A COMPREHENSIVE LOOK AT LH 72 IN THE CONTEXT OF THE SUPERGIANT SHELL LMC 4

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ABSTRACT

Stellar spectroscopy, $UBV$ photometry, $Hz$ imaging, and analysis of data from the Australia Telescope Compact Array $H\alpha$ survey of the LMC are combined in a study of the LMC OB association LH 72 and its surroundings. LH 72 lies on the rim of a previously identified $H\alpha$ shell, SGS 14, and in the interior of LMC 4, one of the LMC’s largest known supergiant shells. Our analysis of the $H\alpha$ data finds that SGS 14 is expanding with a velocity of $v_{\text{exp}} \sim 15$ km s$^{-1}$, giving it an expansion age of $\sim 15$ Myr. Through the stellar spectroscopy and photometry, we find similar ages for the oldest stars of LH 72, $\sim 15$–30 Myr. We confirm that LH 72 contains an age spread of $\sim 15$–30 Myr, similar to the range in ages of stars derived for the entire surrounding supergiant shell. Combining analysis of the O and B stars with $Hz$ imaging of the $H\alpha$ region DEM 228, we find that DEM 228 accounts for only 60% of the available ionizing Lyman continuum photons. Comparing the distribution of ionized gas with that of the $H\alpha$, we find that DEM 228 and LH 72 are offset by $\sim 1$–2' from the peak 21 cm emission toward the interior of SGS 14. Taken together, these results imply that SGS 14 has cleared its interior of gas and triggered the formation of LH 72. On the basis of our results, we suggest that LMC 4 was not formed as a unit but by overlapping shells, such as SGS 14, and that LH 72 will evolve to produce a stellar arc similar to others seen within LMC 4.

Key words: Magellanic Clouds — ISM: bubbles — $H\alpha$ regions — ISM: $H\alpha$ — stars: early-type

1. INTRODUCTION

The Constellation III region in the LMC has drawn considerable interest over the last 50 years for a number of reasons. One is that the region contains several structures noteworthy enough to be given names. At the wavelength of $Hz$, the most striking feature is a kiloparsec-sized ring of $H\alpha$ regions, dubbed LMC 4 by Meaburn (1980). The void of LMC 4’s interior is almost empty of other ionized gas, or a high-velocity clear it, perhaps produced in a “super-supernova” (Efremov, Elmegreen, & Hodge 1998), a gamma-ray burst (Efremov, Elmegreen, & Hodge 1998), or a high-velocity cloud impact with the LMC disk (Braun 1996). Dopita, Mathewson, & Ford (1985) offered a less dramatic solution, in which star formation has propagated outward from a central location, clearing a cavity through the combined action of supernovae and stellar winds. The predicted age gradient in the stellar population interior to LMC 4 has not been observed in the most recent work (Olsen et al. 1997; Braun et al. 1997; Dolphin & Hunter 1998); however, stochastic self-propagating star formation is often still believed to play some role in the formation of LMC 4. An age gradient would not be produced if star formation within LMC 4 initiated over a large area at the same time, as in the bow shock–induced star formation scenario of de Boer et al. (1998).

The models above focus mostly on the size of LMC 4’s central cavity and less so on the substructure of the interior stellar population. Efremov & Elmegreen (1998) tackled the problem of the substructure by considering the formation of the Quadrant and Sextant stellar arcs. They found evidence for a concentration of 30 Myr old stars close to the center of the Quadrant arc; if these stars represent the remnants of a stellar cluster, they could provide the necessary pressure to sweep up a shell of $H\alpha$ gas out of which Quadrant could have condensed. Efremov & Elmegreen (1998) thus showed that smaller scale star formation events have contributed, in some degree, to the formation of LMC 4.

For a comprehensive understanding of how LMC 4 formed and has evolved, with attention paid to both the size of the supershell and its substructure, it will be necessary to survey its entire massive star population, measure the properties of all its individual $H\alpha$ regions, and study the
Fig. 1.—Montage showing the relationships of LH 72 and DEM 228 to SGS 14, LMC 4, and the LMC. Proceeding counterclockwise from top left, the images are as follows: Boyden Observatory photograph of the LMC, courtesy of P. Hodge and H. Shapley; same photograph with a close-up of the region containing LMC 4; section of H i map (Kim et al. 1998) showing the location of SGS 14; true-color $UBV$ combined image of OB association LH 72 taken with the CTIO 1.5 m telescope; and CTIO 1.5 m Hz image of the H ii region DEM 228.
relationship of the stars and ionized gas with the full distribution and kinematics of the neutral atomic and molecular gas. While many of these pieces are coming into or are already in place, much remains to be done, particularly in the areas of stellar spectroscopy and the analysis of large existing data sets. This work takes a small step in the direction of taking a comprehensive look at LMC 4 by focusing on the individual OB association LH 72, its embedded H II region DEM 228, and its associated H II gas. Because of its isolation, LH 72 is a relatively uncomplicated object with which to begin the analysis. In addition, as remarked by Olsen et al. (1997), its location in LMC 4's interior may yield a special clue as to the formation and evolution of the surrounding supershell. Figure 1 displays images of LH 72 and DEM 228, showing their relationship to SGS 14 and LMC 4.

