of region B in the prototype starburst galaxy M82 obtained with the Gemini North 8.1 m telescope. By coupling the spectroscopy with UBV1 photometry acquired with the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope (HST), we derive ages, extinctions, and radial velocities for seven young massive clusters (YMCs) in region B. We find the clusters to have ages between 80 and 200 Myr and velocities in the range 230–350 km s−1, while the extinctions vary between −1 and 2.5 mag. We also find evidence of differential extinction across the faces of some clusters, which hinders the photometric determination of ages and extinctions in these cases. The cluster radial velocities indicate that the clusters are located at different depths within the disk and are on regular disk orbits. Our results overall contradict the findings of previous studies, in which region B was thought to be a bound region populated by intermediate-age clusters that formed in an independent, offset starburst episode that commenced 600 Myr–1 Gyr ago. Our findings instead suggest that region B is optically bright because of low-extinction patches, and that this allows us to view the cluster population of the inner M82 disk, which probably formed as a result of the last encounter with M81. This study forms part of a series of papers whose aim is to study the cluster population of M82 using deep optical spectroscopy and multiband photometry.

Subject headings: galaxies: evolution — galaxies: individual (M82) — galaxies: photometry — galaxies: starburst — galaxies: star clusters

Online material: color figures

1. INTRODUCTION

The extensively studied galaxy M82 is a local example of a nuclear starburst galaxy. O’Connell & Mangano (1978, hereafter OM78) first cataloged the complex star-forming regions seen in ground-based images of the M82 disk, and they introduced the nomenclature A–H for individual regions. Region B is the brightest region in the disk and is located 350–1050 pc northeast of the nucleus. OM78 and Marcum & O’Connell (1996) find that the integrated spectrum of this region is indicative of a fossil starburst region, as it shows the characteristic ‘E+A’ poststarburst spectrum, suggestive of a truncated burst of star formation occurring 100–1000 Myr ago. Moreover, they find that the intrinsic brightness of region B is such that the burst must have been of comparable intensity to that of the present starburst in the nucleus.

More recently, de Grijs et al. (2001) studied the M82-B cluster population using photometry obtained with the Wide Field and Planetary Camera 2 (WFPC2) and the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) on board the Hubble Space Telescope (HST). They identified 113 clusters and, by estimating ages and extinctions from BVI photometry, they found that a concentrated episode of cluster formation occurred 400–1000 Myr ago, with a peak at 600 Myr. Subsequent to this analysis, de Grijs et al. (2003b) rederived the ages and extinctions by combining BV1 and JH photometry; they find that the peak of cluster formation occurred at 1.10 Gyr, with an age spread of 500–1500 Myr. De Grijs et al. (2003a) used these new ages to derive the cluster luminosity function (CLF) for a fiducial age of 1.0 Gyr and find that it has a Gaussian shape, similar to those of globular clusters (GCs), rather than the standard power-law CLF found for populations of young massive clusters (YMCs; e.g., Larsen 2004; Gieles et al. 2006a). This result is surprising, but it supports theoretical models advocating that an initial power-law distribution of cluster masses will be transformed into a Gaussian distribution because low-mass clusters will be preferentially disrupted (e.g., Fall & Zhang 2001; Vesperini & Zepf 2003; Gieles et al. 2006b). De Grijs et al. (2003a) therefore suggest that because M82-B is of intermediate age, it provides the “missing evolutionary link” between the power-law CLFs found for YMCs and the Gaussian CLFs of globular clusters. However, for an environment as turbulent as that of M82, one would expect a timescale of several Gyr in order for preferential disruption to produce this effect (e.g., Goudreauj et al. [2004, 2007], in which such a timescale is calculated for NGC 1316 and NGC 3610, respectively).

To date, spectroscopy of the region B cluster population has been extremely limited; the only published spectra are those of Smith et al. (2006) for the two brightest members. The spectra were obtained with the Space Telescope Imaging Spectrograph...
and, although the spectra are of low quality, the derived ages of $350 \pm 100$ Myr are much lower than the photometrically based ages of $\sim 0.7$–6 Gyr (Smith et al. 2006; de Grijs et al. 2003b) for the same clusters. This discrepancy hints at the possibility that region B may be younger than expected and that the ages derived from the photometry are too high. It is important to determine accurate ages for the M82-B cluster population to verify its unusual CLF, as well as to understand the cluster formation history of M82 and its relationship to encounters with its close neighbor M81.

We therefore acquired new spectroscopic and photometric data for the M82-B cluster population. By using both techniques, we are able to obtain information for a large number of clusters and also overcome the degeneracy between age and extinction that presents a hurdle in the analysis of photometric data (Trancho et al. 2007a, 2007b). In this paper, we present optical spectroscopy for seven clusters that was obtained with the Gemini North 8.1 m telescope, and in a companion paper (Smith et al. 2007), we present new HST imaging, including $U$-band photometry of the clusters.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Spectroscopy

The spectroscopic data presented in this paper were obtained with the Gemini North 8.1 m telescope, using the Gemini Multi-Object Spectrograph (GMOS-N), as part of program GN-2006A-Q-38 (PI: L. J. Smith). The target selection was made on the basis of photometric criteria, with the potential YMCs identified on GMOS pre-imaging that was taken as part of the observing program. A multislit mask was designed, using a slit width of 0.75 $''$, with a variable slit length that we tried to keep to a minimum of 6.5 $''$, in order to include an area of sky that would ensure a good background subtraction. In some cases, however, a smaller slit length was used so as to include a greater number of sources on the mask, resulting in a total of 39 objects being targeted across the M82 galactic disk. In this paper we focus on 7 of these 39 clusters that are situated within region B. Figure 1 indicates the positions of the clusters and the slits, and the fully reduced rectified spectra are presented in Figure 2. A list of cluster identifiers and coordinates can be found in Table 1.

