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SHAPLEY CONSTELLATION III: A REGION OF SELF-PROPAGATING STAR FORMATION

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ABSTRACT

We present results of an H I survey of the Shapley Constellation III region associated with the supergiant loop H II region complex, LMC 4, in the northern part of the Large Magellanic Cloud. We find three components, one associated with the disk H I with a mean $V_{LSR} = 285$ km s^{-1}, and the other two associated with shells of gas ejected above and below the plane of the LMC with an expansion velocity of 36 km s^{-1}. The approaching shell is complete and has a diameter of about 2 kpc, but the receding shell is incomplete. The disk H I shows a ringlike structure, 1.8 kpc in diameter with a very pronounced central hole, and the H II regions form a ring of 1.4 kpc in diameter. Star formation appears to have started approximately 15 Myr ago near the center and has propagated outwards at a constant speed of 36 km s^{-1}. The energetics of this whole region strongly suggests that newly formed stars generate a local overpressure in the interstellar medium as a result of H II region formation. This overpressure drives a shock in the intercloud medium, sweeping over and around dense H I clouds and so initiating new episodes of star formation. The cycle of star formation, ejection of gas to large Z-heights in the plane, return of this gas, adjustment of the H I cloud size distribution and z-velocity dispersion, and the renewed onset of star formation appears to represent a stochastic and self-limiting feedback process in the LMC.

Subject headings: galaxies: Magellanic Clouds — nebulae: H II regions — stars: formation

I. INTRODUCTION

Many years ago, Nail and Shapley (1953) drew attention to the fact that, in the LMC, the bright stars clustered together in prominent constellations, suggesting that large bursts of star formation occur in localized regions. Later, Westerlund and Mathewson (1966) showed that one of these, Shapley's Constellation III, is also associated with a shell of H I, an enhancement in the radio continuum, a ring of H II regions, and at least two supernovae.

A total of nine supergiant shells or rings of ionized material covering 12%–15% of the total surface area are now known in the Large Magellanic Cloud (LMC), thanks to very deep Hα plates taken with the 48 inch (1.2 m) UK Schmidt Telescope (Goudis and Meaburn 1978; Meaburn 1980, 1981). These shells have diameters between 600 and 1400 pc and consist of a series of isolated H II regions, giant loop H II regions, and H II region complexes connected by faint and often filamentary emission. On the basis of their size distribution alone, Meaburn (1981) showed that they form a population of objects quite distinct from "normal" H II regions in the LMC, suggesting that their physics may be quantitatively or qualitatively distinct.

It is clear that star formation, which now is confined to the periphery of the shells, recently occurred close to their centers. In almost all cases, a Lucke and Hodge (1970) cluster containing relatively young ($<2 \times 10^7$ yr) stars is found near or at the center, and most show a field population of young blue stars which is prominent in the far UV atlas of Page and Carruthers (1981). If the stellar ages given by Isserstedt (1984) are adopted, then, in all cases, the stars at the center of these loops are older than those near the periphery, demonstrating that the star-forming region propagates outward.

At least five of the supergiant shells (LMC 2, 3, 4, 7, and 8 in the notation of Meaburn 1981) are associated with looplike features or central depletions in the H I distribution, and total H I masses can be estimated to lie in the range 0.6–2.5 × 10^7 $M_\odot$.

There has been an adequate investigation of the dynamics of only one region, LMC 2, located to the southeast of 30 Dor (Caulet *et al.* 1982). This study suggested a model in which one quarter of a shell of H II with a center at $5^h41^m.5$, $-69°25'$ (1975.0) is expanding away from us at a velocity of 30 km s^{-1}. There has not been a specific H I study of this region, but the survey by McGee and Milton (1966*a*, *b*) is not inconsistent with this picture, and an estimated total of 5×10^6 $M_\odot$ of H I is involved in a high-velocity expanding shell. The parameters of this shell are comparable with the largest Heiles (1979) shells seen in our Galaxy. Caulet *et al.* (1982) suggest that LMC 2 might result from the combined action of stellar winds and supernova explosions.

Perhaps the best example of the supergiant loop phenomenon, and indeed the largest such region, is the supergiant loop LMC 4 associated with the Shapley Constellation III of bright stars. It consists of an H II loop which, when projection effects are taken into account, is almost perfectly circular with a diameter of 1400 pc centered at $5^h31^m.0$, $-66°54'$ (1950.0). Four Lucke and Hodge (1970) clusters lie within the ring of H II regions (Nos. 65, 70, 72, 77, and 84), and many more on the periphery (Nos. 51, 52, 53, 54, 55, 60, 63, 75, 76, 78, 79, 82, 83, 86, 88, 91, 92, and 95), most of which are associated with bright H II regions for which Braunsfurth and Feitzinger (1983) have given the physical parameters. Both Westerlund and Mathewson (1966) and Meaburn (1981) have emphasized the association of the stars and H II regions, and they have also pointed out the rather fine H I shell surrounding this whole region, using the survey results of McGee and Milton (1966*a*, *b*).

In view of the close association between the H I and H II, we undertook a detailed H I survey to investigate, in particular, the energetics of this major complex of star formation. The result of the survey is the subject matter of this paper.