2. OBSERVATIONS

Optical imaging and spectroscopy of LH 72 and narrowband imaging of the embedded H II region DEM 228 were performed during three runs with the Cerro Tololo Inter-American Observatory (CTIO) 1.5 and 0.9 m telescopes. The primary broad- and narrowband imaging was carried out on the nights of 1998 November 24–26 with the 1.5 m Cassegrain focus imager at f/7.5, using the SITe 2048 × 2048 CCD No. 6. The f/7.5 secondary mirror produces a pixel scale of 0.44 pixel⁻¹, yielding a 15′ × 15′ field of view at the expense of a somewhat erratically varying point-spread function (PSF). We observed through 3 × 3 inch (0.08 m) Johnson UBV filters and 2 × 2 inch (0.05 m) narrowband Hz and continuum filters. The 2 inch filters vignette the edges of the field, leaving a useful area of ~10′ × 10′. Total object exposure times were 1680 s in U, 690 s in B, and 600 s in V. We also observed Landolt (1992) and Graham (1982) standards at a variety of air masses each night, so as to calibrate the UBV photometry. Calibration of the Hz images was achieved through 1.5 and 0.9 m observations of spectrophotometric standards from Hamuy et al. (1994) and selected H II regions in the LMC and NGC 6822.

Spectra of 12 of the brightest blue stars in LH 72 were taken with the 1.5 m R-C spectrograph and Loral 3K detector on the nights of 1998 December 30 and 1999 January 2–5. Using grating 58 in second order and a CuSO₄ filter to block contamination from first order, our spectra cover the wavelength range 3600–5000 Å, spanning the classical spectral classification region of 4000–4700 Å. Exposure times were chosen to achieve a signal-to-noise ratio of ~75–100 per resolution element. Comparison lamp exposures were taken at regular intervals to provide wavelength calibration. Observations of the spectrophotometric standards EG 21 and Hiltner 600 (Hamuy et al. 1994) were used to provide flux calibration.

3. H I DATA

The H I data analyzed here comes from a combination of the Australia Telescope Compact Array 21 cm survey of the Magellanic Clouds (Kim et al. 1998) and Parkes single-dish observations of the LMC. The mosaic of interferometer data gives a spatial resolution of 1' and a velocity resolution of 1.6 km s⁻¹. The single-dish observations provide for the zero-spacing flux, so that the total mass in H I may be accurately calculated. For this project, we worked on a subset of the H I data cube covering a 48' × 48' region centered on 5°23'34.7" and −69°44'22" (J2000.0) and spanning heliocentric velocities between 190 and 390 km s⁻¹.

4. BASIC REDUCTION PROCEDURES

All the CTIO frames were overscan-corrected, bias-subtracted, and flat-fielded using IRAF routines with calibration data taken at the beginning and end of each night. For the imaging program, we used twilight sky flats to correct for pixel-to-pixel sensitivity variation. Because many of the flat-field and standard-star exposure times were necessarily short, we applied a shutter-shading correction to images with exposure times less than 20 s. The shutter-shading map was derived by comparing 20 s R dome flats with R dome exposures during which the shutter was repeatedly opened for 1 s and then closed. We also produced a bad pixel mask from short- and long-exposure R domes, which we applied to the final reduced images.

We discovered during the later analysis that all the 1.5 m CCD images had been written to the data acquisition computer, missing the central row of pixels. The problem manifested itself as a 1 pixel shift in the positions of stars along the y-axis during dithered exposures. To account for the dropped row, we manually inserted a row of pixels into all the images, while flagging the row in the bad pixel mask.

For the spectral program, we used quartz lamp dome flats to correct for pixel sensitivity. Before applying the flats to the data, we corrected them for the shape of the quartz lamp spectrum and for the slit illumination function by fitting the flats with a cubic spline surface. Obvious cosmic rays were manually removed from the flat-fielded data by linearly interpolating over the bad pixels along the spatial direction. Following experimentation with its parameters, we used the IRAF package DOSLIT to extract wavelength- and flux-calibrated spectra. While flux calibration may seem unnecessary for spectral classification work, we found it easier to fit the continuum after the flux calibration was applied, as the spectral response curve is wiggly compared with the smooth continuum of the tail of the blackbody spectrum. Our final spectral analysis was performed on continuum-flattened spectra, boxcar smoothed with a 3 pixel-wide kernel. For the stars with multiple observations, we combined the continuum-flattened extracted spectra before smoothing.

