# THE RADIO CONTINUUM OF THE LARGE MAGELLANIC CLOUD

## IV.* SPECTRA OF SOURCES

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*Abstract*

The continuum radio sources in the direction of the Large Magellanic Cloud are classified in terms of their spectral indices. Of 52 sources for which spectral data were available three distinct classes exist: (1) sources with spectral indices $\geqslant -0 \cdot 20$, of which 21 out of 23 have been identified with HII regions in the Henize catalogue; (2) sources with spectral indices $< -0 \cdot 20$ that have been identified with Henize objects, of which it is possible that many are supernova remnants; and (3) sources with spectral indices $< -0 \cdot 20$ that have not been identified with optical objects and are considered to be outside the LMC. Six "double sources" with one member belonging to class (1) and the other to class (2) were found. The background continuum radiation is also discussed.

## I. Introduction

Although contour maps have been published of the radio emission from the Large Magellanic Cloud (LMC) at a number of wavelengths down to 21 cm, no serious attempt has been made to delineate and classify the individual sources of emission. In these earlier surveys the low resolving power of the observing instruments and the presence of a considerable nonthermal background made the task difficult. However, the measurements at shorter wavelengths discussed in Parts I (McGee, Brooks, and Batchelor 1972*a*, present issue pp. 581–97) and III (McGee, Brooks, and Batchelor 1972*b*, present issue pp. 613–17) afford much better angular resolution and provide source catalogues with fairly accurate flux densities and angular sizes.

In this paper the sources of the LMC are classified on the basis of estimates of their spectral indices over as large a range as practicable. The sources with well-determined spectra fall into three classes: sources with spectral indices $\geqslant -0 \cdot 20$, most of which are identified with HII regions from the Henize (1956) catalogue; sources with spectral indices $< -0 \cdot 20$ and which have been identified with entries in the Henize catalogue; and finally other sources with spectral indices $< -0 \cdot 20$, which are likely to be external to the LMC.

## II. Disposition and Identification of Sources

Three diagrams (Figs. 1–3) are introduced here to assist in showing the disposition of sources in the LMC. Contours of 6 cm wavelength emission from all the sources catalogued in Part I (except MC 1, 3, 4, and 9) are displayed on a composite diagram in Figure 1. Figure 2 reproduces part of this diagram superimposed on a

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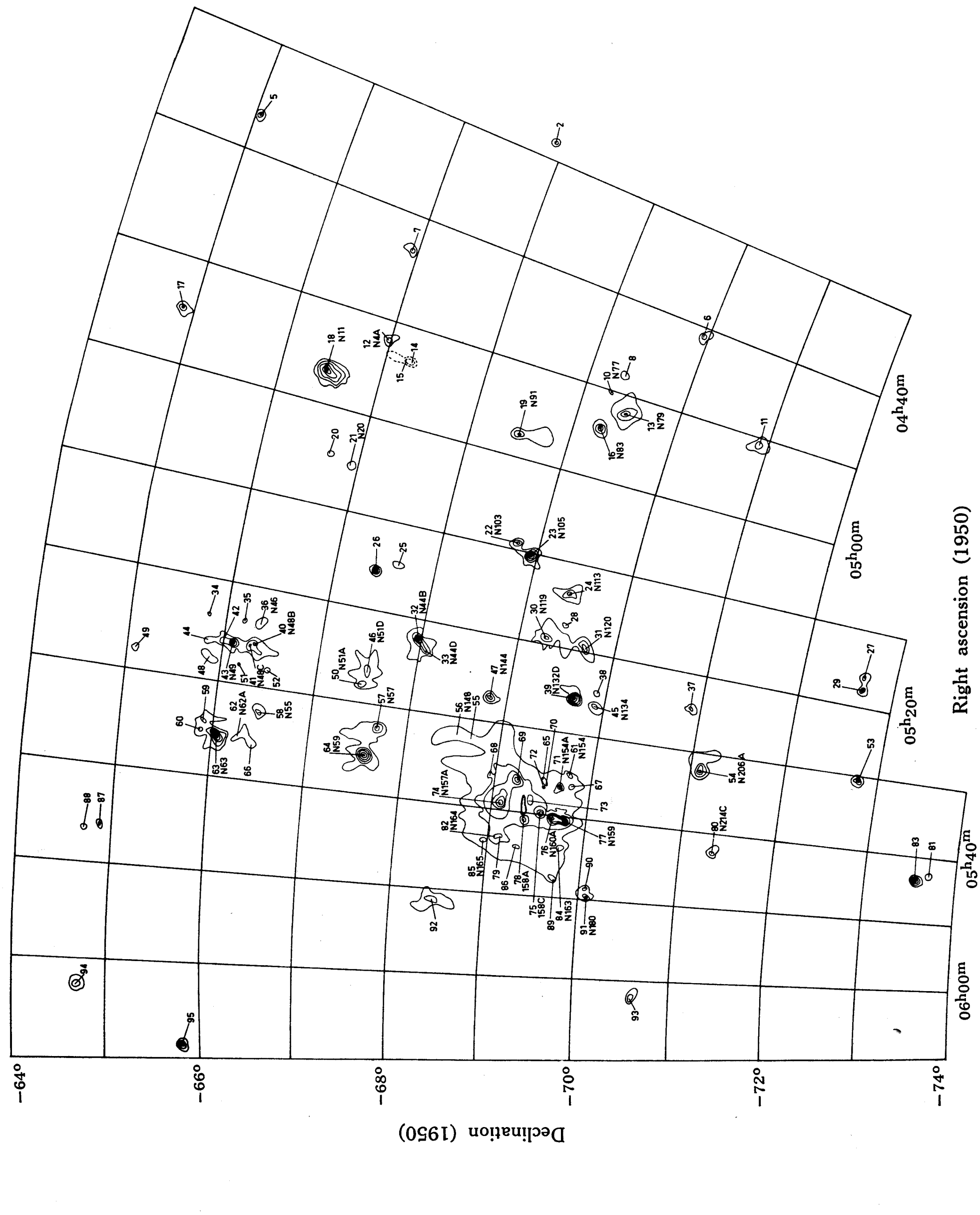



Fig. 1.—Composite map of the continuum sources of the LMC at 6 cm wavelength, sketched from the diagrams of Part I. The contour interval is 0·1 K in brightness temperature. The 6 cm and Henize catalogue numbers are indicated for each source.