The data were acquired on the night of 2006 April 5, under good seeing conditions (0.8 $''$ at 5000 Å). We used the B600 grating, and the data were read out in $2 \times 2$ binning mode, resulting in a dispersion of 0.9 Å pixel$^{-1}$. As this is multobject spectroscopy, the central wavelength varies slightly with every slit, so the resulting spectral range of the data is approximately 3700–6500 Å. Although we used all three GMOS-N CCDs to achieve this broad range, the sensitivity of the silver-mirrored chips is lower at the blue end, resulting in a poor signal-to-noise ratio (S/N) and loss of accuracy in the wavelength calibration below 4000 Å, thus setting a lower limit to our effective wavelength range.

The data were acquired in eight 1800 s exposures, totalling 4 hr of integration time. More specifically, there were two sets of four exposures that differed in terms of central wavelength. This is standard GMOS procedure, which allows the observer to compensate for the interchip gaps through co-adding/merging the spectra; the two values of $\lambda_{\text{central}}$ were 5080 and 5120 Å. CuAr (copper-argon) arc exposures and quartz-halogen flat fields were taken in between target exposures. Bias frames were taken as part of the Gemini baseline calibrations (GCAL).
The data were subsequently reduced using mainly standard IRAF\(^9\) reduction tools, as well as tasks from the purpose-developed Gemini IRAF tool. The wavelength calibration was performed using the obtained CuAr arc frames, resulting in residuals of typically less than 0.15 Å.

One complication that arises when observing in multislit mode is that the exposures are not perfectly aligned with the parallactic angle for the duration of an exposure. To alleviate this effect, the combined data were corrected for parallactic angle using a purpose-built IDL (Interactive Data Language) routine written by B. W. Miller (2006, private communication) that was based on Filippenko (1982), where the effects of atmospheric differential refraction are discussed.

At this point we extracted all 39 spectra from each multidimensional multiobject spectroscopy frame and merged all available exposures of each target. In most cases we decided not to use all the available spectra, as some exposures were of poor quality (caused by seeing degradation) and thus would have lowered the quality of the merged spectrum.

Finally, the spectra were flux-calibrated using a response function derived from the standard star Wolf 1346. It should be noted here that the observations used were taken on a different night (2006 May 25), due to problems that arose with the exposure of the original flux standard, Feige 34. This unfortunately led to an increased uncertainty in the absolute flux scale.

Having completed the extraction procedure, we measured the width of the skyline at 5577 Å, in order to measure the spectral resolution of our data, which we found to be 3.5 Å (FWHM). We also tested the wavelength calibration by measuring the exact position of this line and found it to be well within the predicted errors. The signal-to-noise ratios of the spectra were determined using two continuum windows between 4400 and 5000 Å.


duration of 11 and 1 pixels, respectively.

We also used U-band (F330W) ACS HRC imaging of region B, obtained as part of HST program 10853 (PI: L. J. Smith), which extends our photometric coverage to the near-UV. The combination of optical and UV data enables us to set a strong constraint on age and extinction determinations of young stellar clusters (e.g., Anders et al. 2004). The HRC data were processed with the standard automatic HST pipeline and were drizzled (using the MultiDrizzle package; Koekemoer et al. 2002) to a scale of 0.025" pixel\(^{-1}\). For a more detailed discussion of the data, we refer the reader to Smith et al. (2007). We also performed aperture photometry on the HRC images with apertures of the same physical size (0.5" as projected onto M82); that is, an aperture

\(^{9}\) IRAF is distributed by the National Optical Astronomical Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

| No.a | Alt. No. b | Previous Name c | R.A. d (J2000.0) | Decl. d (J2000.0) |
|------|-----------|----------------|-----------------|-----------------|
| 91   | 34        | B2-12, H\(^{+}\), B1-2 f | 09 55 54.60     | 69 41 01.7     |
| 97   | 25        | B2-26          | 09 55 55.65     | 69 41 05.9     |
| 103  | 20        | B2-41          | 09 55 57.04     | 69 41 07.4     |
| 108  | ...       | B2-49          | 09 55 58.41     | 69 41 08.7     |
| 113  | 14        | B1-6           | 09 56 00.63     | 69 41 02.5     |
| 126  | 6         | B1-20          | 09 56 02.52     | 69 41 08.1     |
| 131  | 1         | B1-28, B2-1 f  | 09 56 03.40     | 69 41 12.3     |
| 91   | 34        | B2-12, H\(^{+}\), B1-2 f | 09 55 54.60     | 69 41 01.7     |
| 97   | 25        | B2-26          | 09 55 55.65     | 69 41 05.9     |
| 103  | 20        | B2-41          | 09 55 57.04     | 69 41 07.4     |
| 108  | ...       | B2-49          | 09 55 58.41     | 69 41 08.7     |
| 113  | 14        | B1-6           | 09 56 00.63     | 69 41 02.5     |
| 126  | 6         | B1-20          | 09 56 02.52     | 69 41 08.1     |
| 131  | 1         | B1-28, B2-1 f  | 09 56 03.40     | 69 41 12.3     |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

