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A COMPLETE CO SURVEY OF THE LARGE MAGELLANIC CLOUD

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ABSTRACT

The central 6° × 6° of the LMC have been fully surveyed at an angular resolution of 8'.8 in the $J = 1 \rightarrow 0$ rotational transition of CO. At least 10% of the region studied exhibits CO line emission, with peak line temperatures of order 0.15 K. The emission is dominated by an extremely large complex of molecular clouds extending south from 30 Doradus for nearly 2400 pc. In the vicinity of 30 Dor itself there is an extended high-velocity CO component, presumably molecular material accelerated by stellar winds, supernovae, or both.

Positions, masses, other physical characteristics, and related objects at other wavelengths are given for the 40 molecular clouds identified. The general correspondence of these clouds to other Population I is extremely close. The clouds follow a relation between CO luminosity and linewidth similar to that of Galactic clouds, but, for a given line width appear ~6 times fainter, suggesting that CO luminosity scales roughly with metallicity or gas-to-dust ratio. The total mass of molecular clouds in the LMC is estimated to be $1.4 \times 10^8\ M_\odot$, implying a ratio of molecular to atomic mass over the survey region of ~30%.

Subject headings: galaxies: Magellanic Clouds — interstellar: molecules

To determine the distribution of molecular clouds in the LMC, we undertook a complete CO survey of its central 6° × 6° with the Columbia 1.2 m Millimeter-Wave Telescope after its installation at CTIO in Chile in 1982 December. CO and a few other molecules had previously been observed at several positions (Israel 1984; Israel *et al.* 1986), but none over an area comparable to that covered by the many regions of conspicuous star formation. Emission by the CO line we studied, the $J = 1 \rightarrow 0$ transition at 115 GHz, is much more extensive in the LMC than could be inferred from the previous observations, but it is generally so weak that it cannot be studied without sensitive instrumentation and long integrations. With a very stable and reliable cryogenic receiver and a typical integration time of nearly 1 hr, our survey required several years of observation with the 1.2 m telescope working about 6 hr per day.

At 115 GHz the beamwidth of the telescope is 8'.8, for a linear resolution at the LMC of 140 pc, and the velocity resolution and range of its 256 channel filter bank spectrometer are 1.3 km s^{-1} and 333 km s^{-1}, respectively. Position-switched spectra were obtained on a regular square grid every 7'.5 in right ascension and declination, each typically until the rms noise per channel was reduced to 0.06 K in radiation temperature (antenna temperature corrected for beam efficiency).

One of the most informative summaries of the survey, a map of W_{CO}, the velocity-integrated CO emission thought to trace the total molecular column density, is shown in Figure 1. To bring out the extensive weak emission, this map has been smoothed slightly, to a resolution of 12'. Nearly 10% of the 38 deg^2 of the LMC we surveyed exhibits emission at this resolution; there is probably more emission over a wider area beneath the lowest contour since much of that detected is near the limit of sensitivity, but probably little beyond the boundary of the survey (*dashed line*) since almost all the classical Population I objects of the LMC fall within.

Because it is so close, is viewed only 30° from face on, and consists of objects at about the same distance, the LMC is a superb exhibit on a galactic scale of the intimate relation of molecular clouds to star formation and all its immediate products. As Figure 1 shows, nearly all the known supernova remnants of the LMC—including supernova 1987A—and most of the H II regions detected as 6 cm continuum sources, lie toward a molecular cloud, or so close to one that an association can plausibly be inferred. There is also a striking large-scale correlation between CO and both the 21 cm (Rubio 1987) and *IRAS* 100 μm emissions. In either case the molecular clouds delineate the core of the distribution: averaged over a scale of several hundred parsecs, CO emission generally appears when the H I column density exceeds $\sim 2 \times 10^{21}$ cm^{-2} or the 100 μm flux exceeds ~50 MJy sr^{-1}.

Much of the CO emission from the LMC comes from a huge complex of moleclar clouds which extends south from 30 Dor and SN 1987A for nearly 2400 pc. There appears to be no counterpart in the outer Milky Way to this apparently isolated concentration of molecular gas. The 30 Dor complex is quite unlike the most conspicuous molecular object near the Galactic center, the nuclear disk: it is less massive and far less compact, and quite far from the kinematic center of the LMC, which, as Figure 1 shows, lies about 1500 pc to the NW in a region largely devoid of CO.