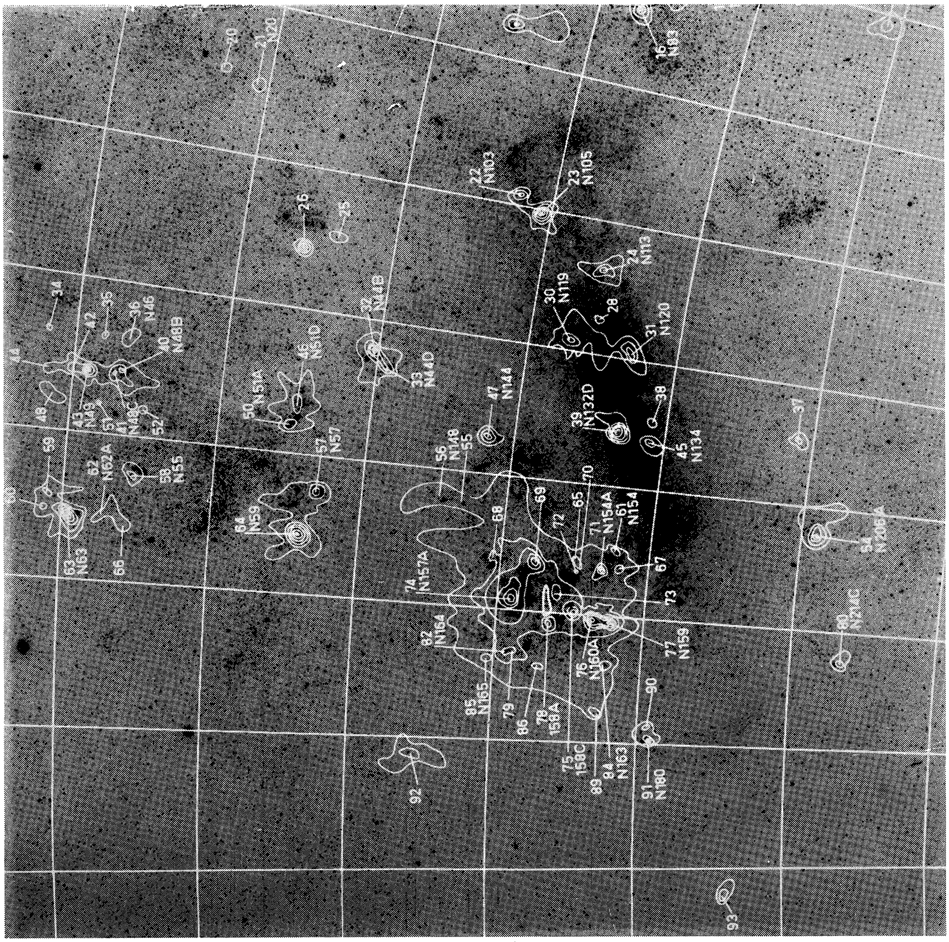



Fig. 2.—Superimposition of part of the 6 cm contours of Figure 1 on a Mount Stromlo photograph of the LMC.

Mount Stromlo photograph in yellow light. The catalogue numbers are given alongside each source and, where there is agreement in position with a gaseous nebula of the Henize (1956) catalogue, this number is included as well. The latter is the most extensive catalogue of optical objects with which radio sources are likely to be

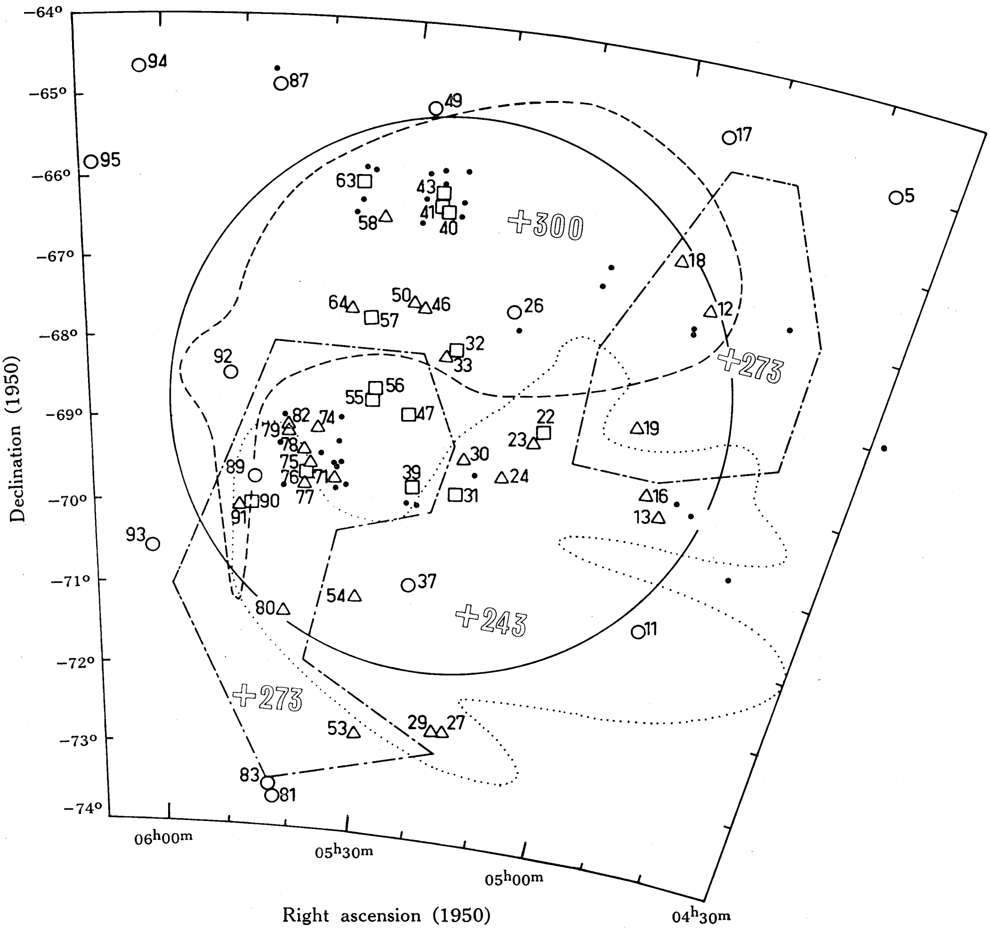



Fig. 3.—Schematic diagram of the LMC showing the 6 cm source positions superimposed on the HI spiral arms:

△, thermal sources in LMC; □, nonthermal sources in LMC;
○, nonthermal sources possibly extra-LMC; •, sources not discussed here.

The +300 km s$^{-1}$ spiral arm is indicated by the dashed outline, the +243 km s$^{-1}$ arm by the dotted outline, and the two +273 km s$^{-1}$ arms by the dash–dot outlines. The large circle divides the region for statistical purposes.

associated in the LMC. It is compiled from photographs in H$\alpha$ light, and lists the positions, sizes, and intensities of more than 200 emission regions. Allowing for discrepancies between the radio and optical positions of up to 3′ arc, 45 identifications with nebulosities in the Henize catalogue are suggested. The estimated uncertainty in the radio positions caused by pointing errors of the telescope is $0'\cdot 7$ arc, while the probable errors in the Henize positions are $0'\cdot 3$ arc in each coordinate. Thus the average positional difference of $1'\cdot 3$ arc for "agreement" seems reasonable. In addition, for the well-established identification of source MC 43 with Henize N49 (Westerlund and Mathewson 1966) the difference is $1'\cdot 2$ arc. The individual identifications, which are listed in Tables 1(*a*) and 1(*b*), are discussed in Sections V and VII.