a Cluster identifier in our Gemini program.
b Identifier in Smith et al. (2007).
c Identification by de Grijs et al. (2001) unless otherwise stated, where “B1” and “B2” refer to the part of the region to which the cluster belongs.
d Coordinates as measured on the F555W ACS mosaic image.
e Notation follows OM78.
f As in STIS study by Smith et al. (2006).
The combination of $UBVI$ photometry and high-S/N optical spectra allows us to determine the age and extinction of each of the seven clusters in our sample. Throughout this section, we assume that the clusters have solar metallicity, in agreement with ISM studies of M82 (McLeod et al. 1993). In addition, we adopt a standard Galactic extinction law (Savage & Mathis 1979).

We note here that these assumptions on the metallicity and extinction laws do not have a large impact on our conclusions. In particular, if we were to use the starburst extinction law of Calzetti (1997), the photometric ages and extinctions would remain virtually unchanged.

3.1. Ages and Extinctions from Photometry

As a first method to determine the ages and extinctions of the clusters, we compare their colors to simple stellar population (SSP) models. We choose the GALEV SSP models (Anders & Fritze-v. Alvensleben 2003), with solar metallicity and a Salpeter IMF. These models use the Padova stellar isochrones, and the evolution of magnitude is given as a function of time directly in the VEGAmag system for $HST$ filters. Thus there is no need to convert the measured cluster magnitudes to the more standard Cousins-Johnson system, which would introduce additional errors.

In Figure 3 we show the $U - B$ versus $V - I$ colors of the clusters in region B for which we have $UBVI$ photometry and spectra. In addition, we demonstrate the evolution of the GALEV SSP models by labeling six ages, and we show extinction vectors of magnitude $A_V = 3.0$ starting from these ages to guide the eye. From this plot we can deduce that all but one of the clusters (No. 91) have ages between 50 Myr and 1 Gyr. Cluster 91 (cluster H, following notation by OM78) will be discussed in § 3.4.

However, as the SSP colors do not evolve monotonically in color space, the $U - B$ versus $V - I$ diagram provides simply one of the possible color projections of the photometry. In order to fully exploit the available data, we have used the three-dimensional maximum likelihood fitting (3DEF) method presented in Bik et al. (2003) and further tested in Bastian et al. (2005). Briefly, this method compares the photometry of each cluster to that of the SSP models, to which it applies an extinction ($A_V$) between 0 and 5 mag, in steps of $\Delta A_V = 0.2$ mag, and calculates a value of $\chi^2_v$ (reduced $\chi^2$). The model, i.e., the combination of age and extinction with the lowest value of $\chi^2_v$, is selected as the best fit, and the errors are assigned by the extrema of the set of models that satisfies the condition $\chi^2_v < \chi^2_v,\text{best} + 1$.

![Fig. 3.—Color-color plot for six of the seven clusters in M82-B. The solid line traces the GALEV SSP model colors, with asterisks marking model track ages of 10, 50, 100, 250, 500, and 1000 Myr. The data points represent the cluster colors and their associated errors, as derived from multiband photometry. The arrows represent extinction vectors, along which the "footprint" of the cluster may be traced in order to estimate its age and extinction; the length of the vectors is 3 mag. The large $V - I$ error on cluster 113 is due to contamination from a neighboring red source. The errant cluster 91 has an underestimated $U$-band flux (see § 3.4), and cluster 108 is not included because it is not detected in the $U$ band.](image)

**TABLE 2**

| No. | $F330W$ (mag) | $F435W$ (mag) | $F555W$ (mag) | $F814W$ (mag) | $M_V$ (mag) | $A_V$ ($F555W$) | Age (Myr) | $\sigma_{\text{Age}}$ (Myr) |
|-----|--------------|--------------|--------------|--------------|-------------|-----------------|-----------|-----------------------------|
| 91  | 20.12        | 18.91        | 17.75        | 16.07        | $-12.95$    | 2.4           | ...       | ...                         |
| 97  | 18.93        | 18.81        | 18.28        | 17.25        | $-10.56$    | 1.1           | 180       | [140, 220]                  |
| 103 | 19.21        | 19.08        | 18.35        | 16.94        | $-11.36$    | 1.9           | 90        | [60, 150]                   |
| 108 | $d$          | $d$          | 19.21        | 17.84        | $-12.24$    | 2.5           | ...       | ...                         |
| 113 | 20.41        | 20.10        | 19.35        | 18.01        | $-10.30$    | 1.9           | 170       | [72, 360]                   |
| 126 | 19.77        | 19.34        | 18.64        | 17.47        | $-10.70$    | 1.5           | 260       | [190, 1200]                 |
| 131 | 18.37        | 18.24        | 17.74        | 16.61        | $-11.22$    | 1.2           | 170       | [110, 190]                  |

* Minimum and maximum acceptable values for the cluster age, according to the 3DEF method.
* Value estimated from the extinction map in Fig. 7. This cluster is discussed in § 3.4.
* Not possible to obtain a photometric age because of differential extinction (see § 3.4).
* Cluster is not visible in the $U$ band.
* Estimated from $BVI$ photometry, assuming the spectroscopically derived age.
The photometrically derived best-fit ages range between 90 and 260 Myr, and we find $A_V$ extinction values that are in the range 1.1–2.5. The values for each cluster are shown in Table 2.