Although quasi-continuous at a resolution of 12', the 30 Dor complex evidently contains large component clouds that are at least partially resolved in position and velocity; with the aid of the unsmoothed data it has been possible to dissect it into five large, fairly well defined objects and five lesser ones. These and the 30 complexes into which CO emission elsewhere in the LMC can be broken down are cataloged in Table 1 with positions, other data, and objects at other wavelengths that may be associated. Although some of these complexes may consist of unrelated clouds along the line of sight, because of the thin disk structure of the LMC and the large separation between clouds such accidental blends should be rare. The line widths of the clouds are comparable to those of Galactic clouds and generally about 4 times larger than what would be produced by the gradient in the galactic rotation.

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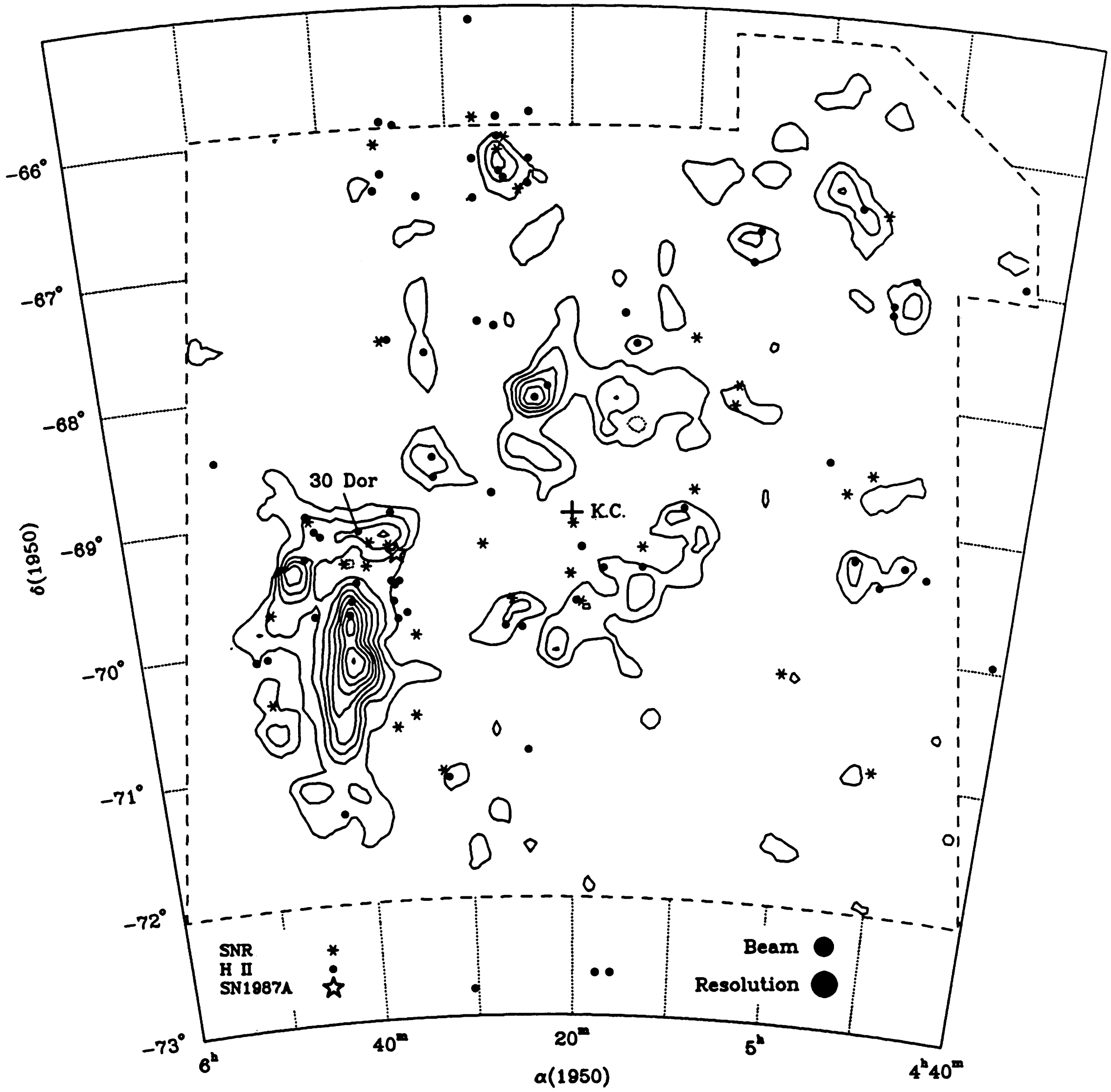