5. ANALYSIS OF THE STELLAR CONTENT

5.1. Spectral Classification

The stellar spectra were classified independently by K. O. and J. B. Following the criteria of Walborn & Fitzpatrick (1990), we first identified the spectral type and then the luminosity class. Briefly, for the O stars observed here, comparison of the strengths of He II 4541 Å to He I 4471 Å and He II 4400 Å to He I + II 4026 Å provide the temperature; the strengths of Si IV 4089 Å and He II 4686 Å are the main luminosity indicators. For the early B stars, the temperature decision depends mainly on the relative strengths of Si II 4552 Å and Si IV 4089 Å, while luminosity is decided through Si IV 4089 Å, Si III 4552 Å, or the strength of Mg II 4480 Å. In all cases, our identifications agreed to within two and usually one spectral subtype and one luminosity class.

Figures 2a and 2b show the continuum-subtracted spectra of the 12 stars, along with identified lines. Three of the stars, L10, L39, and S132, show narrow emission lines indicative of circumstellar disks. Table 1 lists our identifica-
Fig. 2a

(a) Continuum-flattened, wavelength-calibrated spectra of nine O and B stars in LH 72. All spectra are plotted on the same arbitrary flux scale. The locations of a number of typical absorption lines are indicated by vertical lines. (b) As in (a), but showing stars containing Balmer emission lines.

5.2. Stellar Photometry

UBV photometry of LH 72 was performed with the DAOPHOT and ALLSTAR suite of programs (Stetson 1987). Aperture and PSF-fitting photometry was performed on individual frames, with results from multiple frames averaged at the end. We first performed aperture photometry, using a 7" radius for the largest aperture and a 1.75" radius for the smallest. Using DAOGROW, we produced a growth curve to adjust the magnitudes measured within the smaller apertures so as to agree with the largest. DAOGROW produced a single list of magnitudes for each star, using the largest possible aperture with photometric error \( \sigma < 0.02 \) mag, with the magnitude extrapolated to an aperture of 14" radius.

We next performed PSF photometry with ALLSTAR. Approximately 40 PSF stars were chosen automatically by DAOPHOT, the list of which was then edited by hand to select only uncrowded stars. A PSF was derived for each image by fitting a Moffat function to the stars and employing a quadratically varying, empirical lookup table to correct for deviations from the analytic function. Aperture

| Star    | R.A. (J2000.0) | Decl. (J2000.0) | Spectral Type | Luminosity Class | Comments            |
|---------|---------------|----------------|---------------|------------------|---------------------|
| S133    | 5 32 29.2     | −66 28 00.2    | O6            | V                |                     |
| LH 72-1 | 5 32 27.8     | −66 28 20.4    | O8.5          | V                |                     |
| L29     | 5 32 19.9     | −66 28 02.9    | O9            | III              |                     |
| L41     | 5 32 18.4     | −66 25 51.1    | O9.5          | V                |                     |
| S128    | 5 31 53.4     | −66 31 14.3    | O9.7          | Ib               |                     |
| L2      | 5 32 18.1     | −66 28 47.2    | B0            | V                |                     |
| L49     | 5 32 13.0     | −66 25 03.0    | B0.2          | V                |                     |
| L51     | 5 32 20.4     | −66 23 58.2    | B0.5          | III              |                     |
| S135    | 5 32 33.2     | −66 26 12.3    | B3            | Ia–b             |                     |
| L10     | 5 32 33.7     | −66 27 10.0    | O8            | V                | Emission lines      |
| L39     | 5 32 09.9     | −66 26 08.4    | B0.5          | V                | Emission lines      |
| S132    | 5 32 18.8     | −66 24 12.0    | B8            | Ia               | Emission lines      |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
corrections were derived from the previously measured aperture magnitudes, extrapolated to $14^\circ$ radius. Finally, we merged all the aperture and PSF magnitudes through Stetson's COLLECT, which produced a weighted average magnitude for each star in each filter, using the PSF magnitudes whenever those photometric errors were found to be smaller.

The instrumental magnitudes were placed on the standard $UBV$ system through photometry of the Landolt (1992) standard fields SA 92, SA 98, SA 101, and T Phe and Graham's (1982) E2 and E3 fields. The standard-star photometry was performed as for the object frames, including PSF photometry, since the faintest stars were underestimated. We derived transformations through least-squares fitting to the equations

$$u = U + A_0 + A_1(U - B) + A_2(B - V)^2 + A_3 X + A_4 t$$
$$b = B + B_0 + B_1(B - V) + B_3 X + B_4 t$$
$$v = V + C_0 + C_1(B - V) + C_3 X + C_4 t,$$

where lowercase letters represent instrumental magnitudes, uppercase letters represent standard magnitudes, $X$ is the air mass, and $t$ is the time of observation in hours from the middle of the night. The second-order color term $A_2$ for $U$ is necessary because of the steep response curve of the CCD in the ultraviolet. While usually small, variation of the zero point with time may make a difference at the level of a few hundredths of a magnitude.

