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Detection of carbon recombination lines below 100 MHz towards the Galactic Centre and M16

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Summary. We report the detection of highly excited recombination lines of carbon in absorption towards the Galactic Centre at 75 MHz and towards M16 at 68 and 80 MHz. Towards M16 the line was also detected in emission at 325 MHz. The central velocity of the line towards the Galactic Centre is near 0 km s^{-1} and corresponds to any cloud along the line of sight. The central velocity towards M16 is +19 km s^{-1} and agrees with a known H I absorption feature in this direction. The optical depths range from 0.0006 to 0.002 and the linewidths are about 15 km s^{-1}. These linewidths imply upper limits to the electron density in the absorbing clouds of 0.8 cm^{-3}. These two detections were the only positive ones in observations at several frequencies below 100 MHz towards 19 directions in the galactic plane. This indicates that the low-frequency recombination lines of carbon are not widely detectable with presently available telescopes.

1 Introduction

A recombination line from carbon atoms in very highly excited states (principal quantum number $n>600$, frequency <30 MHz) was first identified by Blake, Crutcher & Watson (1980). This was an absorption feature at 26.13 MHz detected by Konovalenko & Sodin (1980) in the direction of Cassiopeia A and attributed by them to a hyperfine transition of interstellar nitrogen. Subsequently this line was confirmed to be a recombination line of carbon by Konovalenko & Sodin (1981) who detected another transition near 26.25 MHz. These were the first detection of recombination lines in absorption; at higher frequencies all recombination lines are found to be only in emission. Detailed theoretical predictions of the level populations, incorporating a dielectronic recombination-like process (Walmsley & Watson 1982a, b), can explain the presence of absorption, and indicate that these very low frequency lines can be a good diagnostic of conditions in cold interstellar clouds. The variation of line-strength with frequency, and the increase in linewidth at lower frequencies due to pressure broadening, are good indicators of electron density in the absorbing clouds. These lines are also of intrinsic interest since they are the lowest frequency radio spectral lines yet detected.

Widespread detectability of these lines from interstellar clouds is yet to be established. Only a few lines of sight have been reported. The direction of Cas A has now been observed over a wide range of frequencies; 16–30 MHz by Konovalenko (1984a), 26–68 MHz by Anantharamaiah, Erickson & Radhakrishnan (1985), 42–84 MHz by Ershov *et al.* (1984), 39–118 MHz by Ershov *et al.* (1987) and 34–325 MHz by Payne, Anantharamaiah & Erickson (1988). The last of these observations show that the recombination lines turn from absorption to emission at frequencies greater than 200 MHz, as predicted. The strong continuum flux of Cas A and the presence of cold neutral gas make this the most favourable line of sight for these studies.

Detection of recombination lines in absorption at 25 MHz has been reported by Konovalenko (1984b) towards two other directions: G75.0+0.0 and NGC 2024. The absorption line towards G75.0+0.0 is of particular interest since there is no known strong background source in that direction. The absorption therefore must occur against the galactic non-thermal background, which is strong at low frequencies.

Here we report searches for these lines in the frequency range 25–140 MHz towards 19 directions in the galactic plane. The directions were chosen based on one or more of the following criteria: the presence of a strong background continuum source (e.g. the Crab Nebula, Cygnus A and the Galactic Centre), high H I optical depth (e.g. W3, G25.4−0.2, 3C123, and W51), the presence of strong galactic non-thermal background emission (e.g. galactic longitudes 0–30°), or nearby molecular cloud complexes (e.g. Taurus Molecular Cloud). Positive detections of lines in absorption were made towards the Galactic Centre at 75 MHz and towards M16 at 68 and 80 MHz. A line was possibly detected towards G75.0+0.0 at 25 MHz. In a recent observation near 325 MHz the line towards M16 was also detected in emission.

