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HUBBLE SPACE TELESCOPE OBSERVATIONS OF THREE VERY YOUNG STAR CLUSTERS IN THE SMALL MAGELLANIC CLOUD[1]

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ABSTRACT

We present Space Telescope Imaging Spectrograph (STIS) broadband imagery and optical slitless spectroscopy of three young star clusters in the Small Magellanic Cloud (SMC). MA 1796 and MG 2 were previously known as planetary nebulae and were observed as such in our *Hubble Space Telescope* (*HST*) survey. With the *HST* spatial resolution, we show that they are instead H II regions, surrounding very young star clusters. A third compact H II region, MA 1797, was serendipitously observed by us since it falls in the same frame of MA 1796. A limited nebular analysis is presented as derived from the slitless spectra. We find that MA 1796 and MG 2 are very heavily extincted, with $c \geq 1.4$, defining them as the most extincted optically discovered star-forming regions in the SMC. MA 1796 and MG 2 are extremely compact (less than 1 pc across), while MA 1797, with diameter of about 3 pc, is similar to the ultracompact H II regions already known in the SMC. Stellar analysis is presented, and approximate reddening correction for the stars is derived from the Balmer decrement. Limited analysis of their stellar content and their ionized radiation shows that these compact H II regions are ionized by small stellar clusters whose hottest stars are at most of the B0 class. These very compact, extremely reddened, and probably very dense H II regions in the SMC offer insight into the most recent star formation episodes in a very low metallicity galaxy.

Subject headings: dust, extinction — galaxies: star clusters — H II regions — Magellanic Clouds — stars: formation

1. INTRODUCTION

The very compact H II regions in the Magellanic Clouds, extremely reddened, yet observable at the optical wavelengths, represent the early evolutionary stage of the cradles of the more recent star formation (SF) (Churchwell 2002). If the duration of SF episodes is related to the size of the SF regions (Elmegreen 2000), then the very compact H II regions in the SMC are ideal probes of recent star formation in a low-metallicity environment.

While completing our *Hubble Space Telescope* (*HST*) snapshot survey of SMC planetary nebulae (PNs; *HST* program 8663, cycle 10; see Stanghellini et al. 2003), we found that two of the target PNs were misclassified in the ground-based catalog (Meyssonnier & Azzopardi 1993). On the basis of their morphological properties in both the narrow- and broadband images, we found that these targets are the most compact and most reddened H II regions in the SMC known to date. Furthermore, in one of the H II region frames we serendipitously observed an additional, very compact H II region, previously classified as an emission-line object (and possibly a H II region) by Meyssonnier & Azzopardi (1993). Our broadband and slitless spectra acquired with STIS disclose some extreme properties of these three regions, including extreme extinction, that are worth discussing.

Only a handful of objects similar to the ones presented here are currently known in the Magellanic Clouds (Testor 2001), and only three of them have been discovered in the SMC (Testor 2001; Testor & Pakull 1985; Heydari-Malayeri, Le Bertre, & Magain 1988). The sample presented in this paper then doubles the existing database of H II regions that are much more compact than the typical Magellanic Cloud H II regions (Copetti 1990) and that have very high reddening.

In this paper we present the *HST* stellar and nebular data of MA 1796, MA 1797, and MG 2. In § 2 we give an overview of the observing strategy. In § 3 we discuss the imaging and spectral analysis, including the determination of the extinction from the nebular Balmer emission, the ionizing flux inferred from nebular Balmer emission, the visual stellar magnitudes of the brightest stars within the regions, and the cluster NIR magnitudes. Section 4 includes a discussion of our findings in the context of star formation in the SMC.

2. OBSERVATIONS

The observations were acquired with STIS. All observations were made with the CCD detector, in direct imaging (50CCD) and slitless mode. The spatial scale of the CCD is 0$''$.051 pixel^{-1}, corresponding to 0.014 pc pixel^{-1} at the dis-

