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Recombination Lines near 6 cm Wavelength in the Large Magellanic Cloud

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Abstract

Recombination lines H 109α have been detected in eight sources in the Large Cloud of Magellan. Low ratios of line temperature to continuum temperature, T_L/T_C, were found in most of the sources and are attributed to the difficulty of obtaining a true continuum value when such a large area is encompassed by the telescope beam. In the 30 Doradus nebula the ratio $N(He^+)/N(H^+)$ was found to be no greater than 0·08, or less than half that previously recorded by radio observations.

Introduction

In an attempt to learn more of the nature of the radio sources in the Large Cloud of Magellan (LMC), we have surveyed some of the more intense members for the presence of hydrogen and helium 109α recombination lines. Of prime interest was the 30 Doradus nebula, the dominating object in this galaxy, since Mezger *et al.* (1970) had reported the detection of the hydrogen and helium recombination lines in 30 Doradus in such proportions that the number ratio of singly ionized helium to hydrogen was more than twice the average ratio in galactic sources.

Since the beam brightness temperatures of the LMC sources, apart from 30 Doradus, were in the range 1·8–0·3 K, and the expectation from galactic measurements of the line-to-continuum temperature ratio was 6%, long integration times were required for each source. In all, 14 sources were surveyed. Recombination lines were detected in 8; no lines were seen in 1 of the weaker thermal sources and in 5 of the nonthermal sources. Two of the source pairs found by McGee and Newton (1972), in which one member was apparently nonthermal and its companion thermal, were included in the 14 sources.

Equipment and Method of Observation

The 109α line and continuum observations were made at 5 GHz with the Parkes 64 m radiotelescope and a receiver equipped with two stages of cryogenically-cooled parametric amplifiers and a multichannel bank of Gaussian-shaped filters, of 100 kHz bandwidth. The system noise temperature on cold sky was 80 K. The telescope beamwidth was 4′·1 arc between half-power points. The receiver and primary feed system have been described by Brooks and Sinclair (1972). Absorbing material was placed in the focal plane to cover the metal plate surrounding the feed horn in order to minimize the 'Fabry–Perot effect' on the spectral baseline, produced by multiple reflections between the focal plane and the vertex (see e.g. Caswell 1973).

Table 1. Recombination-line survey in Large Magellanic Cloud

(1) LMC source No.	(2) Spectral line observed	(3) Position (1950) R.A. h m s	(4) Dec. ° ′ ″	(5) Source T_C (K)	(6) Source spectral index α	(7) Line T_L (K)	(8) Noise r.m.s. (K)	(9) Ratio T_L/T_C (%)	(10) Line half-width (kHz)	(11) $\Delta\nu$ (km s^{-1})	(12) v_R at line centre (km s^{-1})	(13) Line radial velocity data[A] (km s^{-1})
(a) Positive Results												
MC 18 (N11B)	H 109α	04 56 42	−66 28 28	1·1	+0·01	0·04	0·009	3·6	423	25·3	+294·2	+302·8 II F, +292·4 II C, +300·7 II S, +291 II G, +293 I
MC 23 (N105)	H 109α	05 10 02	−68 56 50	0·5	+0·10	0·02	0·009	4·0	805	47·9	+253·5	+255·8 II F, +256·0 II C, +259·3 II S, +265 II G, +257 I
MC 33 (N44D)	H 109α	05 23 11	−68 06 00	0·3	−0·19	0·04	0·016	12·0	605	36·2	+304·3	+311 II G, +296·1 II C. +300 I
MC 69	H 109α	05 36 09	−69 14 08	0·8	−0·34	0·04	0·011	5·3	514	30·8	+250·8	+259·7 II F +262 II G, +273 I
MC 74 (30 Dor) (N157A)	H 109α	05 39 04	−69 06 25	12·2	−0·2	0·22	0·011	1·8	945	56·5	+266·8	+260 II G, +273 I
	He 109α					0·024			656	39·3	+264·4	
	H 137β					0·055			698	41·8	+269·6	
	H 90α	05 39 03	−69 07 24	5·5		0·24	0·05	4·4	1697	57·3	+267·7	+262·6 II C
	He 90α						Not detected					
MC 75 (N158C)	H 109α	05 39 37	−69 30 59	1·0	+0·21	0·02	0·008	2·0	832	49·8	+268·3	+262 II G, +266·5 II C, +259·8 to +270·1 II S, +265 I