II. THE H I SURVEY

The H I survey was carried out in 1979 June using the 64 m reflector of the Australian National Radio Astronomical Observatory at Parkes, New South Wales. This gives a beam width of 15′ (full width, half-maximum) at 21 cm. The survey area covered from −65°45′ to −68°00′ in declination and from $5^h22^m.5$ to 5^h40^m in right ascension (1950.0). The sample interval was 15′ in declination and $2^m.5$ in right ascension. Thus the survey was marginally subsampled, and therefore the highest spatial frequency detail present may have been lost in the maps.

At each sample point, spectra were obtained using 512 channels of the Parkes digital auto correlation spectrometer (Ables *et al.* 1974), covering a rotal range of 1055 km s^{-1}, which after a Hanning smoothing operation gave a velocity resolution of 4.12 km s^{-1}.

With an integration time of 4 minutes, the rms noise on the signal is 0.2 K.

In the reduction, the data were reduced to velocity with respect to local standard of rest (V_{LSR}), and any residual baseline curvature was removed. Figure 1 shows the variety of line profiles observed and the full range in signal-to-noise ratio obtained. All profiles shows a prominent peak within 12 km s^{-1} of $V_{LSR} = 285$ km s^{-1}. A substantial fraction also show a second peak at negative velocity, and some show a third peak at positive velocity with respect to this main feature. In the reduction, therefore, we have decomposed the observed profile into three Gaussian components and determined the H I column density, radial velocity, and velocity dispersion (full width half-maximum) for each component.

III. THE H I DYNAMICS

The H I velocity field divides very naturally into three components.

The first component consists of a prominent shell of H I at rest in the plane of the LMC. This has a systemic velocity of 285 ± 1 km s^{-1} with respect to local standard of rest (V_{LSR}) and shows a maximal velocity spread from 268–294 km s^{-1}. The H I column density peaks in the northwest of the shell at 5^h25^m, −66°15′ (1950.0) at 2.4×10^{21} cm^{-2}, and the central hole is very deep, dropping to a column density of only 5×10^{19} cm^{-2} at 5^h30^m, −66°45′. In fact, at this point the total H I column density is only 1.0×10^{20} cm^{-2}. Since the gas-to-dust ratio [N(H I/$E(B-V)$] is approximately 2×10^{22} atoms cm^{-2}

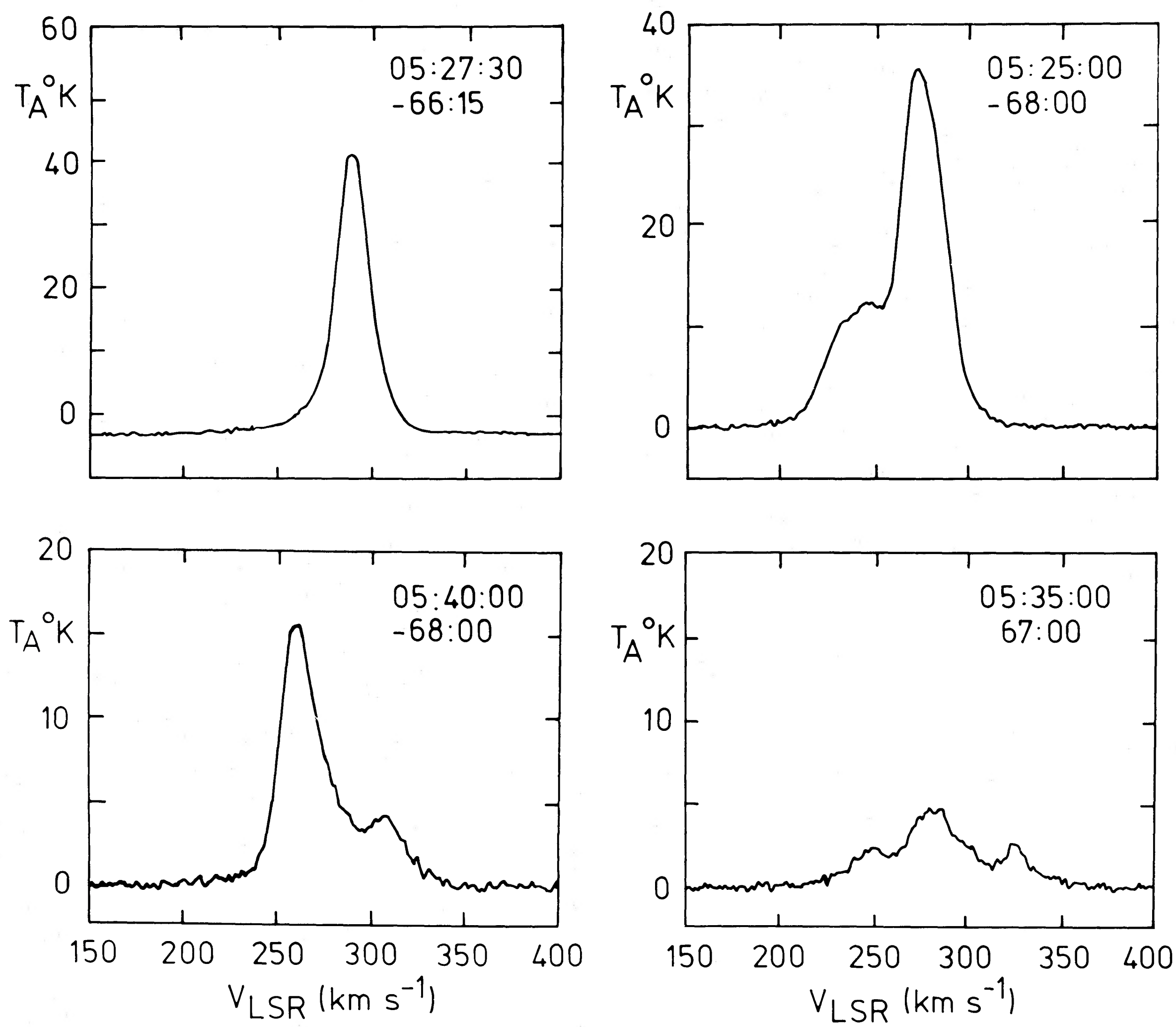

FIG. 1.—A sample of profiles obtained in the H I survey of LMC 4. These are representative of both the variety of profile shapes and of the signal-to-noise ratio obtained.