Figure 3 is entirely schematic, showing firstly the spiral arms as revealed from the radial velocity distributions of neutral hydrogen, ionized hydrogen, and supergiant O–B stars (McGee and Milton 1966). The two main arms whose average radial velocities with respect to the Sun were +300 and +243 km $s^{-1}$ are shown by the dashed and dotted outlines respectively. A secondary system of spiral arms represented by the dash–dot outlines had an average radial velocity of +273 km $s^{-1}$. For convenience we shall refer to the spiral arms as either "the +300", "the +243", or "the +273". The sources, whose spectra are discussed below, are indicated in Figure 3 as belonging to one of three separate classes.

It can be seen from Figure 1 that, with the beam size of 4′ arc (equivalent to 64 pc at the 55 kpc distance of the LMC), the radio emission is resolved into either individual sources or isolated small groups of sources. This contrasts markedly with the 21 cm (14′ arc beam) picture of Mathewson and Healey (1964) and to some extent with the 11 cm ($7'\cdot 4$ arc beam) maps in Part II (Broten 1972, present issue pp. 599–612). The background radiation which was so prominent in the 21 cm survey has largely disappeared at 6 cm wavelength, although it was detected near some of the small source groups, e.g. in the intense and rather closely spaced collection of sources near 30 Doradus (MC 74) the background rises to $0\cdot 2$ K. This 30 Doradus region, of approximate dimensions 1° in right ascension and $1^\circ\cdot 5$ in declination, contains some 20 sources, of which MC 74, 76, and 77 are the most intense in the catalogue. A second group of continuum sources includes MC 80, 54, 31, 24, 23, and 22 stretching in a north-west direction from R.A. $05^h 42^m$, Dec. $-71^\circ 21'$ and also, about 1 kpc further west, MC 16 and 13. McGee and Milton (1966) showed that these objects have the same radial velocities as the surrounding neutral hydrogen, and that they belong to the +243 spiral arm and lie in front of the stellar bar (see Figs. 2 and 3).

Two interesting groups are arranged in convex arcs to the north and south of the stellar X-shaped region known as Shapley's Constellation III (Fig. 2). Included in the north arc are MC 63, 58, 40, 41, and 43 and in the south arc MC 64, 57, 50, 46, 32, and 33. McGee and Milton (1966) showed that these nebulae are associated with the +300 spiral arm. The absence of any radio emission in the vicinity of the dense distribution of stars in Constellation III parallels the deficiency of neutral hydrogen over the same area. Sources MC 18 and 12 are members of the +300 arm.

## III. Flux Densities used for Estimation of Spectral Indices

Estimates of spectral indices of the radio sources have been based on flux densities obtained from:

(1) the 95-source 6 cm catalogue of Part I;

(2) the 38-source 11 cm catalogue of Part III, together with supplementary information derived from the 11 cm contours of Part II;

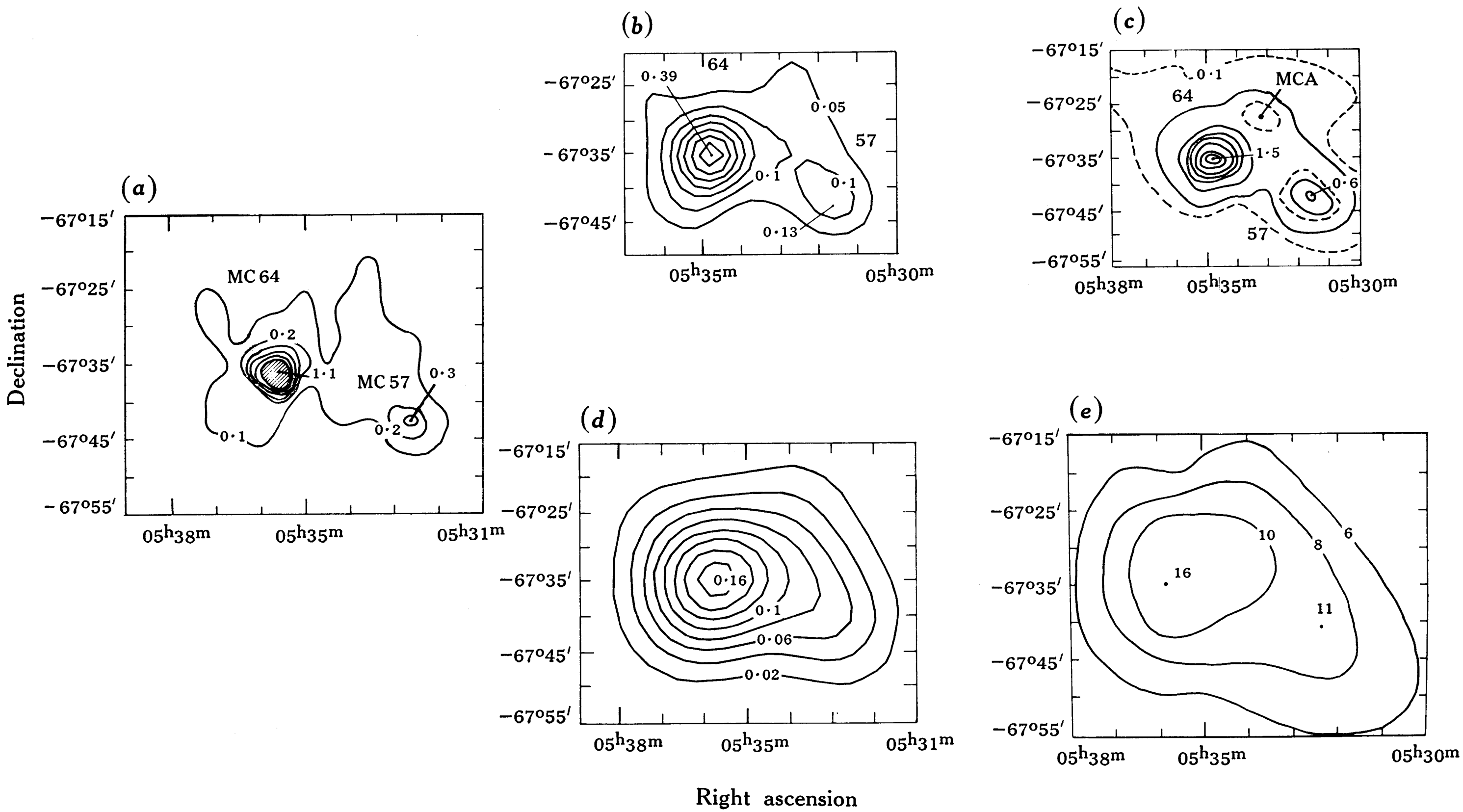



Fig. 4.—Example of the comparison of convolved 6 cm contours with observations made at 11 and 21 cm. Sources MC 57 and 64 are illustrated: (*a*) 6 cm contours, (*b*) 6 cm contours convolved with 7′·7 arc beam, (*c*) 11 cm map made with 7′·7 arc beam (Part III), (*d*) 6 cm contours convolved with 14′ arc beam, (*e*) 21 cm map made with 14′ arc beam (from Mathewson and Healey 1964).

(3) the 21 cm survey of Mathewson and Healey (1964), the delineation of 41 sources from the contour map and the estimates of flux densities having been made by the present authors; and

(4) information for 10 sources observed at 73 cm wavelength with resolution $2'\cdot 9 \times 3'\cdot 4$ arc (Le Marne 1968; Clarke 1971; Mills and Aller 1971).