MC 76 (N160A)	H 109α	05	40	12	−69	39	33	1·38	−0·43	0·04	0·011	2·9	761	45·5	+254·8	+245·6 II F, +253·3 II C, (+256) II G, +247·7 to +252·9 II S, +259 I
MC 77 (N159D)	H 109α	05	40	24	−69	46	00	1·8	+0·1	0·07	0·008	3·9	497	29·8	+254·7	+251·6 II S, +251·9 II F, +255 I
	H 137β									0·016			494	29·6	+255·4	
(b) Negative Results																
MC 13 (N79A)	H 109α	04	52	10	−69	27	00	0·41	−0·01		0·014					
MC 32 (N44A, B)	H 109α	05	22	11	−67	59	14	0·55	−0·65		0·013					
MC 39 (N132D)	H 109α	05	25	23	−69	40	33	1·40	−0·57		0·015					
MC 43 (N49)	H 109α	05	25	56	−66	06	38	0·91	−0·46		0·013					
MC 63 (N63A)	H 109α	05	35	25	−66	02	51	0·67	−0·42		0·017					
408B (N157B)	H 109α	05	38	08	−69	11	46	(2·5)	−0·26		0·039					

[A] Abbreviations used:
II, HII measurements;
F, Feast (1964);
S, Smith and Weedman (1971);
I, HI cloud values from McGee and Milton (1966);
C, Chériguene and Monnet (1972);
G, Georgelin and Monnet (1970).

The temperature scale used here is in units of beam brightness temperature. This was determined by comparing a noise lamp deflection with continuum measurements of the radio source Hydra A. The flux density of Hydra A was assumed to be 13·0 Jy* at 5 GHz. The ratio of point source flux density to beam brightness temperature is $1 \cdot 23\ \mathrm{Jy\,K^{-1}}$.

Observations were made with the receiver input switched between the 2*HE*-mode corrugated feed horn and a cold (20 K) load. Measurements on source were continued for periods of 20 min, and corresponding sky reference points at the same declinations were then measured over the same range of hour angles. In this way zenith-angle effects were eliminated.

In order to support the results reported here on the 30 Doradus source, measurements on the 90α recombination lines of hydrogen and helium were also made. Details of the equipment used at the wavelengths of these lines (3·4 cm) have been given by McGee *et al.* (1973).

Results

The information obtained from the survey is summarized in Table 1. The first part of the table contains the sources in which spectral lines were detected, given in order of increasing right ascension, while the second part lists those sources in which no detections were made. The sources are designated by their LMC radio catalogue numbers (McGee *et al.* 1972), and the reference numbers of optical objects (Henize 1956) assumed to be associated with them are given in parentheses. The beam brightness temperature T_C of the source and the spectral index α (McGee and Newton 1972) are given in columns 5 and 6. The estimated errors in the continuum temperatures are $\pm 10\%$. Line temperatures T_L appear in column 7. The r.m.s. noise levels in the spectral line measurements, shown in column 8, have been calculated from the channel-to-channel variation in those parts of the final averaged profiles which are outside the lines. In most cases the spectral lines have been observed several times with different local oscillator frequencies so that the line appeared in different places along the multichannel filter bank in order to avoid possible instrumental errors. Hence the estimate of noise is conservative because of the inclusion of 'outer' channels which have not had as much integration time as the more central channels containing the line profiles.

The ratios of line temperature to continuum temperature, T_L/T_C, are given in column 9 of Table 1. The line temperatures, the half-widths $\Delta\nu$ (columns 10 and 11) and the radial velocities v_R at line centres (column 12) have been determined by fitting Gaussian curves to the observed points. The estimated errors in the half-widths are ± 35 kHz ($\pm 2\ \mathrm{km\,s^{-1}}$) and in the radial velocities $\pm 1\ \mathrm{km\,s^{-1}}$. Radial velocities of other optical and radio lines measured at or close to the nebulae are listed for comparison in column 13.