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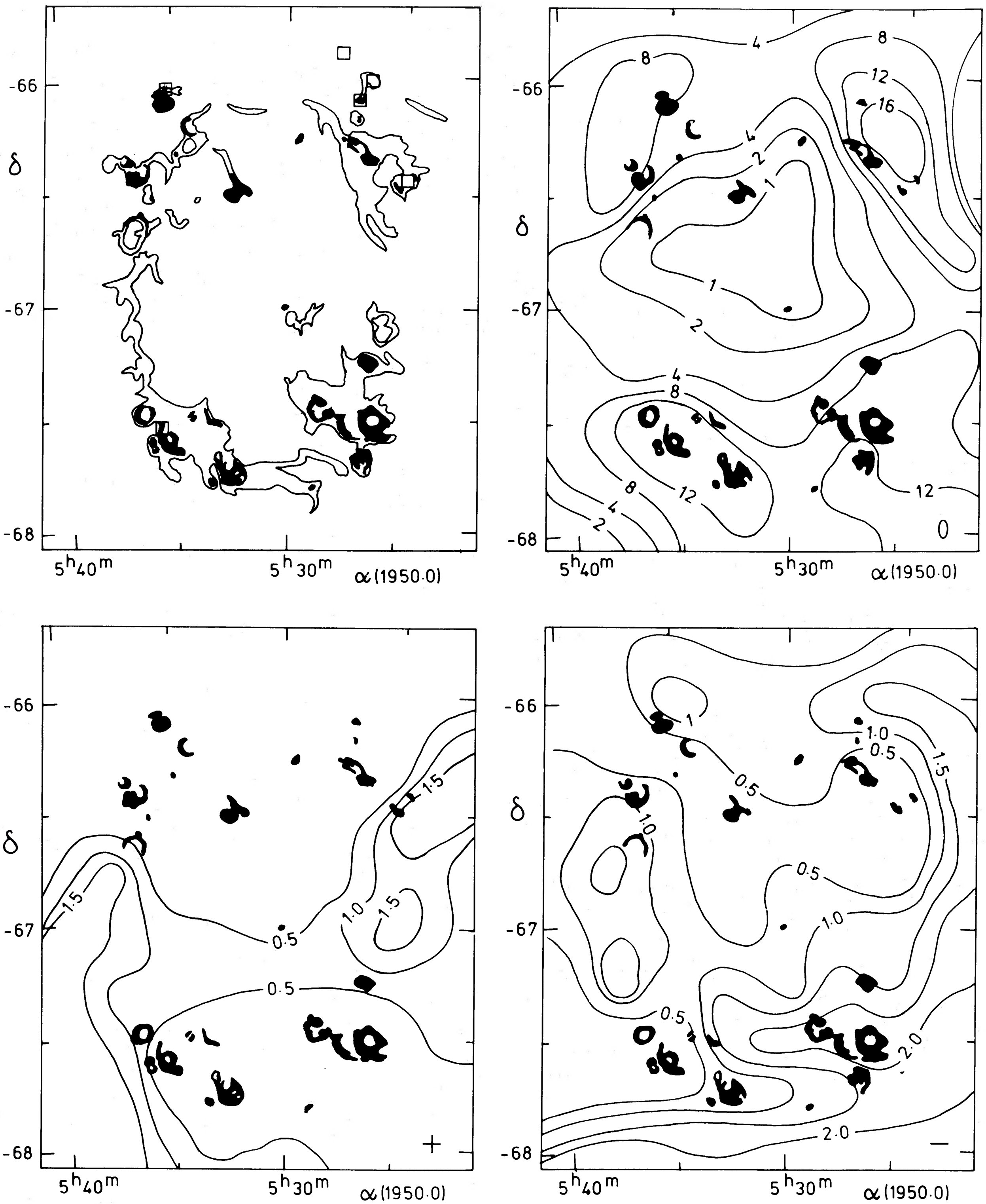

FIG. 2.—The results of the H I survey. The map on the top left shows the bright H II regions (*filled*) and the fainter H II regions (*outlined*). Objects identified as supernova remnants are in boxes. The maps on the top right, bottom left, and bottom right show the distribution column density of the material at rest in the plane of the LMC, the receding high-velocity material, and the approaching high-velocity shell respectively. The contour unit is 10^{20} cm^{-2}, and bright H II regions are also shown.

mag^{-1} in the LMC (Koornneef 1982), the observed H I column density implies a limit on LMC reddening of $E(B-V) = 0.005$ mag. This is consistent with the very low values found by Isserstedt (1975*b*) for stars in this region. Indeed, the only reddening seen appears to be caused by Galactic foreground material with $E(B-V) = 0.034$ (McNamara and Feltz 1980).