From these data reasonable estimates of the spectral index in the decimetric wavelength range could be made for 61 sources.

The flux densities at 21 cm were all obtained from the map of Mathewson and Healey (1964) by integration of the appropriate brightness contours after removal of the background contributions. Only moderate accuracy can be placed on such determinations owing to the lack of knowledge of the extent and possible variations of the general nonthermal background component found by Mathewson and Healey. Despite these difficulties of separation and the comparatively large telescope beam (14′ arc) the positions of most sources at 21 and 6 cm agreed reasonably well. The mean difference of positions for 41 sources was $3'\cdot 0$ arc.

For the few well-isolated sources the spectral index was determined from the catalogued flux densities or those obtained from the brightness contours. In most cases, however, at the longer wavelengths some degree of confusion exists. We have attempted to unravel this by using the 6 cm positions and flux densities as a starting point and convolving the 6 and 11 cm source brightness contours with the largest aerial beam ($7'\cdot 7$ or 14′ arc) in use for the estimate of the spectral index. However, in six cases where two sources were close together the convolution produced contours in which the original positions were no longer obvious. The individual source contributions could then only be extracted from a knowledge of these positions and by taking cross sections through them. The situation is illustrated below in the example of sources MC 64 and 57.

The flux densities used here for source pairs are probably accurate to within $\pm 15\%$ for the stronger source and $\pm 25\%$ for the weaker. The original measured values of $S$ are found in Table 1 of Part I for 6 cm wavelength and Table 1 of Part III for 11 cm wavelength.

An example of the effects of convolution and comparisons with observations made at 11 and 21 cm are illustrated by the series of diagrams Figures 4(*a*)–4(*e*). The 6 cm map in Figure 4(*a*) shows a clear separation of sources MC 64 and 57 by the 4′ arc beam. This map convolved with the $7'\cdot 7$ arc beam is shown in Figure 4(*b*). It is seen to be in close agreement with an unpublished section of the 11 cm map (Part III) shown in Figure 4(*c*). Both sources are still well resolved and a protrusion in the convolved 6 cm contours corresponds to a third weak object, source MC A, in the 11 cm catalogue (Part III).

The corresponding effects of convolution with a 14′ arc beam and the comparison with the Mathewson and Healey (1964) contours at 21 cm are shown in Figures 4(*d*) and 4(*e*). The two sources are now merged into one extended source. Here separation into two 6 and 21 cm sources was effected by taking cross sections through the line-of-centres of the original 6 cm source positions and at right angles through these centres. The relative prominence of MC 57 in both the 11 and 21 cm maps compared with the convolved 6 cm maps illustrates the difference in spectral index between MC 64 ($+0\cdot 08$) and 57 ($-0\cdot 46$).

Flux density estimates at four wavelengths were available in 15% of cases, at three wavelengths in 43%, and at two wavelengths (mostly 21 and 6 cm) in 42%. Of the remainder of the 95 sources in the 6 cm catalogue, 11, although well isolated, are relatively weak at 6 cm and do not appear in the 11 and 21 cm maps. A further 23 weak 6 cm sources blend with nearby strong objects at the longer wavelengths.

## IV. Estimation of Spectral Indices

The spectral index $\alpha$ has been defined in accordance with the relation $S \propto \nu^{\alpha}$, where $\nu$ is the frequency (5009, 2700, 1410, and 408 MHz corresponding to 6, 11, 21, and 73 cm wavelengths). The values of flux densities at the various frequencies (given in Table 1) were plotted on coordinates of $\log S$, $\log \nu$ and straight lines were fitted to produce the best *estimates* of spectral index for 52 sources in the region of

Table 1

FLUX DENSITIES AND SPECTRAL INDEX OF SOURCES IN LMC

| (1) Source number | (2) Henize number | (3) $\Delta_{6-H}$* (′) | (4) $S_{73}$ (f.u.) | (5) $S_{21}$ (f.u.) | (6) $S_{11}$ (f.u.) | (7) $S_6$ (f.u.) | (8) $\alpha$ | (9) Spiral arm | (10) Notes† |
|---|---|---|---|---|---|---|---|---|---|
| | | | | *(a) Sources with $\alpha \geqslant -0\cdot20$* | | | | | |
| MC 12 | N4A | 0·8 | — | 0·24 | 0·24 | 0·26 | +0·04 | +300 | |
| MC 13 | N79A | 2·0 | — | 1·83 | 1·88 | 1·81 | −0·01 | +243 | 1 |
| MC 16 | N83B | 1·0 | — | 0·54 | 0·58 | 0·66 | +0·19 | +243 | |
| MC 18 | N11 | 2·6 | ~2 | 3·28 | (3·44) | 3·37 | +0·01 | +300 | 2 |
| MC 19 | N91 | 0·6 | — | 1·25 | (0·86) | 1·36 | +0·07 | +273 | 3 |
| MC 23 | N105A | 1·7 | — | (0·90) | 0·99 | 0·90 | +0·10 | +243 | 4 |
| MC 24 | N113C | 0·5 | — | — | 0·88 | 0·98 | +0·02 | +243 | |
| MC 29,27 | — | — | — | 0·72 | (0·38) | 0·69 | −0·03 | — | 5 |
| MC 30 | N119 | 2·6 | (1·22) | 1·43 | 1·25 | 1·01 | −0·04 | (+243) | 6 |
| MC 33 | N44D | 2·3 | — | 0·80 | 0·86 | 0·62 | −0·19 | +300 | |
| MC 46,50 | N51D,A | 0·5 | — | 2·51 | 2·00 | 1·93 | −0·13 | (+300) | |
| MC 53 | — | — | — | 0·48 | 0·46 | 0·54 | +0·07 | — | |
| MC 54 | N206A | 0·4 | — | 1·53 | 1·71 | 1·55 | +0·02 | +243 | |
| MC 58 | N55 | 1·4 | 0·61 | — | 0·40 | 0·48 | −0·10 | +300 | |
| MC 64 | N59A | 0·1 | 2·90 | 3·41 | 3·43 | 3·76 | +0·08 | (+300) | |
| MC 71 | N154A | 0·5 | — | 1·67 | (0·90) | 1·71 | +0·02 | +273 | 7 |
| MC 74 | N157A | 1·0 | 39·1 | 34·0 | 29·8 | 25·1 | −0·2 | +273 | 8 |
| MC 75 | N158C | 1·3 | — | — | 3·2 | 3·7 | +0·21 | (+243) | |
| MC 77 | N159A | 1·9 | — | — | (3·03) | 1·93 | (+0·1) | +243 | 9 |
| MC 78 | N158A | 2·5 | — | — | 0·54 | 0·51 | −0·05 | (+243) | |
| MC 80 | N214C | 1·4 | — | — | 0·28 | 0·37 | +0·06 | +243 | |
| MC 82,79 | N164 | 0·4 | — | — | 0·27 | 0·33 | +0·20 | (+273) | |
| MC 91 | N180A | 2·1 | 1·0 | (0·48) | 0·44 | 0·61 | −0·19 | (+243) | 10 |
| | | | | *(b) Sources with $\alpha < -0\cdot20$ and identified with Henize objects* | | | | | |
| MC 22 | N103A | 3·0 | — | (1·06) | 0·90 | 0·53 | −0·53 | (+243) | 11 |
| MC 31 | N120A | 1·0 | — | 2·75 | 2·30 | 1·47 | −0·54 | +243 | |
| MC 32 | N44A,B | 2·9 | — | 3·23 | 2·00 | 1·21 | −0·65 | +300 | |
| MC 39 | N132D | 0·9 | 8·7 | 4·8 | 2·80 | 2·20 | −0·57 | — | 12 |
| MC 40,41 | N48B | 1·1 | — | — | 2·14 | 1·28 | −0·75 | (+300) | 13 |
| MC 43 | N49 | 1·2 | 4·73 | 5·46 | 3·62 | 3·25 | −0·46 | — | 14 |
| MC 47 | N144A | 0·8 | — | 1·48 | 1·12 | 0·64 | −0·46 | (+273) | |
| MC 55 | N148I | 0·7 } | — | 0·71 | 0·64 | 0·27 } | −0·46 | — | |
| MC 56 | N148C | 1·6 } | | | | 0·14 } | | | |
| MC 57 | N57A | 0·4 | (1·90) | 1·56 | 1·07 | 0·81 | −0·46 | +300 | 15 |
| MC 63 | N63A | 1·8 | 3·2 | 2·61 | 1·64 | 1·15 | −0·42 | (+300) | 16 |
| MC 76 | N160A | 0·4 | — | — | 2·52 | 1·80 | −0·43 | +243 | |
| MC 90 | N180C | 2·2 | — | — | 0·31 | 0·26 | −0·28 | (+243) | |