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TABLE 1
OBSERVING LOG

Name	R.A. (J2000.0)[a]	Decl. (J2000.0)[a]	Date	Data Set	Disperser	t_{exp} (s)	N_{exp}
MA 1796.........	1 14 47.26	−73 20 14.2	2000 Sep 27	O65S26010	MIRVIS	120	2
				O65S26020	G750M	100	2
				O65S26030	G750M	400	2
				O65S26040	G430M	200	2
				O65S26KGQ	MIRVIS	15	1
MA 1797 [b].......	1 14 47.17	−73 19 46.7	2000 Sep 27	O65S26010	MIRVIS	120	2
				O65S26020	G750M	100	2
				O65S26030	G750M	400	2
				O65S26040	G430M	200	2
				O65S26KGQ	MIRVIS	15	1
MG 2	0 28 10.13	−72 58 44.1	2000 Nov 7	O65S28010	MIRVIS	300	2
				O65S28020	G750M	1300	2
				O65S28030	G430M	800	2

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] Coordinates measured from data.
[b] MA 1797 was serendipitously observed in the MA 1796 field (same exposures).

tance of the SMC. This allows a good spatial resolution for studing the H II region structures. Each imaging observation was split in two to allow easy cosmic-ray removal. The slitless spectra were acquired with the G430M and G750M gratings. Observations with the G430M grating cover the range 4818–5104 Å at 0.28 Å pixel^{-1}, and those with the G750M grating cover the range 6295–6867 Å at 0.56 Å pixel^{-1}. The exposures where originally planned to get a good signal-to-noise ratio in the brightest emission lines of PNs and thus were not ideally designed with H II regions in mind.

The observing log is reported in Table 1, where we list the targets, their coordinates, the observing date, the data set name, the spectral element used in the observations, and the exposure time and number of exposures obtained.

MA 1796 has been classified as a new SMC PN by Meyssonnier & Azzopardi (1993) (SIMBAD resolver: [MA 93] 1796). It is located on the outer side of the larger, young stellar cluster NGC 456. MA 1796 and NGC 456 could be physically associated, but our data are not helpful in establishing any connection.

MG 2 is cataloged as a PN in Morgan & Good (1985) (SIMBAD resolver: MGPN SMC 2). There are no published spectra of this object, nor images that resolve the H II region spatially.

MA 1797 (SIMBAD resolver: [MA 93] 1797) was previously cataloged as a possible H II region by Meyssonnier & Azzopardi (1993), possibly part of the DEM 152 cluster.

The STIS data were calibrated using the standard pipeline system, as in the LMC PN data (Shaw et al. 2001). Figure 1 shows the observed H II regions in the three observing modes: broadband CCD, [O III], and Hα images. The images are to scale, to reflect the relative physical scales. The apparent and physical dimensions of the nebulae are listed in Table 2, columns (2) and (3).

Spectral analyses have been performed in the same way to that of LMC and SMC PNs (Stanghellini et al. 2002, 2003). The combination of dispersion and spatial scale allows a clear separation of the monochromatic images for the major emission lines. We extracted the one-dimensional spectra and applied a photometric calibration using the standard STIS calibration pipeline module *x1d* (McGrath, Busko, & Hodge 1999). We used extraction boxes for the regions large enough to encompass the nebular features but snug enough to exclude most of the sky background from the extraction. Sky background regions were selected for each object to avoid stray stellar photons from field stars. The background was then averaged and subtracted.

We measured emission-line intensities with IRAF[3] *splot* task, fitting Gaussians to individual lines while estimating the continuum level. In the cases in which the emission lines

[3] IRAF is distributed by the National Optical Astronomical Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

TABLE 2
NEBULAR ANALYSIS

Name (1)	Size (arcsec) (2)	Radius (pc) (3)	$\log F_{(\mathrm{H}\beta)}$ (ergs cm^{-2} s^{-1}) (4)	c (5)	$\log F_{[\mathrm{O\,III}]\,\lambda5007}$ (ergs cm^{-2} s^{-1}) (6)	$\log F_{\mathrm{H}\alpha}$[a] (ergs cm^{-2} s^{-1}) (7)	$\log N_{rms}$ (cm^{-3}) (8)	$\log Q_{\mathrm{H}}$ (9)
MA 1796...	3.0	0.424	−13.85 ± 0.25	1.53	−13.71 ± 0.25	−12.85 ± 0.2	2.61	47.61
MA 1797...	11.0	1.554	...	...	...	−11.38 ± 0.15	2.07	48.23
MG 2	3.5	0.495	−14.35 ± 0.25	1.4	−13.14 ± 0.2	−13.41 ± 0.2	2.20	46.98

[a] Intensity of the blend of Hα and [N II] $\lambda\lambda$6548, 6584.