Second, component consists of receding gas which is concentrated at the east and west edges of the supergiant loop, but which has a faint filament extending between these components just south of the center of the shell. This is seen in the velocity range $229 \leq V_{\mathrm{LSR}} \leq 275$ km s^{-1}.

Third component of the H I distribution is a well-defined and almost complete shell of material which is observed in the velocity range $300 \leq V_{\mathrm{LSR}} \leq 325$ km s^{-1}.

The spatial distribution of column density in these components is shown in Figure 2, which also compares the H I data with the spatial distribution of prominent (*filled*) and faint (*outlined*) H II regions and supernova remnants from the catalogs of Mathewson *et al.* (1983*a*, 1984). These are marked as open squares.

The high-velocity components of the H I define a shell with a (deprojected) diameter of 1.9 kpc, somewhat larger than the size of the rest H I ring (1.8 kpc diameter) and appreciably larger than the ring defined by the H II material (1.4 kpc diameter). Thus, the young stars tend to lie on the inner edge of the H I shell, and the high-velocity gas has ballooned out above and below the galactic plane around the dense H I shell. From the depth of the central minimum of the rest H I, there is no doubt that the high-velocity material has escaped from the galactic plane, sweeping clear the vast majority of the H I left from star formation. Thus the rest H I forms a ring or doughnut of material rather than a shell.

The velocity field of the high-velocity material can be fairly well represented by an expanding shell. Figure 3 shows the velocities of individual components in terms of the projected distance from the center of the supergiant loop at 5$^{\mathrm{h}}$31$^{\mathrm{m}}$.0, $-66°54'$ (1950.0). The solid curve is a velocity ellipsoid with a diameter of 2.0 kpc and an expansion velocity of 36 km s^{-1}. This is an excellent fit to the data out to about a diameter of 1.6 kpc, but the projected velocities observed outside this tend to lie systematically too high, requiring that there is a *z*-component to the gas motions here rather than simple radial expansion of a shell.

Finally, we have evidence of strongly anomalous motions in the northwest region of the shell around 5$^{\mathrm{h}}$25$^{\mathrm{m}}$, $-66°00'$ (1950.0). These take the form of both extreme negative velocities about $V_{\mathrm{LSR}} = 230$ km s^{-1} and of a well-defined extreme positive velocity at $V_{\mathrm{LSR}} = 356$ km s^{-1}. This has already been reported (Mathewson *et al.* 1983*b*). These high velocities all occur in the region of a concentration of four supernova remnants around N49, suggesting that the energy fed into the interstellar medium by a concentration of supernova events can generate local H I motions as high as 55–70 km s^{-1}.

The total mass involved in the principal components of the H I profile was estimated by integrating around the contours in Figure 2. We find that the approaching and receding matter have H I masses of 1.6×10^6 $M_\odot$ and 9.0×10^5 $M_\odot$ respectively, and that the rest H I ring contains a total of 1.2×10^7 $M_\odot$. Thus about 20% of the H I is involved in high-velocity motions, similar to that derived for supergiant shell LMC 2 (McGee and Milton 1966*a*, *b*). It is possible that there may also be a great deal of high-velocity ionized hydrogen. Such material was definitely seen in LMC 2 by Caulet *et al.* (1982), but the lower emission measure in LMC 4 would make it very difficult to observe. Even if there were a shell of 10^7 $M_\odot$ and 300 pc thick, the emission measure resulting would only be 8 pc cm^{-1}, which is on the lower edge of observability.

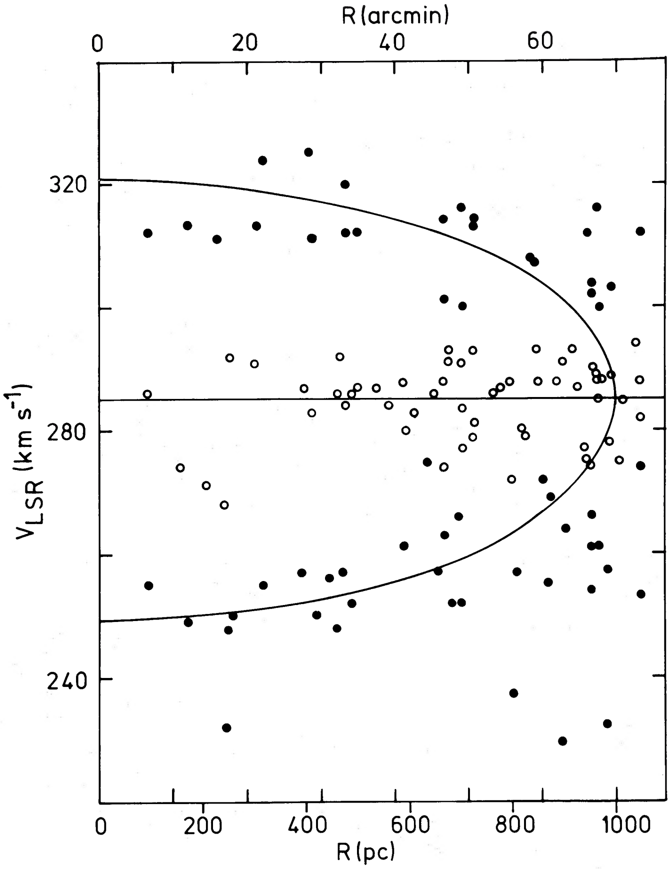

FIG. 3.—A velocity ellipsoid for the H I material. *Filled circles*, high-velocity components; *open circles*, "rest" velocity component. The curve is a "best fit" velocity ellipsoid having an expansion velocity of 36 km s^{-1}, a diameter of 2.0 kpc, and an expansion center at 5$^{\mathrm{h}}$31$^{\mathrm{m}}$.0, $-66°54'$ (1950.0).