TABLE 1 (*Continued*)

| Source number | $S_{21}$ (f.u.) | $S_{11}$ (f.u.) | $S_6$ (f.u.) | $\alpha$ | Source number | $S_{21}$ (f.u.) | $S_{11}$ (f.u.) | $S_6$ (f.u.) | $\alpha$ |
|---|---|---|---|---|---|---|---|---|---|
| (*c*) *Sources with* $\alpha < -0 \cdot 20$ *and possibly outside the LMC* | | | | | | | | | |
| MC 1 | 2·15 | — | 0·53 | −1·11 | MC 49 | 0·77 | — | 0·27 | −0·83 |
| MC 2 | 0·96 | — | 0·24 | −1·07 | MC 83,81 | 1·91 | 0·93 | 0·83 | −0·64 |
| MC 3,4 | 1·17 | — | 0·59 | −0·54 | MC 87 | 0·99 | — | 0·30 | −0·94 |
| MC 5 | 1·90 | — | 0·38 | −1·23 | MC 89 | 2·19 | 1·62 | 1·00 | −0·67 |
| MC 11 | 0·97 | — | 0·53 | −0·48 | MC 92 | 2·35 | — | 1·55 | −0·33 |
| MC 17 | 1·44 | — | 0·57 | −0·73 | MC 93 | 0·96 | 0·44 | 0·28 | −0·85 |
| MC 26 | 1·67 | 1·00 | 0·62 | −0·76 | MC 94 | 1·67 | — | 0·30 | −1·20 |
| MC 37 | 1·51 | 0·64 | 0·38 | −1·04 | MC 95 | 1·43 | — | 0·62 | −0·66 |

* $\Delta_{6-H}$ represents the difference between the position of the continuum maximum at 6 cm and the position of the nebula as given by Henize (1956).

† Notes on particular sources

1. MC 13. $S_6$ includes flux densities of MC 8 and 10 as these blend with MC 13 at longer wavelengths.
2. MC 18. $S_{11}$ is from Part II.
3. MC 19. $S_{11}$ is from Part II.
4. MC 23. $S_{21}$ is an estimate only.
5. MC 29,27. $S_{11}$ value is unexplained.
6. MC 30. $S_{73}$ is an estimate only.
7. MC 71. $S_6$ includes flux densities of MC 61, 65, 67, 70, and 72 as these blend with MC 71 at longer wavelengths; $S_{11}$ is from Part II.
8. MC 74. 30 Doradus.
9. MC 77. Flux density at 3·4 cm wavelength is 2·1 f.u.; $S_{11}$ is an estimate only.
10. MC 91. $S_{21}$ is an estimate only.
11. MC 22. $S_{21}$ is an estimate only.
12. MC 39. $S_6$ includes flux densities of MC 38 and 45 as these blend with MC 39 at longer wavelengths.
13. MC 40,41. $S_6$ includes the flux density of MC 52 as this blends with MC 40 and 41 at longer wavelengths.
14. MC 43. $S_6$ includes flux densities of MC 42, 44, 48, and 51 as these blend with MC 43 at longer wavelengths.
15. MC 57. $S_{73}$ is obtained after convolution.
16. MC 63. $S_6$ includes flux densities of MC 59 and 60 as these blend with MC 63 at longer wavelengths.

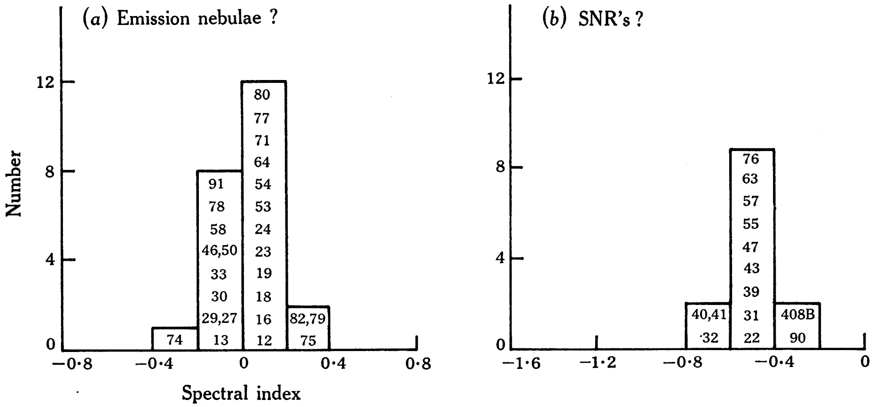
the LMC. The 73 cm flux densities, which were measured at a resolution better than 4′ arc, supplied additional estimates of $\alpha$ based on 6 and 73 cm information only. In 8 of the 10 cases the original estimates were confirmed in this way.

The flux densities and spectral indices are given in three sections in Table 1: Table 1(*a*) contains sources with $\alpha \geqslant -0 \cdot 20$, of which 21 of the 23 entries are identifiable with nebulae catalogued by Henize (1956) and are almost certainly HII regions; Table 1(*b*) contains all sources having $\alpha < -0 \cdot 20$ which were identified with Henize objects; and Table 1(*c*) contains the remaining sources with $\alpha < -0 \cdot 20$ which could not be identified with Henize objects and which are probably not in the LMC. Histograms showing the number of sources as a function of spectral index for each of the three types of sources are given in Figure 5. The catalogue numbers of the sources in each interval are shown.