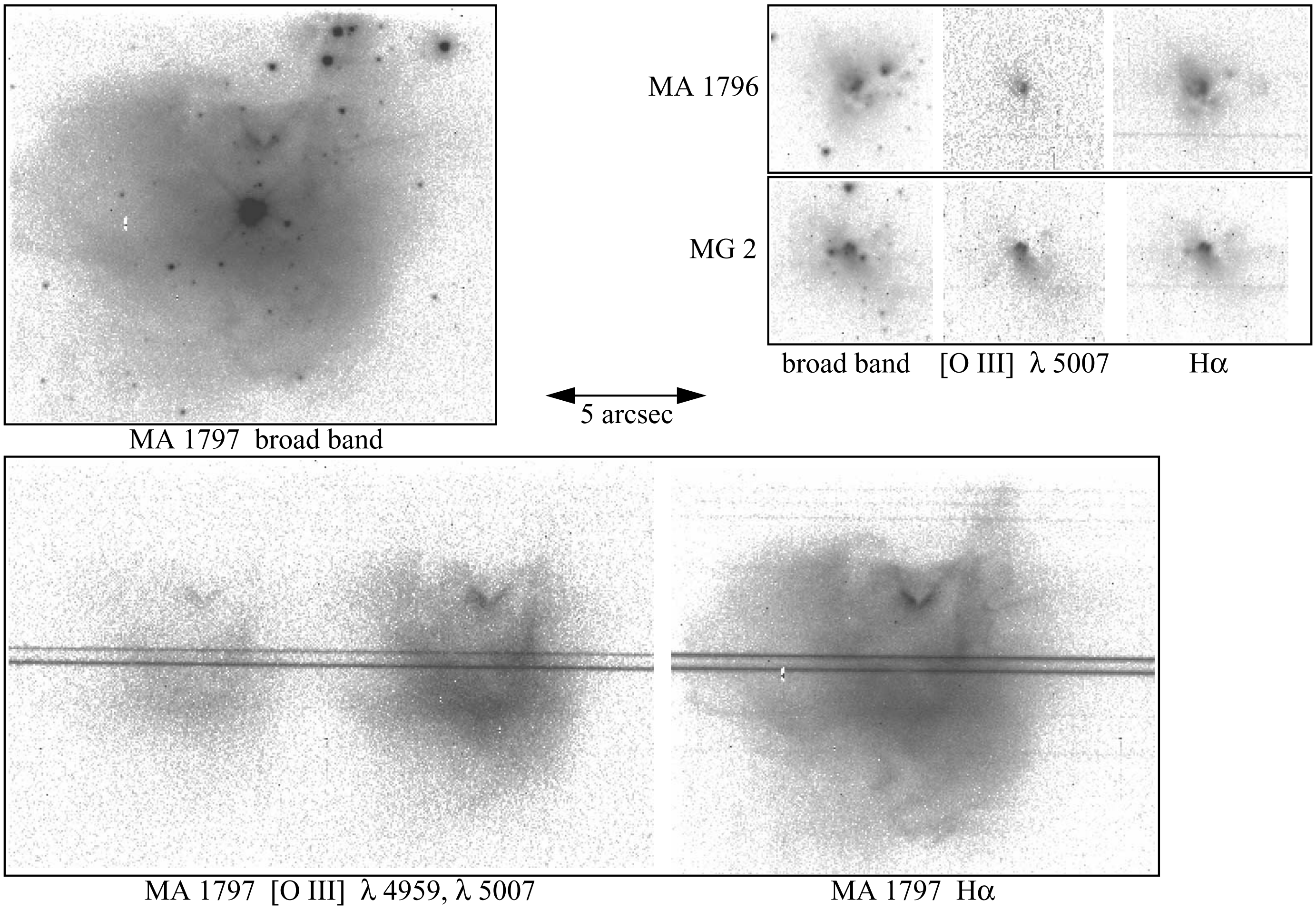

FIG. 1.—Broad- and narrowband images of the new SMC H II regions. *Clockwise from top left:* MA 1796 broadband image; MA 1796 and MG 2 broadband, [O III] λ5007, and Hα images; and MA 1797 Hα and [O III] $\lambda\lambda$4959 and 5007 images.

were notably non-Gaussian, we estimated the line flux as measured from the area above the continuum. The measured fluxes are listed in Table 2, columns (4), (6), and (7).