In view of the above discussion, the H I data give only a lower limit on the kinetic energy associated with supergiant shell LMC 4. We derive a figure of 3.2×10^{52} ergs for this limit. If, however, we assume that all the material required to fill the central hole to a column density of 8×10^{20} cm^{-2} (7.7×10^6 $M_\odot$) is now moving at 36 km s^{-1}, we have a reasonable estimate for the total kinetic energy in LMC 4; 1×10^{53} ergs.

IV. THE STELLAR CONTENT OF SHAPLEY III

In order to understand the dynamics of the supergiant loop LMC 4, we need to know a good deal about the stellar content of the Shapley Constellation III and the associated clusters in order to estimate ionizing flux energy input from stellar winds and energy input from supernovae.

The best source of optical photometric data is that for the Lucke and Hodge (1970) clusters obtained by Lucke (1974), although the photoelectric *UBV* data of Ardeberg *et al.* (1972) and Isserstedt (1975*a*) give the most accurate data set for the supergiants. The only complete UV data are in the Page and Carruthers (1981) revised catalog. Braunsfurth and Feitzinger (1983) have compiled data for each of the Lucke and Hodge

TABLE 1

ESTIMATES FOR THE IONIZING FLUX N_c IN N51

Lucke and Hodge Cluster Number	F_{UV}[a,b]	$E(B-V)$[a] (mag)	F_{UV}[c] (corrected)	N_c (UV)[d] (10^{50} s^{-1})	N_c (radio)[e] (10^{50} s^{-1})
51...........	662	...	...	...	...
54...........	654	0.06	6820	...	...
55...........	562	...	...	6.8	5.2
60...........	1008	...	...	...	...
63...........	588	0.09	11555	...	...

[a] From Braunsfurth and Feitzinger 1983.

[b] Unit of flux, 5.33×10^{-10} ergs cm^{-2} s^{-1} (Page and Carruthers 1981).

[c] A combination of LMC and Galactic reddening laws has been used, i.e.,

$$A_\lambda = 8.6E(B-V)\,, \qquad E(B-V) \leq 0.03\,,$$

$$A_\lambda = 10.0E(B-V) - 0.04\,, \quad E(B-V) > 0.03\,.$$

[d] Assumes $\langle T_* \rangle = 41{,}000$ K (Evans and Dopita 1984), hence using Page and Carruthers 1981, unit of flux = 3.7×10^{46} Lyman continuum photons s^{-1}.

[e] From McGee, Brooks, and Batchelor 1972 using conversion of Caulet *et al.* 1982.

(1970) clusters and their associated H II regions, and we draw heavily on these data in Tables 1 and 2.

In LMC 4, there is a steady progression of stellar ages, the youngest being found around the periphery and the oldest near the center. This is most clearly seen in the work of Isserstedt (1984). Adopting the ages given in that paper, we have plotted on Figure 4 the mean projected diameter of the star-forming region as a function of stellar age range. This shows that the star-forming region has expanded with a *uniform* velocity of 36 km s^{-1} over the past 14 Myr and is alone sufficient to show that self-propagating star formation has occurred in this region. The fact that the outward expansion velocity in the (x, y)-plane is the same as in the z-plane is probably coincidental but tends to justify our approximation of the geometry of the high-velocity material by a spherical shell.

In order to estimate the total ionizing flux of the stars involved with supergiant Loop LMC 4, we consider in Table 1 only those stars involved with N51, which is a bright source of thermal continuum radiation at 6 cm (McGee, Brooks, and Batchelor 1972). This allows an estimate of the ionizing flux either from the radio data or from the integrated properties of the exciting clusters. In correcting the UV flux for the effects of extinction, we have accounted for the difference between the LMC and Galactic extinction laws (e.g., Nandy 1984) and have assumed a Galactic foreground reddening of $E(B-V) = 0.03$ (McNamara and Feltz 1980). The radio flux has been transformed directly by a Lyman continuum flux using the Mezger (1972) relationship employed by Caulet *et al.* (1982) in their study of supergiant loop LMC 2. The agreement (to within 25%) of these two estimates is very satisfactory and, in our view, validates the extension of the UV technique to the remainder of the Lucke and Hodge (1970) clusters and star clouds associated with LMC 4.

In Table 2 we distinguish between those clusters lying within the ring of H II regions, and those associated with the H II regions or diffuse H II around the periphery. The columns have the following meanings: (1) the Lucke and Hodge (1970) cluster number; (2) the number of stars brighter than $m_v = 14$ mag; (3) the number of blue stars (Lucke 1974); (4) the Page and Carruthers (1981) UV flux; (5) the reddening $E(B-V)$ in magnitudes,