3.2. Spectroscopy

While photometry presents a useful tool for constraining ages and extinctions, its limitations (such as the need for detection in four filters spanning 5000 Å) are apparent even in a sample of seven clusters. Spectroscopy has long been recognized as the method providing the most accurate means of determining cluster ages using SSP models. We have measured ages for our cluster sample using the solar metallicity models of González Delgado et al. (2005, hereafter GD05), which are designed specifically for young clusters, in the age range 4 Myr–1 Gyr. The parameters of the models match those assumed for the photometric fitting (solar metallicity, Salpeter IMF, and Padova stellar isochrones), and their wavelength range of 3000–7000 Å is well matched with that of our observed spectra. All model spectra have been degraded to match the observed spectral resolution of 3.5 Å.

We prefer using these theoretical models over the more established Bruzual & Charlot (2003) templates for a number of reasons. First, the good age resolution means that cluster ages can be determined with higher precision. Second, the high sampling resolution of 0.3 Å allows us to downgrade the resolution of the models, rather than that of the data, in order to match the two.

We determine the ages of the clusters using two separate statistical methods, a model-spectrum residual method (MSRM) and a cumulative $\chi^2$ method (CCM). We choose, for these clusters, to investigate the fit of the models on the lower Balmer series spectral lines. We compare the models and observations directly by first rectifying the spectra on the basis of fits to the continuum and Hγ/C13. We can avoid having to make any presumptions about the shape of the line in cases where there is noise or nebular emission. We use many aspects of the feature in order to determine the best fit: we check the agreement in line width, how well the overall line profile is fitted, and how closely the depth of the line is fitted or predicted. In most of the clusters we find emission superposed on the absorption line. This emission presumably comes from diffuse ionized gas in the region and is not centered at the same wavelength as the absorption, which means that it is not directly associated with the clusters.

The main obstacle that arises when using automated statistical methods is the age degeneracy of the Balmer line strength; i.e., multiple models of very different ages have similar line strengths. This means that the ages cannot be determined by simply finding the model that best predicts the depth of the line. In addition to the age degeneracy, the observed spectra may also feature superposed emission, so the fit would not in such cases reflect the actual absorption-line profile.

The first method employed (the MSRM) fits a model and calculates the minimized absolute value of the model-spectrum residual. The best fit is then chosen as the model with the lowest mean residual. The second method (the CCM) uses all available data points to calculate the value of $\chi^2$ cumulatively for each model fit. This offers a more realistic interpretation of a good fit to the entire line profile. In that way, the best-fitting template will be the one that traces the Balmer line profile, including the wings, thus overcoming the observed line strength degeneracy.

As mentioned above, most of the clusters contain emission features within the Balmer absorption lines. Therefore, in fitting the data we have carefully avoided regions that are contaminated by emission. This is shown in Figure 5, where the top panel shows the Hγ line for cluster 97 (black solid line) and the two dashed boxes show where the fit was carried out. We would like to note here that including the profile center in the fit causes degradation of the fit quality; however, it leaves the cluster age distribution largely unaffected, with ages shifting by an average of $\sim$20 Myr toward younger values. The bottom panel of Figure 5 shows the results of the two fitting methods applied as a function of age. The solid light gray line shows the CCM and the dash-dotted medium gray line shows the MSRM, and both fits are carried out within the designated boxes. The MSRM is more sensitive to line strength and has two minima for very different ages, whereas the CCM overcomes this obstacle in most cases and has one clear minimum.

The error on the best-fitting age is calculated in a similar way as for the 3DEF method; that is, on the basis of the extrema of the set of models that satisfies the condition $\chi^2 < 2\chi^2_{\text{min}}$. We note here that a second $\chi^2$ minimum does tend to appear in the lower S/N spectra (clusters 103, 108, 113, and 126). In these cases, the very bottom of the second minimum “trough” is low enough to satisfy the mentioned error condition. Nonetheless, we are able...
the use as an error estimate. The vertical axis traces the model-spectrum residual, and traces the value of panel shows the statistical measures as a function of age; the solid light gray line indicate the regions of the spectrum that are considered for the fit. The bottom ing the best-fit model age for each method. In the case of cluster 97, this occurs value of the model-spectrum residual, with corresponding vertical lines denot- ing the best-fit model age for each method. In the case of cluster 97, this occurs 2

Fig. 5—Statistical fits for cluster 97. The top panel shows the region of the observed spectrum (black line; wavelengths are given in units of Å) with the best-fit models overplotted; the dashed light gray and dash-dotted medium gray lines correspond to the CCM (cumulative \( \chi^2 \) method) and MSRM (model-spectrum residual method) best fits, respectively. The dashed dark gray boxes indicate the regions of the spectrum that are considered for the fit. The bottom panel shows the statistical measures as a function of age; the solid light gray line traces the value of \( \chi^2 \), and the dash-dotted medium gray line traces the absolute value of the model-spectrum residual, with corresponding vertical lines denoting the best-fit model age for each method. In the case of cluster 97, this occurs at 180 Myr for both the CCM and the MSRM (this applies to the H\(_\alpha\) fit). The horizontal dashed light gray line denotes the limit of values within 2\( \chi^2 \), which we use as an error estimate. The vertical axis traces the model-spectrum residual, and the \( \chi^2 \) curve has been scaled to 1/20th of its original values in order to fit in the same plot. [See the electronic edition of the Journal for a color version of this figure.]

to confidently reject the higher age values by inspecting the resulting model-spectrum fit, as it shows a clear disagreement in the overall line profile. The derived ages and errors are given in Table 3.