After deriving the color coefficients $A_1$, $A_3$, $B_1$, and $C_1$ independently for each night, we took their average and used them to rederive the remaining nightly coefficients. We found the average scatter around the transformation relations to be $0.035$ mag in $U$, $0.015$ mag in $B$, and $0.008$ mag in $V$. Table 2 lists the coefficients for the three photometric nights.

To place the LH 72 photometry on the $UBV$ system, we first transformed the photometry derived from frames taken on 1998 November 25 using the relation computed for that night. We then selected 25 isolated stars from the LH 72 frame and used their computed $UBV$ magnitudes to transform the photometry taken on the one nonphotometric night. Finally, all the standardized magnitudes were averaged to produce a master photometric table for LH 72.

Figure 3 shows the comparison of our photometry with that from the Magellanic Clouds Photometric Survey (MCPS; Zaritsky et al. 1997), kindly provided by D. Zaritsky. Our photometry agrees to within $3\sigma$ of that of the MCPS: $U - U_{MCPS} = 0.005 \pm 0.010$, $B - B_{MCPS} = 0.017 \pm 0.009$, and $V - V_{MCPS} = 0.033 \pm 0.009$.

**TABLE 2**

| Date          | $A_0$   | $A_1$  | $A_2$  | $A_3$  | $A_4$  |
|---------------|---------|--------|--------|--------|--------|
| 1998 Nov 25… | 4.249 (7)| -0.167 | 0.136  | 0.374 (60) | 0.0   |
| 1998 Nov 26… | 4.323 (5)| -0.167 | 0.136  | 0.555 (42) | -0.009 (2) |
| 1998 Nov 27… | 4.278 (5)| -0.167 | 0.136  | 0.485 (25) | 0.0   |
| 1998 Nov 25… | 2.414 (3)| 0.112  | 0.287 (30) | 0.0   |
| 1998 Nov 26… | 2.426 (2)| 0.112  | 0.302 (16) | -0.003 (1) |
| 1998 Nov 27… | 2.391 (2)| 0.112  | 0.260 (10) | 0.0   |
| 1998 Nov 25… | 2.084 (2)| -0.029 | 0.149 (18) | 0.0   |
| 1998 Nov 26… | 2.102 (2)| -0.029 | 0.139 (14) | -0.005 (1) |
| 1998 Nov 27… | 2.091 (1)| -0.029 | 0.140 (5) | 0.0   |

For comparison, the $UBV$ photometry of LH 72 is shown in Figure 3 along with that from the MCPS (Zaritsky et al. 1997). Points with positive values along the $y$-axes indicate stars for which our photometry is fainter than that of the MCPS. The solid lines are medians through the points, while the dotted lines are $1\sigma$ deviations of the means.
We also find good agreement with the photographic photometry of Lucke (1972): \( V - V_{L72} = 0.022 \pm 0.007 \) (39 stars), \( (B - V) - (B - V)_{L72} = 0.01 \pm 0.02 \) (39 stars), and \( (U - B) - (U - B)_{L72} = -0.05 \pm 0.03 \) (5 stars).

An additional check on the photometry is to compare the intrinsic \((U - B)_{0}\) color expected from the spectral classification with that derived from the photometry after correcting for reddening. Figure 4 shows the comparison; we find \((U - B)_{0,\text{spec}} - (U - B)_{0,\text{phot}} = -0.03 \pm 0.01\), suggesting good agreement between the photometry and spectroscopy. There is, however, a possible discrepancy at the bluest and reddest ends of the scale.

5.3. Analysis of Stellar Photometry
5.3.1. LH 72 Membership

Figure 5a shows the raw \((B - V) - V\) color-magnitude diagram (CMD) produced from our photometry. As is typical of ground-based composite LMC CMDs, we see a broad main sequence down to \( V \sim 21\), an extended giant branch, and a prominent red clump. The presence of an OB association is clearly evidenced by the well-populated upper main sequence; however, the membership of LH 72 is confused by the background field population. To restrict our analysis to probable association members, we selected stars lying within the boundary defined by Lucke (1972). Defining the remaining stars as representatives of the background population, we subtracted the background CMD from the CMD of stars lying within LH 72’s boundary, as done, e.g., by Olsen (1999). Figure 5b shows the result of the subtraction procedure. We see that most of the lower main sequence, giant branch, and red clump have disappeared, while most of the upper main sequence remains. At \( V < 16\), \( \geq 80\% \) of the stars are probable members of LH 72; between \( 16 < V < 17\), the contamination rate is \( \sim 50\%\). For the purposes of our analysis, therefore, we choose as LH 72 members only those stars with \( V < 16\) in the background-subtracted CMD.

5.3.2. Identification of Be Stars

As discussed by, e.g., Maeder, Grebel, & Mermilliod (1999), the presence of emission lines in the spectra of late O and early B stars (the Be star phenomenon) is indicative of...
circumstellar disks. Fast rotation and the presence of circumstellar material causes Be stars to generally be redder and cooler than their non-Be counterparts, a fact that unaccounted for may be misinterpreted as an age difference.