FIG. 1.—Map of velocity-integrated CO intensity in the LMC. The window of velocity integration is 30 km s^{-1} wide, centered at each position on the velocity of the strongest 21 cm component from Rohlfs *et al.* (1984), except toward three clouds in the 30 Dor complex (32, 33, and 35 in Table 1), where the window was widened by 10–20 km s^{-1} to include all emission. The map has been smoothed slightly, to an angular resolution of 12′. The contour interval is 0.38 K km s^{-1}, which is about the 1.6 σ noise level. SNRs (Mathewson *et al.* 1985 and references therein), supernova 1987A, and H II regions (6 cm continuum sources not identified as SNRs; McGee, Brooks, and Batchelor 1972) are shown for comparison. K. C. marks the kinematic center of the LMC (de Vaucouleurs and Freeman 1973).

Following the procedure widely adopted for the Milky Way and other external galaxies, molecular cloud masses were estimated by assuming that W_{CO} is proportional to the molecular column density N_{H_2} (Bloemen *et al.* 1986). However, because of the lower metallicity in the LMC (Dufour 1984), we have not adopted the Galactic value X_G for the ratio N_{H_2}/W_{CO}. Data on star counts and gamma-ray emission, used in the Galaxy to derive X, are not available for the LMC, and calibration using virial masses requires both the measurement of cloud radii that are often near the limit of our resolution and the uncertain assumption of virial equilibrium. We have therefore determined only the ratio X_{LMC}/X_G, adjusting it so that the mass–line width relation of LMC clouds agrees with that of Galactic clouds. As Figure 2 shows, the relation between absolute CO luminosity L_{CO} and line width Δv of LMC clouds is similar to that of Galactic clouds, except that the LMC clouds are $\sim$6 times fainter in CO. We therefore adopt $X_{LMC} = 6X_G$, or, with $X_G = 2.8 \times 10^{20}$ cm^{-2} K^{-1} km^{-1} s (Bloemen *et al.* 1986), $X_{LMC} = 1.7 \times 10^{21}$ cm^{-2} K^{-1} km^{-1} s.

A value of X_{LMC} at least this large seems required to explain why the molecular clouds in the LMC are visible as dark nebulae at all. Most of the dark nebulae cataloged by Hodge (1972) can be associated with molecular clouds in either the 30 Dor complex or the ridge running along the optical bar. Taking a gas-to-dust ratio in the LMC 4 times the Galactic value (Koornneef 1982), and $A_v = 3.1E_{B-V}$ (Koornneef 1982), and assuming complete conversion of H to H_2 in the molecular clouds, yields $N_{H_2} = 3.7 \times 10^{21}$ cm^{-2} A_v. Since these clouds typically have $W_{CO} \approx 1$ K km s^{-1} and must have $A_v \geq 0.5$ to be visible as dark nebulae, $X_{LMC} > 1.9 \times 10^{21}$ cm^{-2} K^{-1} km^{-1} s $= 6.7X_G$.