TABLE 2

PARAMETERS OF THE CLUSTERS ASSOCIATED WITH SUPERGIANT LOOP LMC 4

Lucke and Hodge Cluster Number (1)	N_* (2)	N_B (3)	F_{UV} (4)	$E(B-V)$ (mag) (5)	N_c(UV) (10^{50} s^{-1}) (6)
Clusters Lying inside H II Loop					
65...........	7	5	2017	0.03	1.35
70...........	46	10	2801	0.01	1.26
72...........	27	16	429	0.00	0.16
77...........	210	138	10338	0.06	13.9
84...........	50	38	2084	0.10	7.03
$\sum$.........	340	207			23.7
Clusters Coincident with H II Loop					
51...........	8	5	662	0.06	0.89
52...........	38	15	528	0.02	0.29
53...........	62	19	666	0.02	0.37
54...........	18	12	654	0.06	0.89
55...........	4	3	562	0.06	0.76
60...........	21	16	1008	0.09	2.70
63...........	16	14	588	0.09	1.58
75...........	27	...	409	0.06	0.55
76...........	41	34	1605	0.04	0.35
78...........	15	13	21	0.06	0.03
79...........	22	15	152	0.07	0.26
82...........	10	...	328	(0.09)	0.88
83...........	11	10	244	0.04	0.21
86...........	10	13	78	0.06	0.10
88...........	6	9	216	0.06	0.29
91...........	9	4	32	0.01	0.01
92...........	5	3	56	0.06	0.07
95...........	3	2	2607	0.01	1.18
$\sum$.........	326	~224			11.4

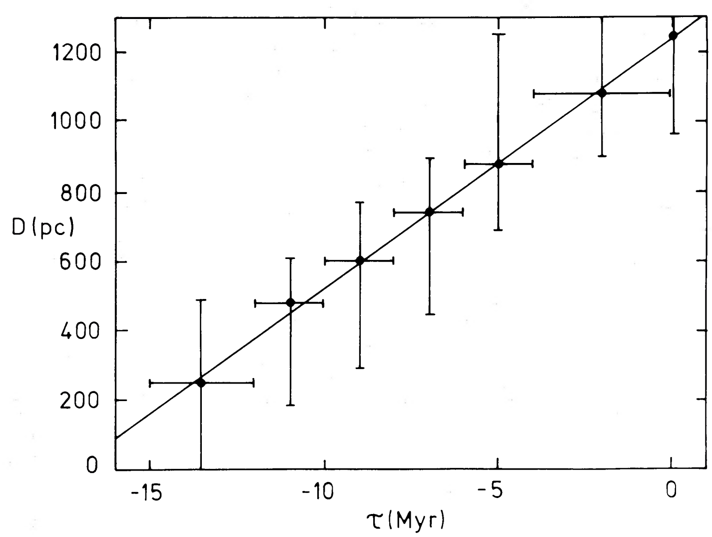

FIG. 4.—The progression of the mean projected diameter of the star-forming region with time in Constellation III using results by Isserstedt (1984). The horizontal bars represent the age range of the stars and the vertical bars the radial extent of the star-forming region of the epochs. A low level of star formation occurs across the whole region at all times, and a major burst of star formation occurred 8–10 Myr ago.

from Lucke (1974) (cols. [1]–[5] are taken from Braunsfurth and Feitzinger 1983); (6) the Lyman continuum flux derived for each cluster assuming $\langle T_* \rangle = 41{,}000$ K (Evans and Dopita 1985) and using the transformation given by Page and Carruthers (1981). Since, for a cluster of a given stellar content and age, $\langle T_* \rangle$ will decline slowly with age (Maeder 1981), we can expect that the Lyman continuum flux estimated for the clusters lying inside the loop is an overestimate. However, for the clusters coincident with H II regions, the Lyman continuum flux may well be underestimated because of reddening and possible complete obscuration of clusters younger than about 2 Myr (Braunsfurth and Feitzinger 1983). We therefore estimate the *total* Lyman continuum flux as $3.5 \pm 1.0 \times 10^{51}$ per photon.

V. THE ENERGETICS OF SHAPLEY III/LMC 4

Any model for the dynamics of this region must explain the linear expansion of the star-forming region and the shell with time and be capable of explaining how approximately 10^{53} ergs of kinetic energy can be imparted to the gas. Since the region is approximately 15 Myr old, this implies a source of mechanical energy of at least 2.2×10^{38} ergs s^{-1}.

A viable source of energy is that of supernova explosions and mass loss of massive stars ($M_* \gtrsim 15\ M_\odot$). The stellar mass loss can be estimated directly from Table 2. Wilson (1983) showed that the mechanical luminosity in the wind L_w is directly related to N_c by a constant of proportionality $L_w/N_c = 3.2 \times 10^{-13}$ ergs per photon. Thus we estimate

$$L_w = (8\text{–}14) \times 10^{38} \text{ ergs s}^{-1} .$$

Each supernova is, in principle, capable of depositing an energy of the order of its thermal energy, which for LMC remnants is $1\text{–}2 \times 10^{50}$ ergs (Dopita 1979; Long 1983). We can estimate the supernova rate from the fact that seven out of 32 LMC remnants are associated with LMC 4, which given the (Type II) rate of one per 260 years in the LMC (Dopita 1984) implies a supernova energy input $L_{\rm SNR}$ of

$$L_{\rm SNR} = 2.5\text{–}5.0 \times 10^{39} \text{ ergs s}^{-1} .$$

An alternative estimate which is less prone to statistical fluctuations can be derived from the stellar content of blue stars (Table 2). These stars have $M_v \leq -4.5$ and have typical ages in the range 2–7 Myr. Since fainter stars of age up to 15 Myr are present, and since all of these are capable of exploding as Type II supernovae, we can estimate a total stellar content of ~ 1000 blue stars with a mean life expectancy of order 2–5 Myr. If each deposits $1\text{–}2 \times 10^{50}$ ergs, then the supernova energy input implied is:

$$L_{\rm SNR} = 0.6\text{–}3.3 \times 10^{39} \text{ ergs s}^{-1} .$$

Apparently, therefore, there is an abundance of energy, but in practice only a fraction of this can be imparted to bulk gaseous motions.