Discussion

Ratio of Line-to-continuum Temperature

We have calculated the mean ratio T_L/T_C for the H 109α line in the 130 galactic sources observed by Wilson *et al.* (1970) to be 6·1%. Milne *et al.* (1969), after

* 1 jansky (Jy) = $10^{-26}\ \mathrm{W\,m^{-2}\,Hz^{-1}}$.

examining 54 galactic sources, concluded that sources for which the H 109α line-to-continuum ratio was greater than 3% were thermal. It is seen from Table 1*a* that in the LMC most of the T_L/T_C ratios appear to be quite low, often less than 6%. We attribute this to the difficulty of obtaining the true continuum temperature of the thermal region in which the recombination line is observed. At the distance of the LMC (55 kpc), the 4′·1 arc telescope beam encompasses a region of some 65 pc diameter. Thus several components, some of which are nonthermal, could well contribute to the observed continuum temperature. A good example is the 30 Doradus nebula. For H 109α the ratio T_L/T_C in this source is only 1·8%, i.e. 30% of an expectation of 6·1%. However, for the H 90α line, where the telescope beam is 2′·6 arc at half-power points, T_L/T_C is 4·4%, i.e. 48% of the galactic expectation of 9·1% (McGee *et al.* 1974). The spectral index, $\alpha = -0\cdot2$, for 30 Doradus also points to the presence of nonthermal components in the central core source of this complex.

Of the other results in Table 1*a*, the abnormally high T_L/T_C ratio in MC 33 is scarcely significant in view of the low-intensity signal compared with the r.m.s. noise level. Also, the source MC 69, which is of comparatively large dimensions (5′·4 × 8′·0 arc), has a T_L/T_C ratio of 5·3%. Further investigation seems desirable here, since no corresponding optical objects have been reported in this area; an additional complication is the spectral index, $\alpha = -0\cdot34$, found by McGee and Newton (1972), indicating a significant nonthermal component.

Line Half-widths

The half-widths, which range between 423 and 945 kHz indicate similar internal velocities to those found in galactic HII regions. The average half-width of the 130 H 109α lines in the Wilson *et al.* (1970) survey was 589 kHz, with approximate extremes at 300 and 1200 kHz. The lack of influence of the telescope beam size on the half-widths is demonstrated in the 30 Doradus case, where values for H 109α and H 90α differ by only 0·8 km s^{-1}.

Comparison of Radial Velocity Measurements

Several sets of radial velocity measurements have been carried out on HII regions in the LMC. Feast (1964) used [OII] and Hα lines, Georgelin and Monnet (1970) and Chériguene and Monnet (1972) used Hα interferometry, and Smith and Weedman (1971) used [OIII] and Hα lines in their observations. Radial velocities measured by these authors are given in the last column of Table 1*a*. The agreement of these velocities with the recombination line velocities is very close and probably within the experimental errors. Neutral hydrogen (HI) velocities at the source positions, taken from McGee and Milton (1966), have also been included in Table 1*a*. These values again illustrate the close correspondence between HI and HII velocities previously noted by McGee (1964).

LMC Source Pairs MC 32, 33 and MC 76, 77

McGee and Newton (1972) discovered six source pairs in the LMC in which one source had a thermal spectrum and its companion a nonthermal spectrum. Two of these were sufficiently intense to be included in the present investigation. Recombination lines should therefore be detectable in one component but not in the other.

In one of the two examples the H 109α line was detected in the component with a thermal spectrum, MC 33, but not in the other (stronger) component, MC 32. This appears to confirm the surprising result that MC 32, corresponding in position to the important Henize nebulae N44A and B, is nonthermal in character.

In the second set of sources the test was not successful, however, because the H 109α line was detected in the component with the apparently nonthermal spectrum, MC 76. The recombination line in MC 76 is 50% broader than that in MC 77 and the T_L/T_C ratio is lower by 30%. Thus Milne's (1972) statement that MC 76 has a thermal spectrum could well be supported. Recently we have surveyed the region in the continuum at 9 GHz with a $2'\cdot 6$ arc beam, and we find integrated flux densities which appear to confirm the previous findings of a nonthermal spectrum for MC 76 and a thermal spectrum for MC 77. We believe that our estimate of spectral index ($\alpha \approx -0\cdot 4$) and the low T_L/T_C ratio indicate the presence of nonthermal and thermal components in MC 76. Further interest in the pair has been raised by Byrne and Butler (1973), who draw attention to the proximity of the X-ray source LMC X–1 (2U0540−69). These authors suggest the possibility that MC 76 is variable. We think it unlikely, because at 5·0 GHz we measured the $T_{b,max}$ as 1·38 K in 1968, 1·24 K in January 1971 and 1·53 K in September 1971; Milne (1972) found 1·27 K in 1972. All values are within ±10% of our adopted value.