As done by, e.g., Grebel (1997), we identified Be star candidates photometrically by looking for the presence of excess Hα emission. Hα magnitudes were measured from the calibrated, continuum-subtracted Hα image of DEM 228 (discussed in § 6) through aperture photometry with DAOPHOT. Figure 6 plots the Hα magnitudes versus B − V. The spectroscopically identified emission-line stars L10 and S132 show an Hα excess that separates them from the bulk of the spectroscopically studied stars. Thus, we label those stars with Hα magnitudes less than 1.6 and B − V < 0.5 as possible Be stars. Figure 7 shows that the stars selected according to this definition are indeed redder than the bulk of the main sequence. However, we do expect some contamination from non-Be stars, since S128, which does not contain obvious Balmer emission, is included as a Be candidate by our definition.

Because we apply a magnitude cutoff of V < 16 for certain LH 72 membership, corresponding to M_V ~ −2.5 and spectral type ~ B1 on the main sequence, we cannot compute the Be star fraction of LH 72 over the full range of possible spectral types. We note, however, that the fraction is at least 10% from the number of Be stars found within the boundaries of LH 72.

5.4. Reddening and the H-R Diagram

We computed the reddenings, temperatures, and luminosities of individual stars through the transformations employed by Massey, Waterhouse, & DeGioia-Eastwood (2000); these are based on the calibrations of Vacca, Garmany, & Shull (1996) for the O stars and a combination of sources, including Humphreys & McElroy (1984), as well as more modern work, for the B stars. For the stars with spectra, we applied the Vacca et al. (1996) and Humphreys & McElroy (1984) calibrations directly; we then used the spectral type–intrinsic color relationship of Fitzgerald (1970) and our measured B − V colors to derive E(B − V).

For those stars observed only in UBV, we used Massey et al.’s (2000) fits of T_eff to the reddening-free index Q. We picked a luminosity class for each star by plotting Schmidt-Kaler’s (1982) magnitude-color relationship on our CMD, assuming (m − M)_LMC = 18.4. While we found supergiants easy to distinguish from main-sequence stars, separating giants from main-sequence stars was made difficult by the differential reddening. Over the range of observed Q, confusing a giant with a main-sequence star will introduce an error of up to ~0.05 dex in log T_eff and ~0.3 mag in M_bol. With T_eff and the bolometric correction known, we again used the spectral type–intrinsic color relationship of Fitzgerald (1970) to derive E(B − V).

Figure 8 shows the E(B − V) distribution for those LH 72 stars with spectra or Q < −0.4. The distribution has a mean of E(B − V) = 0.09, a median of 0.075, a standard deviation of 0.055, and a sharp lower bound at E(B − V) = 0.04. The typical error on an individual value is ±0.01 mag, indicating that the width of the reddening distribution is produced by differential reddening within the LMC and not purely photometric errors. The typical foreground reddening of E(B − V) = 0.075 toward the LMC (Schlegel, Finkbeiner, & Davis 1998) agrees with our median value but not with the minimum. Outside the boundaries of LH 72, the reddening also has a lower bound of E(B − V) = 0.04, with the majority of stars having E(B − V) = 0.07 ± 0.04.

Figure 9 shows the combined H-R diagram for stars with spectra and stars with photometry only, overlaid with stellar evolutionary tracks and isochrones from Schaerer et al. (1993). With the exception of the O6V star S133, all...
LH 72's stars are less massive than 40 $M_\odot$ and appear older than 4–5 Myr. However, as has been seen in a number of LMC OB associations, LH 72 appears to contain a considerable spread in age; the H-R diagram suggests that LH 72 contains stars as old as $\sim 30$ Myr. We see no evidence for the gradient in age that we reported in Olsen et al. (1997); we surmise that the gradient was an artifact of the small number of stars analyzed in that paper.

There are a number of ways besides an age spread within the association to produce a broadened sequence in the observed H-R diagram. Star-to-star differences in the unknown rotation rates may explain the broadening. As shown by Heger & Langer (2000), fast rotation moves main-sequence stars to cooler temperatures and lower luminosities, as compared to the nonrotating main sequence. However, the addition of rotation to a stellar evolutionary track also increases the main-sequence lifetime. The increase in lifetime is such as to produce a real age spread of $\gtrsim 15$ Myr, if the broadening in LH 72's H-R diagram were due entirely to stellar rotation, a number very similar to what we claim on the basis of nonrotating stellar models. A second possibility is that line-of-sight contamination within the LMC produces the broadened sequence. However, because our analysis shows that 80% of the OB stars with $V < 16$ lie within the confines of LH 72's boundary, we consider this possibility unlikely.