For example, supernovae exploding near the center of the H II ring are free to escape and to directly deposit their energy to the halo gas. This zone is therefore a region of high porosity, filled with gas at coronal temperatures as in the Cox and Smith (1974) or Cox (1979, 1981) model of the interstellar medium. Regions such as this feed the hot galactic halo observed with *IUE* (Savage and de Boer 1979; de Boer, Koornneef, and Savage 1980; de Boer and Savage 1980; Gondhalekar *et al.* 1980; de Boer and Nash 1982; Fitzpatrick and Savage 1983; de Boer 1984) but are of little consequence to the H I kinematics.

Supernovae within and at the boundaries of the dense H I clouds are much more effective in depositing energy to the disk interstellar medium. In an exponential atmosphere such as that used in the Kompaneets (1960) solution, Falle, Garlick, and Pidsley (1984) find that gas in a cone of semiangle θ_0 will remain hot and escape in the halo where

$$|\beta \cos \theta_0| = 2.8 \tag{5.1}$$

and

$$\beta = 0.65 H_{100}{}^{-1} E_{51}{}^{2/7} \rho_{-24}{}^{-3/7} , \tag{5.2}$$

where H_{100} is the scale height of the gas in units of 100 pc, E_{51} is the supernova explosion energy in units of 10^{51} ergs, and ρ_{-24} is the local density of the gas plane in units of 10^{-24} g cm^{-3} for intercloud material (of order 0.2 in the plane). The scale height in the LMC has been estimated by Freeman, Illingworth, and Oemler (1983) to be of order 300 pc, derived from the z-velocity dispersion of young clusters. For hot gas to escape to the halo, therefore, the supernova must be of order 4–5 scale heights high.

At the time of cooling, each supernova has swept up about 200 $M_\odot$ of intercloud gas to a velocity of about 300 km s^{-1}. To eject gas from the galactic plane at a velocity of 36 km s^{-1} therefore implies that a total of 1600 $M_\odot$ is involved (by conservation of momentum). Since only about one-third of this is moving with an appreciable z-component of velocity, each supernova can eject of order 500 $M_\odot$ of H I as high-velocity gas. With the mean supernova rate between 1 per 1500 yr and 1 per 5000 yr, appropriate to LMC 4, a total mass of $1.5\text{–}5 \times 10^6$ $M_\odot$ may have been ejected with an energy of 4×10^{52} ergs. Thus, supernovae are capable of throwing up the H I shell observed during their momentum-conserving phase of evolution.

In the phase of evolution of LMC 4 which occurred prior to its breakout into the halo ($D < 600$ pc), stellar winds may well have been important in its dynamics. This is for two reasons; first, stellar winds are in principle more efficient in depositing momentum to the interstellar medium that supernovae, and second, they are the dominant source of energy input to the interstellar medium in a very young stellar population dominated by massive stars.

The radius $R(t)$ and the velocity $V(t)$ of the outer isothermal shock of a stellar wind bubble are given by (Castor, McCray, and Weaver 1975)

$$R(t) = 27 L_{36}{}^{1/5} n_1{}^{-1/5} t_6{}^{3/5} \text{ pc}$$

and

$$V(t) = 16 L_{36}{}^{1/5} n_1{}^{-1/5} t_6{}^{-2/5} \text{ km s}^{-1} \tag{5.3}$$

where L_{36} is the mechanical luminosity of the cluster(s) in units of 10^{36} ergs s^{-1}, n_1 is the density of the (intercloud) interstellar medium in units of cm^{-3}, and t_6 is the nebular age in units of 10^6 yr. At the time of shock breakout, $t_6 \lesssim 5$. Using a figure of 0.1 cm^{-3} for the density of the intercloud implied by observations of both Type I and Type II supernovae (Tuohy *et al.* 1982; Long, Dopita, and Tuohy 1982; Long 1983), then both the radius and velocity equations require

$$L_w \approx 1.4 \times 10^{38} \text{ ergs s}^{-1} .$$

If, on the other hand, we assume that the H I in the plane (10^{21} cm^{-2}) is evenly distributed throughout a zone 600 pc thick, our estimate of n_1 rises to 0.55, requiring

$$L_w \approx 7.7 \times 10^{38} \text{ ergs s}^{-1} .$$

The very rich and dominant cluster Lucke and Hodge 1977 can supply 4.5×10^{38} ergs s^{-1}, which therefore satisfies these energy requirements.

Following the breakout and draining of the hot gas contained in the stellar wind bubble into the halo of the LMC, the pressure driving the shock would rapidly decline, and the expansion velocity would slow in a momentum-conserving phase. For cylindrical symmetry in the plane this would give a radius-time (r, t) relationship

$$(t - t_1) = C(R^3 - R_1{}^3) , \quad (5.4)$$

where t_1, R_1 are, respectively, the time of breakout and the corresponding radius. However, we believe that the expansion can be maintained by the local overpressure in the disk generated by newly formed stars.