For the brightest cluster, No. 91, it is possible to use a third technique to further reinforce our results: the ratio of He\(_i\) 4471 to Mg ii 24481. By comparing the values of this ratio between the spectrum and the model, we can get one more estimate of the \( \tau \) (Myr)

The spectroscopic age measurements are summarized in Table 3. In all, we find ages in the range 80–200 Myr. We have adopted the age for each cluster to be the average of all available spectroscopic age determinations that provide a good fit. The ages are listed in Table 4. These results disagree with work previously published on region B (de Grijs et al. 2001, 2003a), in which it was suggested that the ages of most clusters in the region are in excess of 400 Myr. In the de Grijs et al. (2003a) sample of 113 clusters, there are only 4 that have derived ages that are younger than 400 Myr. This age difference and its implications are discussed in more detail in § 4.2.

3.3. Radial Velocities

The clusters observed reside in a region that is rich in diffuse ionized gas. As a result, there is a small amount of Balmer line emission from their environment, and therefore the Balmer line profiles of the clusters are a blend of the deep stellar absorption lines with narrow nebular emission lines, which in some cases are offset. This makes the precise determination of the profile center by inspection of Balmer lines practically impossible; therefore, we resort to automated routines that also focus on other features in order to calculate the radial velocities of the clusters. To determine the velocity of the neutral gas in our line of sight, we use the Na i D interstellar lines.

In order to derive the best possible estimates for the radial velocities, we used a number of measurements (from three to six measurements, depending on the S/N), each one for a different spectral region, and combined all the results to get a value for the velocity (the arithmetic mean) and its error (the standard deviation).

The first method employed was the FXCOR cross-correlating routine in IRAF, which we applied to various regions of the spectrum, each time including a different set of absorption lines. We also used the penalized pixel-fitting (pPXF) routine, taking care not to include the emission component of the Balmer line profiles in the fit. We will not provide a detailed description of this method here; instead, we refer the reader to Cappellari & Emsellem (2004).

In brief, the method simply cross-correlates selected regions of a

![Image of Table 3](image-url)

**TABLE 3**

| No. | S/N\(^a\) | \( \tau_R \) (km s\(^{-1}\)) | \( \tau_Na\) \( ^b\) (km s\(^{-1}\)) | \( \tau_{MSRM} \) \( ^c\) (Myr) | \( \tau_{CCM} \) (Myr) | \( \sigma_x \) \( ^d\) (Myr) |
|-----|-----|-----|-----|-----|-----|-----|
| 91  | 44  | 230 ± 20 | 270 ± 10 | 180  | 190  | [110, 250] |
| 97  | 34  | 290 ± 20 | 285 ± 10 | 180  | 200  | [130, 320] |
| 103 | 23  | 270 ± 20 | 270 ± 10 | 710  | 100  | [30, 180] |
| 108 | 16  | 340 ± 40 | 200 ± 30 | 140  | 140  | [60, 250] |
| 113 | 24  | 280 ± 20 | 225 ± 10 | 100  | 100  | [20, 180] |
| 126 | 24  | 350 ± 30 | 220 ± 20 | 200  | 200  | [130, 280] |
| 131 | 40  | 260 ± 10 | 245 ± 10 | 80   | 70   | [40, 160] |

\(^a\) Average of calculations for two different continuum regions, 4400–4800 Å and 5000–5800 Å.

\(^b\) Errors quoted here are adopted as a 0.25 pixel measurement error, which roughly corresponds to 10 km s\(^{-1}\). In all but two cases, the agreement between the two individual doublet line measurements gives rise to an error that is lower than the adopted systematic error.

\(^c\) The model-spectrum residual method (MSRM) and cumulative \( \chi^2 \) method (CCM) best-fit ages (as explained in § 3.2).

\(^d\) Minimum and maximum acceptable ages, according to the CCM.
given the same templates to fit, resulting in accurate and precise corrections or normalizing the spectra before fitting the templates. This enables us to avoid making not introduce extra degrees of freedom into our calculation.

It also means that only one measurement is required; thus, it does not introduce extra degrees of freedom into our calculation.

We find that the two methods provide consistent results when given the same templates to fit, resulting in accurate and precise radial velocity measurements. Correcting the cluster velocities to the heliocentric frame of reference gives values ranging between 230 and 350 km s\(^{-1}\) (see Table 3). This range corresponds to 30–150 km s\(^{-1}\) with respect to the center of the galaxy, where we adopt a systemic velocity of 200 km s\(^{-1}\) for M82 (McKeith et al. 1993). The results are discussed in §4.3.

### 3.4. Differential Extinction on Clusters 91 and 108

In §3.1 we briefly discussed the fact that the age of cluster 91 (M82-H) cannot be determined photometrically, as it lies beyond the area in color space covered by the SSP model evolutionary track, once extinction has been accounted for. This appears to be caused by an underestimation of its \(U\)-band flux, so it also affects the analytical photometric method applied (3DEF).