A third, more likely possibility is that a systematic error in the photometry is responsible for the broadened sequence. During our comparison of the intrinsic colors of the stars with spectra with their observed $Q$ values, we found good agreement of the colors derived from spectroscopy with those from photometry. However, if we assume that we should lower the $Q$'s of stars with only photometry by as much as 0.05 mag, then we produce the H-R diagram of Figure 10. The shift in $Q$ makes LH 72 appear younger; the envelope of the youngest stars now suggests an age of $\sim 3$ Myr instead of 5 Myr. The apparent age spread is reduced by a factor $\sim 2$; the oldest stars now have ages of $\sim 20$ Myr, suggesting an age spread of $\sim 15$ Myr. Such an age spread is still significant compared with the measurement errors in $T_{\text{eff}}$ and $M_{\text{bol}}$.

6. ANALYSIS OF THE IONIZED GAS

6.1. Calibration

The individual Hα and off-band images of DEM 228 were
first background-subtracted. We used a 400 pixel-wide box placed in one corner of each image to measure the modal sky value. The observations of spectrophotometric standards were next used to measure the Hα zero point and extinction coefficient. To correct for the different illumination of the filter passband by the standards and by the H II region, we used CTIO’s published filter transmission curve and the Hamuy et al. (1994) published spectra to calculate the number of photons detected at the LMC Doppler-shifted wavelength of Hα. The flux of LMC Hα photons detected through observation of a standard star is

\[ N_{\text{H}\alpha} = N \left( \frac{\int F(\lambda)T(\lambda)\delta(\lambda_{\text{H}\alpha})d\lambda}{\int F(\lambda)T(\lambda)d\lambda} \right), \]

where \( N \) is the flux of photons observed through the filter, \( F(\lambda) \) is the calibrated spectrum of the star, \( T(\lambda) \) is the filter transmission curve, and Hα has been redshifted to the mean velocity of LH 72’s associated H I, \( v = 307 \text{ km s}^{-1} \) (Kim et al. 1998). We used quadratic interpolation to bring Hamuy et al.’s spectra, which are tabulated at 50 Å intervals, to the wavelength grid of \( T(\lambda) \). We then measured the zero point and extinction coefficient by fitting for \( Z_{\text{H}\alpha} \) and \( k_{\text{H}\alpha} \) in the equation

\[ 2.5 \log N_{\text{H}\alpha} = Z_{\text{H}\alpha} + k_{\text{H}\alpha}X + 2.5 \log \int F(\lambda)\delta(\lambda_{\text{H}\alpha})d\lambda, \]

where \( X \) is the air mass. We measured \( k_{\text{H}\alpha} = 0.08 \pm 0.01 \), in good agreement with the usual R extinction coefficient of 0.085 at Cerro Tololo.

After applying the calibration to the individual Hα images, we removed cosmic rays and subtracted the off-band images. Cosmic rays were identified in both Hα and off-band images with the interactive data language (IDL) Astronomy User’s Library routine CR_REJECT and removed by linear interpolation through the surrounding good pixels. We next subtracted the nearest available off-band image, shifting the image to adjust for fractional pixel offsets and scaling it to match the fluxes of point sources through the Hα filter. Finally, we shifted and median-combined the calibrated, continuum-subtracted Hα images into a single image.

**Fig. 11.** Hα image overlaid with smoothed contours of the reddening map, which was derived by interpolating over stellar \( E(B - V) \) values, as described in the text. The contours are labeled by \( E(B - V) \); lines perpendicular to the contours indicate the direction of the local downhill gradient.
6.2. Correction of Hα Flux for Reddening

As shown by the UBV photometry, variable reddening across DEM 228 is significant. One way to correct for the spatially varying reddening would be to observe the Hβ emission line and to construct a map of the Hα/Hβ ratio. However, in the case where the dust is embedded in the ionized gas, scattered nebular light complicates the interpretation of the Hα/Hβ ratio (Mathis 1970; Skelton 1999). Instead, we chose to use the reddening values derived for the stars themselves to construct a reddening map.

We produced the reddening map through linear interpolation of the discrete reddening values. We first constructed a mesh of triangles connecting nearby stars using Delaunay triangulation (through the IDL procedure TRANGULATE), tiling the surface bounded by the locations of the observed stars. We then linearly interpolated the reddening map over the grid using the values at the vertices. Figure 11 shows our Hα image overlaid with smoothed contours of the reddening map. The map shows that the brightest regions of DEM 228 tend to have higher reddening, but that the northern portion of the nebula is more heavily obscured than the southern end. The peak reddening value is $E(B - V) = 0.23$, while we assume $E(B - V) = 0.04$ for the background reddening. We used the reddening curve published by Mathis (1990) to correct the Hα surface flux for absorption by dust.