We identified the Hβ and the [O III] $\lambda\lambda$4959, 5007 lines in the G430M spectrum of MG 2. The Hα emission is the only nebular feature in the G750M spectrum of this H II region. The given Hα flux includes the [N II] emission, although the slitless spectrogram suggest that the [N II] contribution to the flux is marginal.

The analysis of the MA 1796 spectra shows the [O III] and Hβ lines detected with a very good signal-to-noise ratio. The [S II] emission at $\lambda\lambda$6716, 6731 is also detected.

MA 1797 was serendipitously observed at the edge of the field, so the Hβ emission does not appear in the G430M spectrum. The Hα flux is high, comparable with that of the previously observed compact H II regions N81 and N88A.

3. DATA ANALYSIS AND PHYSICAL PROPERTIES

3.1. *Nebular Reddening*

We derive the optical extinction from the analysis of the nebular Balmer lines, and we give the logarithmic extinction constants (c) in Table 2, column (5). We assume that the optical extinction law is the same in the Galaxy and the SMC; thus we do not estimate the foreground extinction separately. The derived extinction is rather a lower limit, since we do not consider possible regions whose optical flux is totally absorbed. Our feeling is that the extinction corrections should be higher than what estimated from the nebular lines.

With a Hα /Hβ flux ratio of 8.7, MG 2 is evidently an extremely reddened object. Note that the flux ratio could be off by a factor of 2, given the flux uncertainties, and still be extremely high for a compact H II regions. By assuming $T_e = 10,000$ K, we estimate the logarithmic optical extinction constant $c = 1.4$ (or $E_{B-V} = 0.95$; Seaton 1979).

The optical extinction constant of MA 1796, $c = 1.53$, is the highest ever measured in a compact SMC H II region. This nebula is a factor of 10 lower in excitation than MG 2.

Given that we do not measured its Hβ flux, we could not derive the extinction constant for MA 1797.

3.2. *Ionizing Flux from the Nebular Balmer Emission*

We computed the rms density of MA 1796 and MG 2 on the basis of our knowledge of the Hβ flux, the average nebular extinction, the known distance to the SMC, and the physical extent of the nebulae, using the formulation:

$$N_{\rm rms} = [(F_\beta/h\nu\alpha)(W/V)]^{0.5} ,$$

where ν is the Hβ (or Hα) frequency, α is the recombination coefficient for Hβ (or Hα), V is the nebular volume, and W is the geometrical dilution factor. The log density is given in column (8) of Table 2. We also estimated the total number of ionizing photons, $Q_{\rm H}$, for the Strömgren spheres corresponding to the sizes of these nebulae (Osterbrock 1989), assuming that all ionizing radiation is contained within the regions. The results, in the last column of Table 3, are roughly consistent with a single B0 or a very late O main-sequence star exciting the region (Osterbrock 1989). The value of $Q_{\rm H}$ is very uncertain because it is proportional to the square of the electron density, which itself is very uncertain. It also depends upon the assumption of high optical depth to ionizing radiation, which is probably a reasonable approximation for ultracompact H II regions. We did not attempt an estimate of the fraction of the ionizing radiation absorbed by dust (see discussion of the reddening).

In the case of MA 1797, we perform the calculation of the density and $Q_{\rm H}$ from the Hα flux, uncorrected for extinction. The resulting analysis for this region is extremely uncertain, and it is given in Table 2 only as an indication. In the next section we make use of these approximate values for $Q_{\rm H}$ in these nebulae to aid our interpretation of the stellar photometry.

3.3. *Visual Stellar Photometry*

With the high spatial resolution of *HST* we can easily resolve the stars individually; thus we can use aperture photometry with confidence. We have measured the magnitudes of the brightest stars within MA 1796 and MG 2. The stellar photometry was performed with the *apphot* package in IRAF, through a circular aperture of 2 pixels of radius. The averaged sky within an annulus 1 pixel wide adjacent to the position of the star was then subtracted to the stellar measurement. The sky includes the nebular emission as well. The measured instrumental magnitudes (STMAG system) use the zero-point calibration by Brown et al. (2002). The aperture correction has been taken from the curve of encircled energy derived by Brown et al. (2002) for stars near the field center.