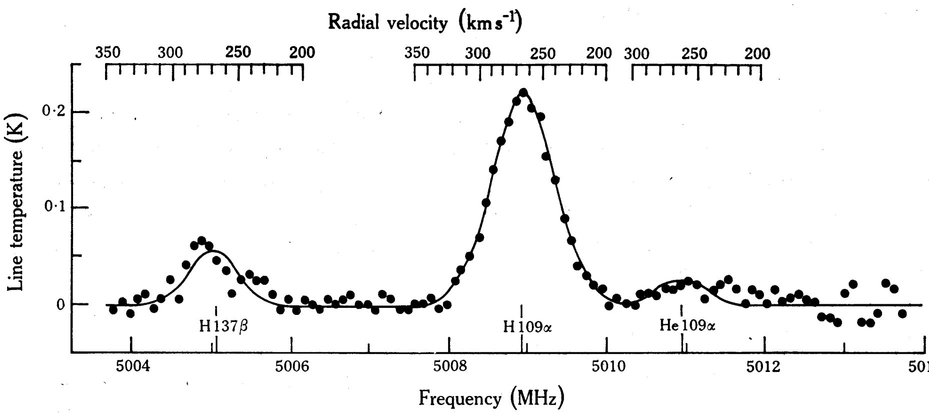

Fig. 1. Spectrum near 5009 MHz of the 30 Doradus nebula (MC 74). The ordinate scale is kelvins of beam brightness temperature. The frequency scale on the abscissa has been adjusted so that the value at the centre of the hydrogen α-line is the natural frequency of 5008·923 MHz, which corresponds to a radial velocity of $+266\cdot 8$ km s^{-1} (referred to the Sun). The dots are the observed points, and the curve is the sum of three Gaussians fitted by a least-squares technique. Radial velocity scales for the H 137β, H 109α and He 109α lines are also included. The frequency resolution was 100 kHz and the r.m.s. noise $\pm 0\cdot 011$ K.

Other Recombination Lines in 30 Doradus and MC 77

Special interest was centred on the He 109α line in 30 Doradus. Mezger *et al.* (1970) had reported $N(He^+)/N(H^+)$ to be 0·17 from observations at 5 GHz. Mathis (1965), using the HeI λ 5876 Å and Hβ lines, found the helium–hydrogen ratio by number equal to 0·14. It is not clear whether this means neutral and ionized gases, but the author states that the ratio is 'normal' and 'about the same as in the Orion Nebula'.

The average spectrum for 30 Doradus from three separate observing sessions is shown in Fig. 1. The curve is the resultant of three Gausians fitted to the observed points. The He 109α line is relatively close to the noise level. The ratio by number $N(\mathrm{He}^+)/N(\mathrm{H}^+) = 0 \cdot 08$ (less than half the value reported by Mezger *et al.* 1970). It is equal to the average ratio obtained from 17 southern Milky Way objects observed in H, He 90α lines (McGee *et al.* 1974). The intensity of the H 137β line is such that the temperature ratio $T_{\mathrm{H}137\beta}/T_{\mathrm{H}109\alpha}$ is $0 \cdot 25$.

The source MC 77 was the only other one where a line other than Hα lines was detected. The H 137β line in MC 77 gives a ratio $T_{\mathrm{H}137\beta}/T_{\mathrm{H}109\alpha} = 0 \cdot 23$; for conditions at local thermodynamic equilibrium the expected ratio is $0 \cdot 28$. The only result we can give for helium in MC 77 is $N(\mathrm{He}^+)/N(\mathrm{H}) < 0 \cdot 1$.

Non-detection of H 109α

No recombination line was detected in the thermal source MC 13. The inference from these observations is $T_L/T_C < 1 \cdot 6\%$. Since MC 39, 43 and 63 are well-established supernova remnants, it was not expected that any lines would be detected in them.

Conclusions

The recombination lines in the Large Magellanic Cloud appear to be similar in form to those in our Galaxy with respect to their half-widths and to the ratio of hydrogen α to hydrogen β and of ionized helium to ionized hydrogen. However, the T_L/T_C ratios are much lower than in the Galaxy, possibly because the large area intercepted by the telescope beam at the Large Magellanic Cloud includes, in addition to the thermal source of the recombination line, other components which increase the value of T_C. The observations of 30 Doradus confirm the results from optical spectroscopy that the ratio of helium to hydrogen in this nebula is normal.

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