Such a second phase of star formation will be induced by this shock moving in the interstellar medium. We envision that it propagates in the intercloud medium, sweeping around and compressing dense clouds of H I. As this isothermal shock moves into the cloud, an increasingly massive layer is swept up. Elmegreen and Elmegreen (1978) show that such a layer with plane geometry can become self–gravitationally unstable when the surface density s exceeds

$$s \geq 0.91(P/\pi G)^{1/2} \text{ g cm}^{-2} , \quad (5.5)$$

where p is the postshock gas pressure. If we equate this with the ram pressure associated with the shock in the intercloud medium moving at 36 km s^{-1} through a medium of density 0.1–0.5 cm^{-3}, then $P = 2\text{–}10 \times 10^{-12}$ dynes cm^{-2}, and gravitational instability can set in when s exceeds the range

$$2.8 \times 10^{-3} < s < 6.3 \times 10^{-3} \text{ g cm}^{-2} .$$

Assume that the H I clouds originally formed a set of isothermal gas spheres in pressure equilibrium with the intercloud medium at a pressure $P/K \approx 600\text{–}3000$ K cm^{-3}. With a temperature of about 50 K, the typical cloud will have a density N_c at its surface in the range 12–60 cm^{-3}. This is similar to that derived for the clouds in supernova remnants in the LMC (Dopita 1979). The *mean* surface density of an isothermal H I cloud of radius R_c is given by

$$s = 4\mu m_{\rm H} N_c R_c \text{ g cm}^{-2} . \quad (5.6)$$

Thus the Elmegreen and Elmegreen (1978) criterion is satisfied for clouds with radii greater than

$$1.8 \lesssim R \lesssim 20 \text{ pc}$$

corresponding to a mass in the range 200–36,000 $M_\odot$. Clouds can be considerably larger than this, and the collapse time scale of the shocked layer (~ 1 Myr) is shorter than either the free-fall time scale or the time scale required for the shock to propagate to the cloud center (~ 10 Myr). Thus in massive H I clouds, primary star formation is induced in the accretion flow some distance from the center of mass, and the subsequent evolution of the cloud may resemble the model developed by Dopita (1981).

Since stars are constantly generated in the region behind the intercloud shock at a rate which only depends on the size distribution and density of the H I clouds, and since the pressure driving the intercloud shock only depends on the star formation rate, the region of star formation expands at a uniform velocity as long as the supply of H I is maintained.

The delay time required to trigger star formation behind the intercloud shock determines the spatial relationship of the H I shell, the region of star formation and the development of prominent H II regions. Using the Elmegreen and Elmegreen (1978) criterion with the pressure we derive, we find that, in plane-parallel geometry, the time scale τ required to generate gravitational instability in the shocked layer is

$$\tau \approx 3.5 n_{100}{}^{-1/2} \text{ Myr} , \quad (5.7)$$

where n_{100} is the cloud H I density in units of 100 cm^{-3}. During this time, the cloud shock has penetrated about 10–20 pc typically. Collapse will then occur over some 1 Myr or so, and a further 2 Myr is required for the newly formed stars to dissipate their dusty envelope and appear as an H II region complex (Braunsfurth and Feitzinger 1983). The total time scale thus implied is sufficient to explain the difference in diameters of the H I ring (1.9 kpc), which delineates the intercloud shock, and the ring of H II regions (1.4 kpc).

Thus, the picture of self-propagating star formation that emerges differs in several respects from that developed by Elmegreen and Lada (1977). Elmegreen and Elmegreen (1978), or Bruhweiler *et al.* (1980) and is altogether on a grander scale, although in both models star formation has some of the characteristics of an infectious disease or mold. In some respects, the processes are self-inoculating, since, by stripping out the H I and throwing the gas outward and upward, star formation is arrested.

What of the material thrown up out of the plane? At an initial velocity of ~ 40 km s^{-1}, the H I and associated H II in the high-velocity shell will rise to a height of about 2.5 kpc and will return to the galactic plane after about 1.8×10^8 yr. The hot coronal material produced by supernovae in the inner parts of the supergiant ring will take even longer to return. Its ejection velocity is of order 60–80 km s^{-1}, judging from the very high velocity gas we detected and from the radial velocity of the highly ionized species seen with *IUE*. This gas eventually cools and falls back as dense cloudlets, but the time scales required for this are very long, $3\text{–}20 \times 10^8$ yr. On the return of H I material to the galactic plane, shocks produced may induce local star formation in disk H I clouds, but the main effect of this returning material would be to increase the z-velocity dispersion of the disk H I and to modify the size distribution of the H I clouds by cloud-cloud collisions.

VI. CONCLUSIONS

This study of the H I dynamics and stellar content of the Shapley III/supergiant loop LMC 4 region has produced very strong evidence in support of the idea that a mode of self-propagating star formation has determined the present-day structure of this region and that this continues to the present day.

The Magellanic Irregular galaxies can produce such well-defined structures simply because they have relatively thin disks of H I with little differential rotation. Currently, about 12%–15% of the LMC is covered by these supergiant loops, and their ages are similar, about 15 Myr. Thus we can expect 50% of the H I in the disk to be processed through such a region in 10^8 yr. This time scale is consistent with the time scale for return of the ejected high-velocity H I; and the mass flux involved, 0.2–0.6 $M_\odot$ yr^{-1} for LMC 4 (perhaps ten times higher across the LMC), suggests that most of the H I in the disk is processed through high-velocity ejection in this time scale. Star formation is stochastically steady-state simply because it is governed by the cycle time of the gas into the halo and back into the disk, and the whole process is therefore a self-regulating feedback loop.

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