Cloud masses calculated with this calibration, as Table 1

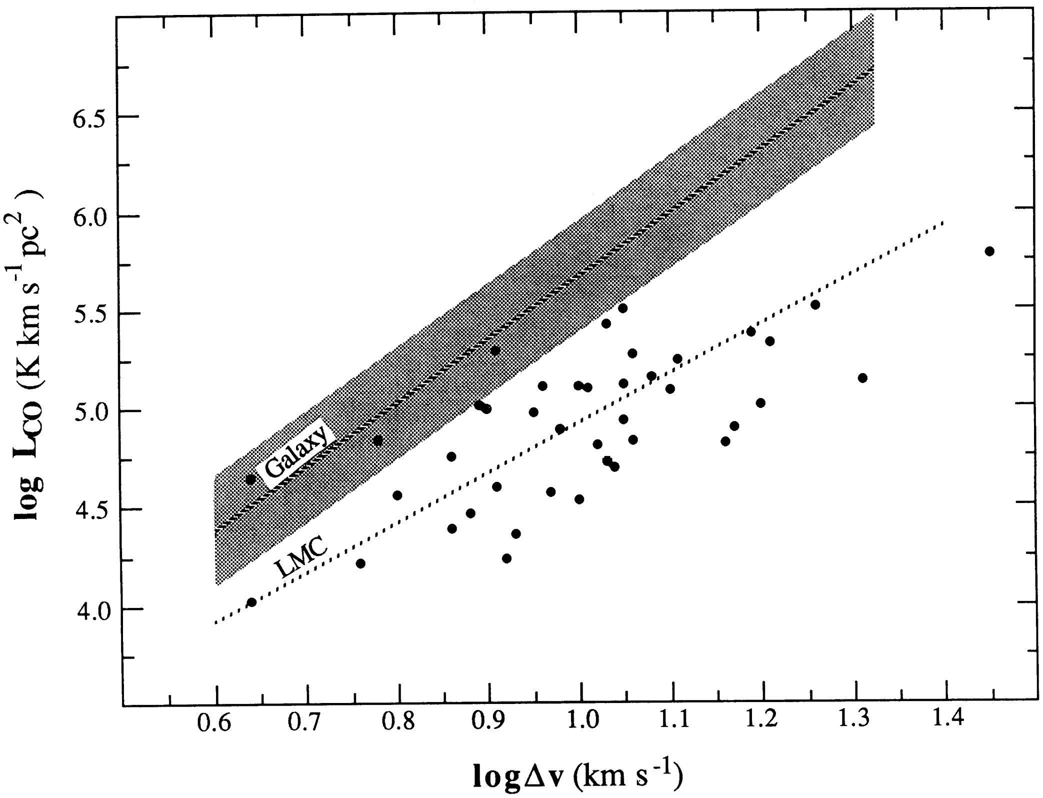

FIG. 2.—CO intensity integrated over velocity and projected area, L_{CO}, vs. FWHM average line width, Δv, for molecular clouds in the LMC (Table 1). L_{CO} is directly proportional to cloud mass. The line labeled LMC, $\log L_{CO} = 2.43 + 2.49 \log \Delta v$, is a least-squares fit to the LMC clouds (*plotted points*). The line labeled Galaxy, $\log L_{CO} = 2.47 + 3.19 \log \Delta v$, is a fit to the 34 large Galactic molecular clouds analyzed by Dame *et al.* (1986), with a calibration correction of 1.29 applied (see Bronfman *et al.* 1988). The Galactic clouds are not plotted, but the shading indicates their $\pm 1\ \sigma$ spread about the linear fit.

shows, are satisfactory: they generally agree with the virial masses to a factor of about 2, but on average are slightly smaller, as they should if the clouds as a result of star formation are only partially bound. The largest molecular clouds in the LMC have masses in the vicinity of $10 \times 10^6\ M_\odot$, and thus are comparable to the largest clouds in the Milky Way. The mass of the 30 Dor complex is about $60 \times 10^6\ M_\odot$, which is comparable to the mass of a 3 kpc segment of the Scutum Arm of the Milky Way. The total molecular cloud mass of the LMC is $1.4 \times 10^8\ M_\odot$, or about 20% of the mass of all the H I (plus associated He) in the LMC (McGee and Milton 1966); since the H I is more widely distributed than the CO, the mass fraction in the inner 3 kpc where the molecular clouds are found may be 30% or greater.

According to Dufour (1984) the abundances of C and O relative to H in the LMC are, respectively, 3.6 and 1.9 times lower than in Galactic H II regions, and according to Koornneef (1982) the gas-to-dust ratio is 4 times lower; it therefore appears from our mass calibration that X scales inversely with metallicity or gas-to-dust ratio, or perhaps somewhat more steeply. If such a scaling applies generally to other metal-poor galaxies, it readily explains why searches for CO in the SMC and other dwarf galaxies have either failed or yielded very faint lines.