6.3. Comparison of Hα Flux with Stellar Ionizing Radiation

Is the Hα emission from DEM 228 fully accounted for by LH 72's O and B stars and those of the field? We estimated
the luminosity of Lyman continuum photons, $Q_\odot$, produced by the observed hot stars, using the calibration of Schaerer & de Koter (1997). This calibration is based on theoretical spectral energy distributions of massive stars, calculated using models incorporating non-LTE effects, stellar winds, and line blanketing. The parameters affecting $Q_\odot$ are temperature, gravity, and metallicity. To derive the gravities, we estimated the masses by fitting to the $Z = 0.008$ Geneva tracks (Schaerer et al. 1993) and calculated the radii through $L = 4\pi R^2 \sigma T_{\text{eff}}^4$, with $L$ and $T_{\text{eff}}$ being known through our spectra and photometry. Next, we identified all entries in Schaerer & de Koter's (1997) Table 3 with temperatures within the errors of the temperatures of the observed stars; from that group of entries, we chose the entry with $\log g$ closest to the calculated $\log g$. Finally, we interpolated $Q_\odot$ for the metallicity of the LMC from the $Z = 0.02$ and 0.004 entries.

Assuming case B recombination (Osterbrock 1989) and an LH 72 distance modulus of $(m - M)_0 = 18.4$, we next derived the H$\alpha$ fluxes that would be produced by the computed Lyman continuum luminosities. To get an idea of the contribution of each star to the morphology of the H II region, we then identified those circular regions in the dereddened H$\alpha$ image that can account for all the stellar ionizing radiation, taking into account all stars simultaneously. Figure 12 shows the dereddened H$\alpha$ image with the circular regions overlaid. The two most luminous stars, S128 and S133, are marked with crosses. Their Lyman continuum photons account for more H$\alpha$ emission than is measured in the image; DEM 228 thus appears to be a density-bounded H II region. The remaining stars account for the bulk of the high surface brightness emission. Most of this emission appears to derive from multiple sources; for example, at least 15 sources contribute to the ionization of the southermmost complex of H II regions. On the other hand, two of the bright knots appear to be single-star H II regions.

Although the total reddening-corrected H$\alpha$ emission accounts for only 60% of the Lyman continuum photons produced, not all the structure in the ionized gas is readily explained by the distribution of hot stars. In particular, the low surface brightness halo of H$\alpha$ emission contains structure suggesting past star formation activity. If true, this implies that the area hosting star formation within LH 72 has shrunk somewhat and drifted northward.

7. H I STRUCTURE AND KINEMATICS

Figure 13 shows the individual channel maps of the H I cube covering the velocity range $272.5 < v < 320.3$ km s$^{-1}$. The eighth-note shape of DEM 228 is mimicked by the nearby H I gas, most prominently between the velocities $300 < v < 310$ km s$^{-1}$. In Kim et al. (1999), we identified this gas as forming the western edge of a supergiant shell, SGS 14, an observation also made by Efremov & Elme-
green (1998). However, because of the apparent lack of evidence for an approaching or receding cap to the shell, we did not then report an expansion velocity for it.

We now propose that the surface of SGS 14 is not smooth, but patchy, and that the H I data indeed suggest that the shell is expanding. We base this claim mainly on the evolution of the H I gas associated with DEM 228 through the sequence of channel maps shown in Figure 13. In the $v = 300.5 \text{ km s}^{-1}$ map, an outline similar in shape to DEM 228 is clearly seen. Following the northeastern tip of the outline, we notice that the tip moves progressively toward the interior of the shell with increasing velocity. The first position-velocity diagram shown in Figure 14 also demonstrates this behavior of the gas, indicating that the filament associated with DEM 228 is expanding with a velocity of $\sim 15 \text{ km s}^{-1}$.

The channel maps showing the eastern rim of SGS 14 also suggest expansion. In the $v = 302 \text{ km s}^{-1}$ map, the faint trace of the C-shaped eastern shell edge can be seen. The arms of the “C” pinch together with increasing velocity, as would be expected if the gas formed part of an expanding shell. The “C” fades into the noise at $v \sim 315$–$320 \text{ km s}^{-1}$, roughly the same velocity at which the tip of the filament forming the western edge of SGS 14 disappears. The second position-velocity diagram shown in Figure 14 implies an expansion velocity of $\sim 10 \text{ km s}^{-1}$.

The $v \sim 274$–$284 \text{ km s}^{-1}$ maps contain what may be a piece of the approaching portion of SGS 14. The elongated cloud of gas lies roughly halfway between the geometric center of SGS 14 and its incomplete southern boundary. The mean velocity of the cloud, $v \sim 280 \text{ km s}^{-1}$, suggests an expansion velocity of $\sim 20 \text{ km s}^{-1}$, as shown in the third panel of Figure 14.