In Tables 1(*a*) and 1(*b*) the radio and Henize catalogue numbers of the sources are listed in columns 1 and 2 respectively. The differences in minutes of arc between the positions of the continuum maxima at 6 cm wavelength and the positions given by Henize (1956) are listed in column 3; the mean difference is 1′·3 arc. Some sources are grouped in pairs because their proximity causes blending at longer wavelengths. Columns 4, 5, 6, and 7 contain the flux densities in flux units* at 73, 21, 11, and 6 cm wavelengths respectively. Column 8 gives the spectral index.

* 1 flux unit (f.u.) = $10^{-26}$ W m$^{-2}$ Hz$^{-1}$.

All the identified sources can be assigned to spiral arms using the data from McGee and Milton (1966). Column 9 indicates whether the source is a member of the +243, +273, or +300 spiral arms. Parentheses are used when the association is inferred only from the position of the source with respect to a corresponding neutral hydrogen cloud rather than from an optical measurement of its radial velocity. The numbers in column 10 identify comments on the flux densities used for obtaining the spectral indices.



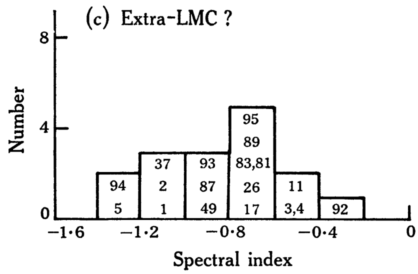




Fig. 5.—Histograms of the three types of sources in the LMC region showing numbers in 0·2 intervals of spectral index. The catalogue numbers of the sources are superimposed.

Table 1(*c*) for "other sources" gives the radio catalogue number, the flux densities at 21, 11, and 6 cm, and the spectral index.

## V. Radio Sources Identified with Optical Objects in LMC

### (*a*) *Sources with* $\alpha \geqslant -0 \cdot 20$

The average size of the 22 Henize nebulae with which the radio sources of Table 1(*a*) have been identified is $4' \cdot 5 \times 4' \cdot 7$ arc while the average radio size is $3' \cdot 4 \times 3' \cdot 5$ arc. It is assumed that these sources are thermal. Their number is considerably less than half of that for which radio spectra are available. In contrast Mathewson and Healey (1964) state "nearly all sources [in the LMC] are of thermal origin". Although sources such as MC 33 (N44D), 74 (30 Doradus), and 91 (N180A) have $\alpha \sim -0 \cdot 2$, they have been included in the "thermal" list because it is considered that they have at least some strong thermal components. This class is shown by the open triangles in Figure 3.

### (*b*) *Sources with* $\alpha < -0 \cdot 20$

Table 1(*b*) contains 13 sources which have been identified with Henize nebulae in the LMC but which have spectral indices less than $-0 \cdot 20$. They are shown in Figure 3 by the open squares. Prominent members of this group are MC 39 (132D), 43 (49), and 63 (63A), the three supernova remnants (SNR's) discussed by Westerlund and Mathewson (1966). We find, as Clarke (1971) did from high resolution measurements at 73 cm, that the spectral indices of MC 39 and 63 compare well with the values given by Westerlund and Mathewson but that $\alpha$ for MC 43 is $-0 \cdot 46$ compared with the previous value of $-1 \cdot 0$.

The spectral indices in Table 1(*b*) range from $-0 \cdot 28$ to $-0 \cdot 75$ with a mean value of $-0 \cdot 50$. The facts that galactic SNR's were found by Milne (1970) to have spectral indices grouped around $-0 \cdot 48$ and that the above three sources are typical of those listed in Table 1(*b*) point to the possibility of some of the others being SNR's.

In contrast to the relatively large optical size of the HII regions in Table 1(*a*) the average size of the Henize objects in Table 1(*b*) is quite small: $1' \cdot 1 \times 1' \cdot 4$ arc. However, the average radio size is effectively the same as for the thermal sources: $3' \cdot 1 \times 3' \cdot 5$ arc.

### (*c*) *Source Pairs in LMC*

An important feature of six of the apparently nonthermal sources is their association with a "companion" thermal source. The pairs, which can be seen in Figure 1, are: MC 22 and 23, 31 and 30, 32 and 33, 57 and 64, 76 and 77, and 90 and 91, where in each case the first-named is the nonthermal component. These pairs are considered briefly below.

*MC 22 and 23* (*N103A and 105A*). These sources have spectral indices (based on 6 and 11 cm flux densities only) of $-0 \cdot 53$ and $+0 \cdot 10$ respectively. Henize (1956) writes of N103: "The compact cluster is brighter than the nebulosity but wisps of $H\alpha$ emission are unmistakably visible along the southern edge of the cluster". Some evidence supporting the different natures of the two sources is found in the 21 cm survey by Mathewson and Healey (1964). The contours are concentrated on the position of MC 22, while MC 23 can scarcely be recognized as a feature.

*MC 31 and 30* (*N120A and 119*). These sources are the furthest apart in space of the six pairs but are linked by a low level ($0 \cdot 1$ K) contour on the 6 cm map.

*MC 32 and 33* (*N44B and 44D*). This pair of sources is perhaps the most interesting combination. The constellation is very well known as one in which considerable stellar evolution is occurring (Bok 1969). The positions of star formation given by Bok are close to the maximum intensity point of MC 33. We had expected this source to be thermal and considered the possibility that the original 6 cm observations (Part I) might have underestimated its flux density. Recently (June 1971) further measurements were made with a more sensitive 6 cm cryogenic receiver and the values of flux density were confirmed. At 11 cm there is close agreement between the measurements given in Parts II and III. It was difficult to decide on the most likely background contributions from the 21 cm contours of Mathewson and Healey (1964). Cross sections in various directions have been used to separate MC 32 and 33 at the two longer wavelengths. It is possible that the spectrum of MC 32 is influenced by a relatively compact but dominating nonthermal source and that the contributions from the other optically identified members of the group N44C, 44D, and 44F are thermal.

Examination of the H$\beta$ isophotes and photographs of the N44 region (Dickel 1965) indicate the possibility of a partial ring of nebulosity such as is seen in SNR's.

*MC 57 and 64* (*N57A and 59A*). Source MC 57 has small dimensions in H$\alpha$ ($0'\cdot 9\times 0'\cdot 7$ arc) but fairly wide 6 cm continuum dimensions ($6'\cdot 8\times 4'\cdot 6$ arc). Its thermal companion MC 64 has three to four times the dimensions in H$\alpha$ but is comparatively compact ($1'\cdot 8\times 2'\cdot 1$ arc) in the 6 cm continuum. The 11 cm map in Figure 4(*c*) indicates that a third source, MC A of Part III, is included in this group. It does not appear as a separate entity at 6 cm and we infer that it must have a nonthermal spectrum. The shape of the 6 cm contours of source MC 64 shows that at least one more unresolved component seems to be present.

*MC 76 and 77* (*N160A and 159A*). These sources are easily resolved with the $4'$ arc beam at 6 cm but are blended with the $7'\cdot 7$ arc beam at 11 cm and also at longer wavelengths. The flux densities at 11 and 21 cm have been obtained by fitting Gaussian curves to cross sections taken in four or five directions through each source.