In support of this hypothesis, Figure 6 shows ACS HRC imaging of the cluster in the \(U\), \(B\), \(V\), and \(I\) bands, obtained from the HST archive (program 10609; PI: W. H. Vacca), from which we note that the cluster profile appears to be highly irregular in the \(U\) band, while becoming smoother and more regular in the redder wavelength bands. This is the result of a complicated differential extinction pattern. Our measurements indicate that parts of the cluster are entirely obscured in the \(U\) and \(B\) bands, which can account for this shift in color space, as it would spuriously raise the \(U - B\) value.

In order to verify this inference, we map out the extinction on and around the cluster pixel by pixel in Figure 7. The color map represents the different levels of reddening, as determined by multiband photometry, and the solid lines represent observed isophotes in the F435W band. The technique we use is explained in Bastian et al. (2007). In brief, we construct a color map by measuring the flux of each pixel in the \(B\), \(V\), and \(I\) bands and thus measure its reddening, while assuming the spectroscopically derived age. In principle, as we assume the cluster to be a SSP, we expect each pixel to have the same color; therefore, it is only the variation of extinction across the face of a cluster that causes the color to change. The extinction map verifies the complexity of the reddening in the immediate vicinity of M82-H, showing a dust lane running through the eastern edge of the cluster. The location and physical characteristics of this extinction patch are consistent with the observed shape of the cluster in the \(U\) band. For cluster 91 we therefore use the age as derived by spectroscopy, as the variable extinction should not change the spectroscopic features of the cluster.

We also find tentative evidence of a similar differential extinction pattern obscuring cluster 108; however, the S/N of this cluster is not high enough for us to quantitatively assess its effects. We are able to place the extinction range at between 1.5 and 2.0 mag in \(A_U\) in a manner that does not appear to be related to the underlying cluster structure. In addition, this cluster is not detected in the \(U\) band, and this is the reason for its absence from the color-color plot (Fig. 3).

### 4. DISCUSSION

In this paper we have presented an analysis of seven YMCs in region B of M82. Our results, along with age dating of a further 29 clusters presented in Smith et al. (2007), suggest that these clusters are consistent with being part of a young cluster population that started forming \(<220\) Myr ago. We find extinctions in the region to vary between 1.1 and 2.5 mag, and we also find differential extinction across the face of cluster 91 and possibly cluster 108. These results largely contradict studies presented in the past, and we discuss them in more detail in the rest of this section.

#### 4.1. Extinction in Region B

M82 is a gas- and dust-rich galaxy that is seen nearly edge-on, which causes its stellar population to be largely hidden in the optical. Using optical/near-UV photometry (Smith et al. 2007) and spectroscopy, we find that the \(A_U\) extinction for clusters in our sample shows a wide range, with evidence of other clusters being more highly reddened. For example, cluster 108 has the highest extinction of 2.5 mag and is not visible in the \(U\) band. This variable extinction suggests that region B presents a line of sight of relatively low extinction into the galaxy, which therefore allows us to probe depths that are not visible on the western side of the galaxy, similar to Baade’s window in the Milky Way. Smith & Gallagher (2001) find a similar patch of high, variable extinction in the vicinity of cluster M82-F, which was measured by Bastian et al. (2007) to have \(A_U\)-values between 2 and 4 mag, with much higher extinction values in the surrounding region.

The study by de Grijs et al. (2003b) concluded that the clusters in that sample were observable because they did not suffer from very much extinction (\(A_U \leq 1.2\) mag). They suggest that all the clusters are situated near the surface of region B with respect to our line of sight, implying that the region must have an extremely steep gas/dust density gradient. In contrast, we find a larger range in extinctions and a variable overall extinction along this line of sight and hence, on average, lower values compared to other regions of the galaxy disk.

The selection effect created by extended areas of variable extinction reaching low values may explain why region B was thought to occupy a special place within M82, as it allows for the observation of a far larger number of clusters in the visible light bands. A high number of clusters could be interpreted as the result of a higher cluster formation rate in the region. The interpretation offered in this paper is that these “holes” in the dust distribution of the galaxy are in fact the source of the discrepancy in appearance between its western and eastern sides. This claim is supported by NICMOS near-IR observations of the galaxy (Alonso-Herrero et al. 2001, 2003), where the two sides seem to have comparable
luminosities and to host a similar number of clusters, indicating a shared cluster formation history.

4.2. Cluster Ages

We find that the spectroscopic ages of the seven clusters we have analyzed in region B are between 80 and 200 Myr. Comparison of the photometric and spectroscopic ages for the five clusters in common show that overall, the preferred spectroscopic ages are toward the younger part of the allowed photometric age range. A good example of this is cluster 126, which has a photometric age range of 200–780 Myr (see Fig. 3 and Table 2), but the spectroscopy results clearly narrow this down to 160–280 Myr, and the spectrum shows that this cluster cannot be as old as 800 Myr.

We now compare our ages with the ages from de Grijs et al. (2003b), as given in Table 4. It is clear that, with the exception...
of cluster 113, the de Grijs et al. ages are considerably older. In the larger photometric sample of 35 clusters presented by Smith et al. (2007), the ages range from 8 to 310 Myr,\(^{10}\) and the peak is at 150 Myr. Overall, we conclude that the region B cluster sample is much younger than that presented in de Grijs et al. (2001, 2003b).