The mass of H I that is involved in the 10–20 km s$^{-1}$ expansion can be calculated from the observed column density of the gas. The bottom left panel of Figure 1 shows the assumed physical boundary of SGS 14. Integrating over this area and the velocity range of 280–320 km s$^{-1}$, we find a mass $M_{\text{GS14}} = 1.8 \times 10^{5} M_{\odot}$, with $3.3 \times 10^{4} M_{\odot}$ purely in the gas associated with LH 72. The kinetic energy carried by the H I of SGS 14 is thus $\sim 4 \times 10^{50}$ ergs, or that produced by $\sim 4$ supernovae, if one assumes that 10% of the explosion energy ($\sim 10^{51}$ ergs) goes into moving the surrounding ISM (Tenorio-Tagle et al. 1991).

Assuming a distance modulus of $(m - M) = 18.4$, the radius of SGS 14 is $\sim 240$ pc. Thus, if the gas in SGS 14 were uniformly distributed over the sphere, it would have an average density of $\rho_0 \sim 0.1 \text{ cm}^{-3}$. If SGS 14 expanded with constant velocity of $\sim 15$ km s$^{-1}$ over its entire lifetime, its age would be $\sim 16$ Myr.

8. DISCUSSION AND CONCLUSION

Having examined the stellar content of LH 72, studied the properties of the ionized gas of the embedded H II region DEM 228, and derived the mass and kinematics of the surrounding H I supershell SGS 14, a plausible story emerges: SGS 14 is an expanding supershell that has cleared the northeastern quadrant of LMC 4 of gas and triggered the formation of the OB association LH 72 behind its shock front.

What is the evidence? First, the ages of the oldest stars in LH 72, $\sim 15$–30 Myr, agree closely with the expansion age of SGS 14, $\sim 15$ Myr. Since the first triggering by the passing supershell, star formation could then have continued in LH 72 until $\lesssim 5$ Myr ago, although without the clear north-south spatial pattern reported by Olsen et al. (1997). Second, the interior of SGS 14 appears empty of gas; the H I maps show that the 21 cm emission is at the level of the noise. Moreover, DEM 228 is density bounded, allowing ionizing photons from the UV-bright stars S128 and S133 to escape into the interior of SGS 14. Third, overlaying our Hx image with contours of H I column density show that while DEM 228 and LH 72 lie close to the rim of SGS 14, they are displaced toward its interior. Figure 15 shows the relationship. The plate solution for the Hx image was calculated using stars in LH 72 with coordinates from SIMBAD. The calculated positions of four of the brightest stars agree to within $\lesssim 1''$ with those listed in the Tycho-2 catalog (Hog et al. 2000); the astrometric solution should thus be excellent. The H I astrometric solution is accurate to $\lesssim 1''$. The

![Fig. 14.—Position-velocity maps at three positions. In each panel, the H I map of SGS 14 is shown, summed over a range of velocities. The white lines simulate a slit—the velocity structure at that slit position is shown either above or to the right of the spatial map. Velocity labels are in kilometers per second.](image-url)
figure shows that the peak Hα emission is offset by 1′–2′ (15–30 pc) from the peak H I column density toward the interior of SGS 14.

This picture of the formation of SGS 14 and LH 72 has an interesting consequence for our understanding of the supergiant shell LMC 4. LMC 4 has often been thought to have formed as a unit (see, e.g., Westerlund & Mathewson 1966; Dopita et al. 1985; Efremov et al. 1998). However, this work shows that one quadrant of LMC 4 consists of an independently expanding shell, which may have triggered the formation of at least one of LMC 4's OB associations, LH 72, along its rim. Thus, a possible formation scenario of LMC 4 is one in which many smaller shells, some triggering star formation from the swept-up gas, have overlapped to produce the ring of H I and H II regions we see today. In this scenario, the energy required to produce LMC 4 is greatly reduced from that needed if it formed as a single unit—the reason being that once a supershell blows out, it becomes difficult to impart additional energy to expansion within the disk plane (see, e.g., Mac Low & McCray 1988). LMC 4, if it formed as a unit, must have blown out long ago, as its diameter of \(~1.4\) kpc is many times the scale height of the LMC’s H I disk of 180 pc (Kim et al. 1999). By contrast, with a radius of \(~240\) pc, SGS 14 should be only in the early stages of blowout.

The scenario proposed here naturally merges with that of Efremov & Elmegreen (1998), in which Quadrant and Sextant formed from swept-up shells that have since merged with SGS 11. Indeed, LH 72 may be a younger, less massive version of Quadrant and Sextant. Like those two structures, it is arc shaped, with an approximate center of curvature near the center of SGS 14. In \(~15\) Myr, by the time the last of the current generation of ionizing stars have disappeared, SGS 14 will have approximately doubled in size, assuming constant expansion velocity. Assuming that LH 72 also grows only in the azimuthal direction, it will still have an overdensity of stars at the tip of the main sequence compared with the field, by a factor \(~4\). LH 72 may then be

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**Fig. 15.**—Hα image, stretched by the logarithm of the intensity, overlaid with contours of H I column density in units of $10^{21}$ atoms cm$^{-2}$. North is up, and east is to the left.
classified as a stellar arc, shorter and less tightly curved than the current Quadrant.

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