One of the most remarkable molecular objects in the LMC is an apparent shell of molecular gas expanding from the 30 Dor region. The molecular cloud toward this region (cloud 32 in Table 1) is well separated in velocity from the other large clouds of the 30 Dor complex and appears as a clumpy ring about 500 pc in diameter. Cloud 32a lies toward the center of the ring, with a velocity nearly 20 km s^{-1} higher than cloud 32 (and some 40–50 km s^{-1} higher than the bulk of the 30 Dor complex). The mass of this high-velocity component is surprisingly large, $3.8 \times 10^6\ M_\odot$, and assuming that clouds 32 and 32a form a shell expanding at ~ 17 km s^{-1}, the kinetic energy of expansion is of order 3×10^{52} ergs. This gas is presumably a remnant of the molecular material from which 30 Dor formed, accelerated by stellar winds from the many young stars or by supernova explosions, or both. There is evidence in the Galaxy for substantial molecular clouds which have been accelerated in this way (e.g., Nyman *et al.* 1987), but nothing on so large a scale.

A large burst of star formation similar to that associated with the 30 Dor complex may have occurred previously in the LMC in the region toward 5^h35^m, $-66°$ in the upper left of Figure 1 (Shapley's Constellation III). The unusually poor correlation of H II regions, SNRs, and other Population I with molecular clouds in this region suggests that clouds once existed there but have already been largely dispersed. The region lies toward a large H I hole ~ 800 pc in diameter (Goudis and Meaburn 1978) which is associated with a perturbation in the 21 cm velocity field of order 15 km s^{-1} (Rohlfs *et al.* 1984); the kinetic energy of expansion is $\sim 7 \times 10^{51}$ ergs, comparable to that of the high-velocity gas associated with 30 Dor, and the characteristic time scale of expansion is ~ 26 million years. It is plausible therefore that Constellation III and its environs are a snapshot of what the 30 Doradus complex will become in a few 10^7 yr, and that star formation in