The 50CCD mirror has broadband transmission, and its response curve is far from that of the standard *V* filter. The transformation between the measured instrumental magnitudes and the standard *V* magnitudes depends on the spectral energy distribution (SED) of the source, which is determined by the amount of extinction and, to a lesser extent, by the stellar temperature. We do not have the stellar temperatures of the stars, but we know that they are hot enough to ionize H II regions; thus we infer their temperatures to be in the range between 30,000 and 50,000 K. We assume that the extinction toward the stars is the average nebular extinction. We feed these parameters to the IRAF/STSDAS routine *synphot*, to perform the synthetic photometric modeling necessary to derive the transformation to the standard *V* magnitudes.

In Table 3 we give the photometric measurements of the three brightest stars in MA 1796 and the five brightest stars in MG 2. The quoted errors in the *V* standard magnitudes include the standard deviation of the transformation for the range of temperatures used. In Figures 2 and 3 we identify the stars with the same numbering as in Table 3, for MA 1796 (Fig. 2) and MG 2 (Fig. 3). We have corrected the *V* magnitudes for extinction by using the approximate relation between the average logarithmic extinction constant derived for the nebula, *c*, and the color excess, E_{B-V} ($c = 1.47 E_{B-V}$; Seaton 1979). The SMC extinction law is very similar to the Galactic law in this wavelength range (Hutchings 1982), so we have used the Galactic reddening curve law of Savage & Mathis (1979) and have assumed that $R_V = 3.1$. The stellar extinction in magnitudes that we apply is then $A_V = 2.1c$.

To derive the absolute visual magnitudes, we have used the average SMC distance modulus obtained with the RR Lyrae method (Westerlund 1997). None of the stellar magnitudes measured and transformed as described above correspond to an O star of any subclass; according to the calibration of Vacca, Garmany, & Shull (1996), the explanation probably lies in the extinction being higher than measured.

3.4. *Cluster NIR Magnitudes*

In order to frame the extinction correction a little better, we have searched the Two Micron All Sky Survey (2MASS) for near-infrared sources within 5″ of the central position of MA 1796 and MG 2. We found that each H II region is uniquely associated with one compact object in the 2MASS point source catalog (All-Sky Point-Source Catalog). The *J*, *H*, and K_s magnitudes corresponding to these two point sources are listed in Table 4.

TABLE 3

STELLAR PHOTOMETRY

Star	ST[a] (mag)	*V* (mag)	M_V (mag)
MA 1796:			
1	21.62 ± 0.11	18.28	−0.55
2	21.73 ± 0.11	18.38	−0.45
3	21.11 ± 0.05	17.76	−1.07
Cluster[b]	18.14 ± 0.01	14.79	−4.04
MG 2:			
1	22.31 ± 0.06	19.21	0.38
2	23.23 ± 0.40	20.13	1.3
3	22.56 ± 0.27	19.46	0.63
4	22.48 ± 0.03	19.38	0.55
5	22.72 ± 0.10	19.62	0.79
Cluster[c]	19.55 ± 0.013	16.45	−2.37

[a] Uncorrected for extinction.
[b] Including the central 1″.5.
[c] Including the central 1″.0.

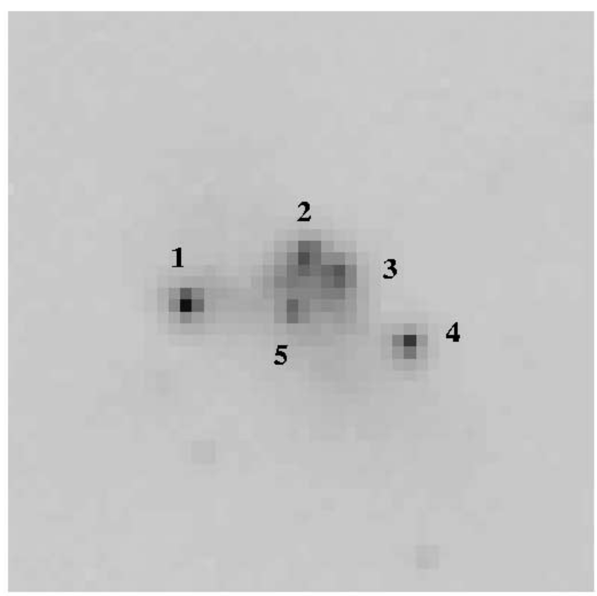

FIG. 2.—Central part of the MA 1796 cluster, with stars labeled as in Table 3.