If the sources are taken together and convolved from the 6 cm resolution to the equivalent resolutions at 11 and 21 cm, the deduced spectral index is negative ($\sim -0\cdot 6$). These two sources (with MC 39) are the brightest in the LMC after 30 Doradus. Observations of recombination lines at 6 and $3\cdot 4$ cm and of the continuum at $3\cdot 4$ cm are being undertaken to try and clarify the situation in this important region.

*MC 90 and 91* (*N180C and 180A*). These sources form a close pair so that it is difficult to obtain reliable longer wavelength information at the angular resolutions available at present.

### (*d*) *Summary of Identified Sources*

The main features emerging from the discussions on the identified sources may be summarized as follows.

(1) The sources with spectral indices $\geqslant -0\cdot 20$ (thermal sources) are 23 in number, which is only 38% of the total in the LMC region.

(2) The identified sources with spectral indices $< -0\cdot 20$ are apparently associated with prominent members of the Henize (1956) catalogue of HII regions.

(3) The average size of the optical objects in (2) appears to be four times less than those in (1).

(4) All the spectral indices in (2) fall close to the average $\alpha = -0\cdot 48$ for galactic SNR's.

(5) Six of the nonthermal sources in (2) have companion sources which are thermal.

## VI. Unidentified Sources

The 16 sources listed in Table 1(*c*) have spectral indices $\leqslant -0\cdot 33$ and, as is evident from Figure 5(*c*), their mean spectral index is $\sim -0\cdot 8$. They are shown by the large open circles in Figure 3. With the sources MC 29, 27 and 53 (with spectral indices $\sim 0$) from Table 1(*a*) they are the unidentified sources in the region.

The expectation of the number of extragalactic (and in the present case "extra-Magellanic") sources with $S_6 \geqslant 0\cdot 24$ f.u. in the area extending from R.A. $04^{\mathrm{h}}\,30^{\mathrm{m}}$ to

$06^h 10^m$ and from Dec. $-64°$ to $-74°$ (approximately 100 sq deg) has been estimated by J. G. Bolton and A. J. Shimmins (personal communication) to be 16. Figure 3 shows that there are 50 sources in this area with $S_6 \geqslant 0 \cdot 24$ f.u. (the lowest value considered in Table 1) and an additional 12 in this category for which spectra have not been discussed (see Fig. 1). Most of these sources fall within a circle of 30 sq deg centred on the LMC. This is consistent with the identifications with LMC optical objects discussed in the previous section.

In the area outside the circle in Figure 3 the expectation of the number of extragalactic sources with $S_6 \geqslant 0 \cdot 24$ f.u. is 12. The number found is 15, which is within the errors ($\pm 4$) placed on this expectation by Bolton and Shimmins. (Source MC 2, although it lies just outside the boundary of Figure 3, has been included, while sources MC 1, 3, and 4 have been omitted from these determinations.) Therefore it is possible that a large proportion of the 20 unidentified sources are outside the LMC.

## VII. Notes on Selected Sources and Continuum Features

### (*a*) *Some Sources in Tables 1*(*a*) *and 1*(*b*)

*MC 29, 27* (*unidentified*). The spectral index for this pair of sources is $-0 \cdot 03$. The Henize catalogue contains no nebulae in the region. Although the source positions are close to a prominent spur of neutral hydrogen in the $+243$ arm (McGee and Milton 1966) the possibility of their being extra-LMC exists.

*Sources near MC 43: MC 42, 44, 48, 51, and 52.* An interesting illustration of the uncertainties which exist in the estimation of spectral indices arises in the case of MC 43 (N49). In the comparison of the 6 cm results with those at 11 and 21 cm, sources MC 43, 42, 44, 48, and 51 were included in the convolutions to the broader beams and the spectral index of $-0 \cdot 46$ given in Table 1(*b*) was obtained. However, Clarke (1971) has resolved four sources in this region which he has called A, B, C, and D and these correspond in position to the 6 cm sources MC 43, a nonlisted spur, MC 42, and MC 44 respectively. When $\alpha$ is calculated for the 73 cm to 6 cm range, the value for MC 43 is $-0 \cdot 36$; the spur (B) and MC 44 have rather steep spectra ($\alpha = -0 \cdot 66$ and $-0 \cdot 77$ respectively), which could be partly due to the uncertain estimates of the low flux density at 6 cm; on the other hand, MC 42 has a flat spectrum with $\alpha = -0 \cdot 04$ and must be thermal. When the four are taken collectively for combined values of flux density at these two wavelengths, $\alpha = -0 \cdot 46$ is obtained, which is identical with the first estimate. Obviously the intense source MC 43 dominates the estimates of spectral index.

*MC 74* (*30 Doradus*). The 30 Doradus source has dominated all previous continuum surveys of the LMC and even with the 4′ arc resolution at 6 cm wavelength its intensity is eight times greater than that of the next strongest source. It now seems to be well established that an intense central core, corresponding in position to the centre of N157A, and a weaker source at N157B exist superimposed on an extended continuum background. The presence of other components is less certain. Mathewson and Healey (1964) proposed three components:

(1) a central thermal source of $\sim 4'$ arc diameter with $S_{21} = 40$ f.u.;

(2) a nonthermal "surrounding" source of $\sim 24'$ arc diameter with a spectral index $\alpha = -0 \cdot 6$; and

(3) an extensive HII region of $\sim 45'$ arc diameter and $S_{21} = 20$ f.u. surrounding components (1) and (2).

Le Marne (1968) with angular resolution $3'\cdot4\times2'\cdot8$ arc at 73 cm wavelength found:

(1) a central thermal source "A" corresponding to N157A of dimensions $3'\cdot8$ (east–west) $\times 4'\cdot9$ arc (north–south) and $S_{73} = 30$ f.u.;

(2) an extended nonthermal component "C" of dimensions $26'\times13'$ arc and $S_{73} = 44$ f.u.; and

(3) a source "B" (N157B), probably nonthermal, of dimensions "unresolved" (east–west) $\times 1'\cdot2$ arc (north–south) and $S_{73} = 4$ f.u.

Le Marne (1968) included a source "D", which is discussed below under the heading MC 78. The background which might have corresponded to Mathewson and Healey's (1964) component (3) was not detected.

We have made extensive use of cross-sectional profiles in a number of directions at 6 and 11 cm wavelengths but believe that the $4'$ arc resolution is not sufficient to produce a clear picture of this complex region. The separation found is:

(1) the central source, which is symmetrical to within $\sim 0'\cdot1$ arc, possesses a diameter of $3'$ arc (after correction for the telescope beamwidth) and flux densities $S_6 = 25$ f.u. and $S_{11} = 30$ f.u.;

(2) at 6 cm it is possible that a "ring" of radiation exists with a brightness temperature $T_b = 0\cdot7$ K, a diameter of $13'$ arc, and a half-width of $\sim 4'\cdot5$ arc although the feature is not visible at 11 cm and therefore instrumental effects at either 6 or 11 cm cannot be ruled out;

(3) a background radiation (to be discussed in subsection (*c*)) which is much more extensive than that proposed by Mathewson and Healey (1964); and

(4) a source corresponding to Le Marne's (1968) "B".