The ages that we find for the clusters agree well with the time scale of the last encounter between M82 and M81, based on a value of 220 Myr (Yun 1999). De Grijs et al. (2001) also suggest that the age of the region B cluster population is consistent with this encounter, but they use an earlier age estimate by Brouillet et al. (1991) of 510 Myr.

### 4.3. Radial Velocities

It has been suggested by de Grijs et al. (2003b) that region B is a gravitationally bound structure. In order to explain how such a large structure could form and survive despite the effects of differential rotation, they suggested that the presence of the stellar bar (Wills et al. 2000) may have caused the formation of a circumnuclear ring, of which region B is a part. It is well known that a ring or torus does indeed exist around the M82 bar, but we note that if the torus were to include region B, it would have to have a width of \(\sim 500\) pc, which is in clear disagreement with observations (\(r = 86\) pc from the center, according to Achtermann \& Lacy [1995]; Weiss et al. [2001] find a radius for the molecular torus of \(r = 65\) pc).

In order to explore the dynamical state of the region B cluster sample, we plot the derived radial velocities and the corresponding Na\(^{1}\) interstellar absorption-line measurements in Figure 8. We have also included near-infrared Ca\(^{2}\)\(\Pi\) \(\lambda\lambda 8498, 8542, 8662\) (Ca\(^{2}\)) stellar absorption and [S\(^{\text{iii}}\)] \(\lambda\lambda 6531, 9069\) and Pa(10) nebular emission-line measurements from McKeith et al. (1993).

Clusters 97 and 103 exhibit stellar and gas kinematics that are consistent with the galaxy rotation curve traced by the Ca\(^{2}\) velocities, and the similarity between the cluster and Na\(^{1}\) measurements shows that the interstellar gas is located near the clusters. The radial velocities of clusters 108 and 126 are consistent with the Ca\(^{2}\) absorption-line measurements and show that they are located within the main stellar disk of M82. However, the corresponding Na\(^{1}\) velocities are close to the systemic value, indicating that a large column of cool interstellar (IS) gas is located in front of these clusters, on the outskirts of the disk. The radial velocities of clusters 91, 113, and 131 are consistent with them being located on either the far or the near side of the disk. The fact that the Na\(^{1}\) IS lines are close to systemic values argues, however, that these three clusters must be on the near side of the disk; otherwise, we would expect the Na\(^{1}\) velocity to be offset because of the greater path length.

We therefore find no indication that our sample of clusters has unusual kinematics; instead, the large range in radial velocities is consistent with the clusters being located at different depths within the M82 disk. This also explains the large variation in extinction that we measure.

Our findings allow us to test the hypothesis that region B is bound. In order for this to be true, the clusters should trace equal angles in equal amounts of time as they orbit about the galaxy center. The galactocentric distances of these seven clusters place them on the gently rising part of the rotation curve. If we assume a constant rotational velocity of \(v_{\text{rot}} = 120\) km s\(^{-1}\) (Fig. 8), this corresponds to the orbital period of 18 and 54 Myr for the inner and outer boundaries of the region (assumed to be marked by clusters 91 and 131, respectively, which are situated 700 pc apart). This would imply that clusters in the outermost regions should have a radial velocity, \(v_{R}\), that is 3 times that of the ones in the innermost regions. This is clearly not the case; we find no correlation between the cluster radial velocities and their spatial positions, as they seem to scatter about the 120 km s\(^{-1}\) mark, and we conclude that the clusters are on regular orbits with respect to the stellar component of the disk.

Finally, we remark that through a number of arguments, de Grijs et al. (2003b) found that the cluster population of region B

---

10 This applies to 33 of the 35 clusters in this sample. The remaining clusters, No. 16 and No. 35, appear to have ages of 2.3 and 1.3 Gyr, respectively, with minimum acceptable values of 130 and 107 Myr. These two values are poorly constrained and therefore are not representative of the overall age distribution.
has a lognormal mass function. This supported their hypothesis that region B is bound, since a normal power-law function would imply unphysically high initial densities.

Smith et al. (2007) suggest that the turnover in the cluster luminosity and mass functions is not real, but rather is caused by neglecting the effect of extended sources on the detection limit. This, in addition to the younger ages that we find, suggests that the disruption timescale derived in de Grijs et al. (2003b) and used in de Grijs et al. (2005) is probably too short. If we do not impose a short disruption timescale on such a young cluster population, the idea of an initial power-law distribution is consistent with the data.

5. CONCLUSIONS

We have presented Gemini GMOS spectroscopy and ACS UBVJ photometry for seven clusters in region B of the starburst galaxy M82. Our aims were to obtain accurate ages, extinctions, and radial velocities for the clusters.

We have used both photometric and spectroscopic methods to determine cluster ages. Our main age determination method is fitting the Balmer spectral lines with all available models and finding the best fit (i.e., the lowest $\chi^2$ on the overall line profile fit), in order to eliminate the known Balmer line strength degeneracy. We find our method to agree with photometric ages derived using the 3DEF method (based on UBVJ colors). This demonstrates that the photometrically derived ages are accurate, but they are not as precise as the ages obtained from spectroscopy, and this confirms that the only truly independently reliable method for age-dating clusters in extragalactic environments is spectroscopy. The inclusion of $U$-band photometry may enhance the accuracy of photometric measurements, but unless they can be cross-checked by spectroscopic means, the potential age degeneracy might not be broken.