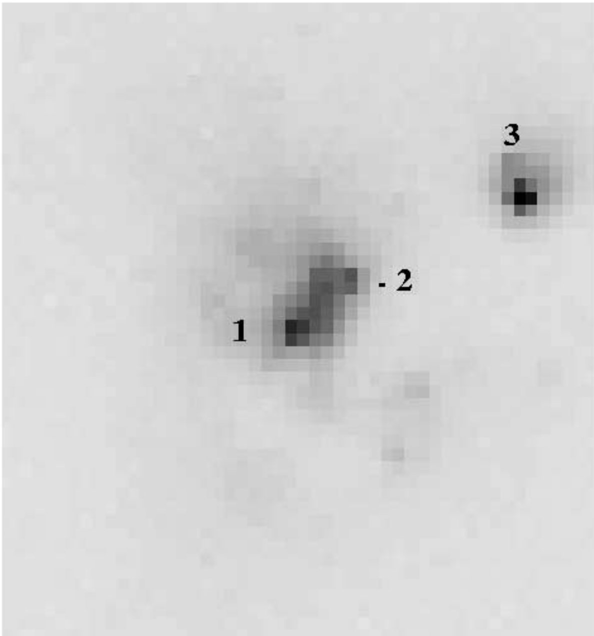

FIG. 3.—Central part of the MG 2 cluster, with stars labeled as in Table 3.

In a *JHK* color-color diagram (e.g., Lada & Adams 1992) MA 1796 and MG 2 would lay outside and to the right of the reddening band, indicating the presence of intrinsic infrared excess. This result alone could have indicated that the objects are not common PNs. Intrinsic infrared excesses are indicative of the presence of circumstellar material. According to Lada & Adams (1992), young stellar objects and Herbig Ae/Be stars populate the part of the near-infrared color-color diagram where our sources are located.

4. SUMMARY

We have identified two new compact young stellar cluster in the SMC that were previously classified as PNs. The unique spatial resolution of *HST* clearly discloses that these objects, merely a few arcseconds across, are not PNs.

Limited analysis of their nebular spectra discloses very high Hα-to-Hβ ratios, placing them among the extreme compact and reddened H II regions in the SMC, as observed at the optical wavelengths. Imaging and the Hα flux are also available for a third, larger H II region that was serendipitously observed in the same frame of one of the misclassified PNs.

TABLE 4
CLUSTER INFRARED PHOTOMETRY

Cluster	J (mag)	H (mag)	K_s (mag)
MA 1796	15.53 ± 0.08	14.96 ± 0.10	14.24 ± 0.08
MG 2	16.11 ± 0.11	15.63 ± 0.16	14.54 ± 0.10

Studying the IR properties of the regions, we found that they present high-IR excesses. These excesses, together with compactness of the regions, indicate that they are very young star-forming regions.

Stellar photometry places the brightest stars in the regions out of the O star domain. The definitive stellar classification is not possible with the present data. If the stars observed near the center of these nebulae are in fact providing all or most of the ionizing photons, then the spectral types inferred from the observed brightness and the bolometric correction are inconsistent with the observed level of nebular ionization. A possible explanation is that the stars suffer greater extinction than is inferred from the nebular Balmer decrement.

We conclude that we observed a few very young clusters of recent star formation, but the details of the populations therein are left to a future investigation. We plan to perform *UBV* photometry of these regions, possibly with *HST* resolution, to disclose the true nature of the component stars. Infrared observations at high resolution are also necessary to analyze in detail the reddening structure of these unique H II regions. A small cluster of stars whose few brightest and hottest members are of early-B or late-O spectral type is consistent both with the level of nebular ionization and with the small physical size of the nebula.

We also plan to obtain the physical parameters of the gas, such as temperature, density, and abundances, from moderate-resolution ground-based optical spectra. Such observations will also verify our estimation of the ionizing photons from the embedded stars.

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