TABLE 1

MOLECULAR CLOUDS OF THE LARGE MAGELLANIC CLOUD

No.	α(1950)[a]	δ(1950)[a]	T^b_{max} (K)	V^c_{LSR} (km s^{-1})	Δv[c] (km s^{-1})	S/N[d]	R^e (pc)	M^f_{co} ($10^6 M_\odot$)	M^g_{vir} ($10^6 M_\odot$)	Associated Objects[h]
1	4ʰ43ᵐ8	−66°45′0	0.13	283 ± 22	8	2.9	96	0.5	1.4	MC7
2	4 51.8	−68 41.6	0.18	248 ± 11	15	5.3	166	2.4	7.8	S453–68.5,S455–68.7
3	4 52.2	−69 20.0	0.20	246 ± 6	9	6.3	204	3.8	3.6	MC16, N83B
4	4 52.4	−67 11.2	0.14	276 ± 7	10	4.1	191	2.3	3.7	MC14,MC15
5	4 54.7	−65 43.3	0.13	277 ± 11	8	3.8	117	1.2	1.6	
6	4 57.6	−66 27.0	0.18	278 ± 2	8	7.5	287	5.7	4.1	MC18,S454–66.5
7	5 03.5	−65 58.6	0.15	277 ± 11	8	3.1	96	0.9	1.1	
8	5 04.4	−66 19.4	0.10	275 ± 12	7	3.0	96	0.7	1.1	
9	5 04.8	−68 04.7	0.10	280 ± 9	11	4.0	166	1.5	4.1	S505–67.9,S506–68.0
10	5 05.3	−66 47.1	0.15	280 ± 4	8	5.2	191	3.1	2.4	MC20,MC21,N20
11	5 08.4	−69 13.4	0.16	241 ± 7	6	4.5	180	2.0	1.4	H3
12	5 09.1	−66 19.4	0.11	277 ± 9	12	4.1	180	2.0	5.0	
13	5 11.0	−68 59.5	0.14	246 ± 12	15	4.6	135	2.0	6.1	MC23(M),N105A
14	5 12.3	−66 57.5	0.14	282 ± 16	9	4.0	96	0.7	1.5	N29
15	5 13.6	−69 35.5	0.21	234 ± 5	13	6.8	225	5.1	7.8	MC24,N113C,H8
16	5 13.9	−68 07.0	0.24	280 ± 2	11	10.7	346	9.4	9.1	N32
17	5 20.3	−69 44.0	0.15	241 ± 7	11	4.7	180	2.5	4.7	MC31,S519–69.7
18	5 20.8	−70 03.3	0.26	240 ± 12	16	5.1	180	3.0	9.3	H19
19	5 22.4	−67 56.3	0.29	282 ± 4	18	8.9	279	9.6	19.4	MC33,N44D,MC32
20	5 23.0	−68 31.9	0.21	260 ± 7	9	4.9	214	2.8	3.5	
21	5 23.0	−66 48.9	0.13	297 ± 7	6	2.6	135	1.1	1.1	
22	5 25.6	−69 50.0	0.16	266 ± 9	7	3.4	166	1.7	1.8	MC45,S525–69.6
23	5 26.0	−66 17.3	0.19	288 ± 9	20	4.6	214	4.0	18.7	MC41,S525–66.1
24	5 27.4	−71 25.1	0.33	226 ± 3	4	6.0	117	1.3	0.5	N205A
25	5 29.6	−71 42.1	0.13	223 ± 12	6	3.2	96	0.5	0.7	N205B
26	5 31.8	−71 07.1	0.15	227 ± 11	9	3.9	117	1.1	2.2	MC54,S532–71.0
27	5 32.0	−68 35.9	0.21	258 ± 4	10	6.7	204	3.7	4.5	MC56,N148C,H38
28	5 32.4	−66 45.0	0.13	280 ± 14	10	3.7	117	1.0	2.5	
29	5 32.5	−67 47.7	0.14	285 ± 8	10	4.8	166	1.9	3.8	MC57,N57
30	5 32.9	−67 18.3	0.14	294 ± 20	11	3.8	152	1.6	3.6	N58
31	5 37.5	−66 22.5	0.14	283 ± 14	4	2.9	68	0.3	0.3	MC66
				30 Doradus Complex:						
32	5 38.2	−69 9.1	0.21	261 ± 4	11	6.7	253	5.6	7.0	SN1987a,30Dor(M),H44
32a	5 39.1	−69 10.4	0.16	278 ± 10	10	5.9	214	3.8	4.5	S536–69.2, S538–69.1
33	5 40.4	−69 46.6	0.52	237 ± 2	11	11.4	253	7.7	6.1	MC77(M),MC72(M),H54
34	5 40.5	−71 17.4	0.14	223 ± 5	12	6.9	214	4.2	6.5	MC80,N214C
35	5 40.5	−70 12.4	0.32	231 ± 3	28	14.8	339	17.9	55.4	H53
36	5 41.6	−70 39.8	0.32	229 ± 4	16	10.0	214	6.9	10.8	N218
37	5 44.7	−69 25.1	0.38	232 ± 4	16	7.4	234	6.3	13.2	MC86,H65,H67
38	5 45.4	−71 15.8	0.16	221 ± 4	11	5.1	214	3.9	5.5	
39	5 47.7	−69 52.4	0.20	227 ± 5	13	6.1	214	3.6	7.1	S547–69.7,MC90,H68
40	5 47.9	−70 34.7	0.24	219 ± 4	8	6.2	191	2.9	2.6	S548–70.4

NOTES.—(a) Emission weighted mean position; (b) at a velocity resolution of 2 km s^{-1}; (c) from a Gaussian fit to the cloud's composite spectrum; Δv is FWHM; (d) signal-to-noise: total CO emission of cloud summed over velocity and solid angle, relative to the 1 σ noise; (e) $(A/\pi)^{1/2}$, where A is the area within the lowest contour in Fig. 1; (f) cloud mass determined from CO, using $N_{H_2}/W_{CO} = 1.68 \times 10^{21}$ cm^{-2} K^{-1} km^{-1} s and a correction of 1.4 for He; (g) mass of a uniform, spherical cloud in virial equilibrium: $M_{vir} = 5R\Delta v^2/(8 G \ln 2)$; (h) MC—6 cm sources from McGee *et al.* 1972; N—emission nebulae from Henize 1956; (M)—masers from Whiteoak *et al.* 1983 and references therein; H—dark nebulae from Hodge 1972; S—supernova remnants from Mathewson *et al.* 1985 and references therein.

the LMC may be highly variable, punctuated on a time scale of $\sim 10^7$ yr by such episodes.

An analysis of the kinematics of the LMC based on the data in Table 1 will be presented elsewhere.

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