We find cluster ages in the range of 80–200 Myr, a distribution that is consistent with the timescale for the last encounter between M82 and M81 as proposed by Yun (1999), namely, 220 Myr. These findings, in combination with the larger photometric sample of Smith et al. (2007), disagree with the "fossil starburst" scenario proposed by de Grijs et al. (2001), in which region B in M82 was identified with the remnant of an off-center starburst that commenced about 600 Myr ago, a timescale based on their photometric determinations of star cluster ages. We suggest that the increased cluster formation rate in region B is representative of the era of increased star formation across the galaxy disk that was triggered by the last encounter with M81.

The extinction along our line of sight in this extended region appears to vary greatly, between 1.1 and 2.5 mag. As M82 is seen virtually edge-on, we find that M82-B presents a view into various depths of the body of the galaxy through an arrangement of "windows" in the dust distribution (as hypothesized for cluster M82-F by Smith & Gallagher 2001). We also find differential extinction across the face of cluster 91 (and also possibly cluster 108), which constitutes a serious obstacle in the photometric determination of extinction and age in these cases. In fact, the effect of dust in this environment is in some cases so grave that photometry cannot be used at all as an age/extinction diagnostic.

We have also used the available spectroscopy to derive cluster kinematics. This allows us to reinforce our extinction-based findings and show that the seven clusters reside at different depths within the disk of M82. The large scatter of cluster velocities about the gently rising component of the rotation curve indicates that the clusters do not move in a coordinated fashion and that region B cannot be bound.

Previous studies of cluster F and its neighbor L on the western side of the disk of M82 show that they both have an age of $60 \pm 20$ Myr (Gallagher & Smith 1999; Bastian et al. 2007). This age fits in well with the region B cluster age distribution presented in this paper and in Smith et al. (2007) and supports our suggestion that the increase in the cluster formation rate was not local to region B, but rather part of a galaxy-wide burst. In addition, the very high masses of clusters F ($\sim 10^6 M_\odot$; Smith & Gallagher 2001; Bastian et al. 2007) and L ($4 \times 10^5 M_\odot$; McCrady & Graham 2007) imply that many lower mass clusters were also likely to have formed along with F and L.

In summary, we find region B to be optically bright because of the presence of low internal extinction patches, thus offering a deep view into the M82 disk at radii between ~400 and 1200 pc. The range of cluster ages and other properties in this region are typical of the evolution of the main body of M82 and reflect the large increase in star formation that occurred about 220 Myr ago, when M82 last passed close to M81. M82’s region B stands out because it is representative of the middisk zone and is relatively clear of dust, rather than being a special substructure. This model also receives support from the larger sample of photometric ages in Smith et al. (2007) and will be further discussed in the I. Konstantopoulos et al. (2008, in preparation) study of another three dozen M82 star clusters distributed across M82.

We thank the staff at Gemini North for obtaining the spectroscopic observations on which this paper is based. We also thank the Hubble Heritage team at the Space Telescope Science Institute for the mosaic image of M82. J. S. G. appreciates support for studies of starburst galaxies provided by the University of Wisconsin–Madison Graduate School. I. S. K. would like to acknowledge the support of the Perren Fund, provided by the Astrophysics Group at University College London. Support for program 10853 was provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

Facilities: Gemini:Gillett (GMOS), HST (ACS/HRC)

REFERENCES

Achtertman, J. M., & Lacy, J. H. 1995, ApJ, 439, 163
Alonso-Herrero, A., Rieke, G. H., Rieke, M. J., & Kelly, D. M. 2003, AJ, 125, 1210
Alonso-Herrero, A., Rieke, M. J., Rieke, G. H., & Kelly, D. M. 2001, Ap&SS, 276, 1109
Anders, P., Bissantz, N., Fritze–v. Alvensleben, U., & de Grijs, R. 2004, MNRAS, 347, 196
Anders, P., & Fritze–v. Alvensleben, U. 2003, A&A, 401, 1063
Bastian, N., Gieles, M., Lammers, H. J. G. L. M., Scheepmaker, R. A., & de Grijs, R. 2005, A&A, 431, 905
Bastian, N., Konstantopoulos, I. S., Smith, L. J., Westmoquette, M. S., Trancho, G., & Gallagher, J. S. 2007, MNRAS, 379, 1333
Bik, A., Lamers, H. J. G. L. M., Bastian, N., Panagia, N., & Romaniello, M. 2003, A&A, 397, 473
Brouillet, N., Baudry, A., Combes, F., Kaufman, M., & Bash, F. 1991, A&A, 242, 35
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Calzetti, D. 1997, AJ, 113, 162
Cappellari, M., & Emsellem, E. 2004, PASP, 116, 138
de Grijs, R., Bastian, N., & Lammers, H. J. G. L. M. 2003a, ApJ, 583, L17
—. 2003b, MNRAS, 340, 1079
de Grijs, R., O'Connell, R. W., & Gallagher, J. S. 2001, AJ, 121, 768
de Grijs, R., Parmentier, G., & Lammers, H. J. G. L. M. 2005, MNRAS, 364, 1054
Fall, S. M., & Zhang, Q. 2001, ApJ, 561, 751

\[ \text{No. 2, 2008} \]