In arriving at a spectral index for the central component, ((1) in each of the above models) we have interpreted the longer wavelength results differently from the original authors. Using cross-sectional profiles to extract the central source and integrating the appropriate contours we find $S_{21} = 34$ f.u. (Mathewson and Healey found $S_{21} = 40$ f.u.) and $S_{73} = 39\cdot1$ f.u. (Le Marne found $S_{73} = 30$ f.u.). The spectral index based on $S_6$, $S_{11}$, $S_{21}$, and $S_{73}$ is $-0\cdot2$, which would indicate that in addition to thermal components nonthermal components must be present in the central source. In support of this statement observations of the H $109\alpha$ recombination line (McGee, Brooks, and Newton, unpublished data) give a line to continuum intensity ratio $T_L/T_C$ of $\sim 1\%$ instead of an expected ratio of $\sim 5\%$ which would apply if all the $T_C$ were of thermal origin.

*408B*. This source has been so named because it was detected at 408 MHz by Le Marne (1968) and is seen to be present in the 6 and 11 cm surveys only by the asymmetry in the contours. The size and flux density of the source have been extracted by taking cross sections through the line-of-centres with MC 74 and at right angles to this line in Figure 11 of Part I and Figure 1 of Part III. Its position corresponds approximately to that of N157B, the 6 cm position being R.A. $05^h 38^m 08^s$, Dec. $-69°\,11'\cdot8$ (1950) and the diameter being $4'\cdot1$ arc. Other details corresponding to the entries in Tables 1(*a*) and 1(*b*) are:

| Source | Henize No. | $\Delta_{6-H}$ | $S_{73}$ | $S_{11}$ | $S_6$ | $\alpha$ |
|---|---|---|---|---|---|---|
| 408B | 157B | $0'\cdot7$ | $6\cdot1$ | $6\cdot3$ | $4\cdot4$ | $-0\cdot26$ |

The value $6\cdot1$ f.u. for $S_{73}$ is our estimate after integrating the 408 MHz contours; it differs from Le Marne's value of 4 f.u. Le Marne suggested that this source might be a SNR.

*MC 78* (*N158A*). Le Marne (1968) included this source in his contour map of the 30 Doradus region at 73 cm. We have integrated the contours to evaluate $S_{73}$ as $1\cdot5$ f.u. Our estimates of flux density and spectral index at 6 and 11 cm would lead us to expect $S_{73} = 0\cdot6$ f.u. We can only presume that a considerable nonthermal contribution must exist at the longer wavelengths.

### (*b*) *Selected Sources not in Table 1*

*MC 8 and 10.* These sources are close to MC 13 and cannot be located with certainty at either the 11 or 21 cm resolutions.

*MC 35 and 36.* Although these sources are not included in the convolution of MC 43 they are obviously blended with the group of sources near MC 43 at the 11 and 21 cm resolutions and cannot be measured for spectral index.

*MC 62* (*N62A*) *and MC 66.* These sources, which at 6 cm are enclosed by a contour of $0\cdot1$ K in $T_b$, are seen merely as spurs of radiation at 11 and 21 cm. No attempt to estimate the flux densities has been considered worth while.

*MC 69.* This source is unresolved at 11 and 21 cm. It is difficult to understand the significance of the two maxima at 6 cm (4′ arc resolution). Le Marne (1968) has partially resolved the source but regards it as part of a large underlying source associated with 30 Doradus. We have obtained $S_{73}$ from Le Marne's contours for an area equivalent to the 6 cm source and estimate the spectral index as $-0\cdot34$. No Henize object corresponds to this prominent source.

*MC 73.* This source is close to 30 Doradus and becomes blended at the lower resolutions.

*MC 84* (*N163*). This source is too close to the pair MC 76 and 77 for any chance of resolution at 11 and 21 cm wavelengths.

*MC 85 and 86.* These sources cannot be identified at the 11 and 21 cm resolutions.

### (*c*) *Background Continuum Radiation in LMC*

Most of the sources shown in the 6 cm diagrams of Part I are surrounded by low-level radiation, as is indicated by the varying shape of the $0\cdot1$ K contour. In some cases there are probably weak sources present with which 21 cm flux densities might have been compared. These sources have not been sought out here, since their intensities are too close to the receiver fluctuation level for reliable estimates to be made.

Mathewson and Healey (1964) found a broad scale background of radiation over most of the LMC with a spectral index of $-0\cdot6$. This contained a central feature which appeared to be associated with the stellar bar. In addition they delineated an extended thermal region centred on R.A. $05^h 40^m$, Dec. $-69° 30'$ of size $2° \times 3°$ and flux density 40 f.u.

The 6 and 11 cm surveys reveal background radiation only in the 30 Doradus complex (see Fig. 11 of Part I and Fig. 1 of Part III). The zero levels for the brightness temperature scales at both wavelengths were referred to regions outside the galaxy where no gradients were detected in the receiver outputs. After removal of the numerous sources in this region we have found at both wavelengths a background centred on R.A. $05^h 39^m$, Dec. $-69° 10'$ with half-power dimensions $\sim 1°$ in right ascension and $\sim 1 \cdot 25°$ in declination. The integrated flux densities, $S_6 = 34 \cdot 2$ f.u. and $S_{11} = 35 \cdot 4$ f.u., give a spectral index of $-0 \cdot 05$. It is not clear whether this thermal region corresponds to component (3) above of Mathewson and Healey (1964).

No background radiation at 6 cm exists over the area of the stellar bar. As stated earlier, the sources themselves appear to fall into regions of the spiral arms which were revealed by the pattern of the neutral hydrogen radial velocities. This again contrasts with Mathewson, Van der Kruit, and Brouw (1972), who make the point that the radio continuum radiation at 21 cm "shows no sign of following out spiral structure".

## VIII. Conclusions

The identification of radio continuum sources in the LMC with Henize nebulae shows that the continuum emission in the galaxy is disposed in the same way as the spiral structure suggested by the neutral hydrogen survey of McGee and Milton (1966).

Estimates of the spectral indices of about 50 sources have led us to assign them to three distinct groups:

(1) Sources of spectral index $\geqslant -0 \cdot 20$ which are identified in almost all cases with HII regions in the LMC.

(2) Sources of apparently nonthermal origin in the spectral index range $-0 \cdot 28$ to $-0 \cdot 75$ which are identified with nebulae in the Henize catalogue. Three of this group had already been classed as SNR's, while the spectral indices of all sources in the group lie in the same range as that for SNR's in our Galaxy.

(3) Nonthermal sources, mostly in the outer regions of the galaxy, not identifiable with Henize objects, and thought to be external to the LMC.

An interesting discovery was the presence of six "double sources" with one component thermal and the other nonthermal. One of these cases was in the Henize region N44, where considerable star formation has been observed. The only extensive background radiation detected at 6 cm was found in the vicinity of sources MC 74, 75, 76, and 77 (the 30 Doradus complex), and was thermal in character.

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