2 Observations

The observations were made using the 93- and 43-m telescopes of the National Radio Astronomy Observatory* at Green Bank and the 305-m telescope of the Arecibo Observatory†. Sources, frequencies of observation, and other relevant parameters for the 93-, 43- and 305-m observations are summarized separately in Tables 1, 2 and 3, respectively. Near each of the frequencies indicated in the tables, two or three transitions were observed simultaneously in bands carefully chosen to be interference-free. Because of the way different transitions were averaged, the velocity scales of the spectra may be in error by up to one spectrometer channel. Except at 325 MHz, all reference spectra were obtained by switching to a noise source adjusted to balance the total on-source system temperature. The system temperature was normally dominated by the contribution from the sky.

The observations with the 93-m telescope were made using three different feeds; a broadband 20–50 MHz dipole, a 50–80 MHz tuneable crossed dipole and a 110–250 MHz broadband crossed dipole. Depending upon the frequency of observation, one of these feeds was mounted on the travelling feed system of the 93-m telescope. The half-power beamwidth (HPBW) in arcmin is roughly half the observing wavelength in centimetres, e.g. 150 arcmin at 100 MHz. The 384-channel autocorrelation receiver was split into four independent spectrometers of 96 channels

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†The Arecibo Observatory is part of the National Astronomy and Ionosphere Center which is operated by Cornell University under contract with the National Science Foundation.

Table 1. Green Bank observations – 93-m telescope.

Source	Frequency (MHz)	Tsys (K)	Velocity Coverage[1] (km/s)	Velocity Resolution (km/s)	Effective Integ time (hours)	rms noise T_L/T_C*10^3	Peak HI Optical Depth
M16	68[2]	11500	-69 to 81	3.5	3.9	0.69[3]	1.3
	80[2]	8500	-54 to 71	3.0	15.0	0.55[3]	
G75.0+0.0	24[4]	17000	-205 to 212	9.7	10.4	0.69[3]	
	34	7900	-210 to 107	6.6	16.3	0.54	
W49	35	7500	-90 to 160	6.8	10.5	0.6	>3.0
W51	35	--	-82 to 170	6.8	8.0	0.7	3.2
	68	7700	-30 to 107	3.8	6.0	0.6	
	78	6150	-12 to 100	3.1	23.0	0.4	
M17	52	14000	-85 to 275	9.3	9.8	0.4	1.5
	110	6400	-18 to 170	2.2	9.3	0.55	
	140	3100	-50 to 90	3.5	11.0	0.4	
G25.4+0.2	68	9400	-40 to 90	3.5	10.7	0.45	3.6
W3	52	5600	-120 to 60	4.7	15.7	0.5	>3.0
	110	2400	-70 to 20	2.2	9.6	0.55	
	140	1500	-80 to 60	3.4	25.4	0.22	
3C 123	110	1700	-40 to 40	2.2	20.0	0.38	2.5
Cyg A	52	16500	-130 to 60	4.7	7.6	0.7	0.3
	110	18400	-145 to 40	4.4	10.5	0.35	
	140	10300	-120 to 20	3.5	21.1	0.26	

[1]With respect to the carbon recombination line.
[2]Line detected in absorption.
[3]Noise in residuals after removal of Gaussian fit to line feature.
[4]Possible detection.

each. Total bandwidths used were 78 kHz at the higher frequencies and 39 kHz at the lower frequencies. After hanning smoothing, this resulted in frequency resolutions of 1.63 and 0.81 kHz, respectively. Sources observed with the 93-m telescope include Cyg A, several well-known galactic sources with known high H I optical depth, and G75.0+0.0.

Table 2. Green Bank observations – 43-m telescope.

Position	Tsys (K)	Species	Velocity Coverage (km/s)	Effective Integ time (hours)	rms noise T_L/T_C*10^3
G00.0+0.0	5420	C[1]	-70 to 140	66.0	0.15[2]
		H	-125 to 140	36.0	0.45
G08.0+0.0	5285	C	-95 to 145	17.3	0.30
		H	-100 to 100	12.5	0.45
G16.0+0.0	4235	C	-95 to 250	32.4	0.21
		H	-245 to 100	32.4	0.21
G24.0+0.0	4140	C	-90 to 350	13.6	0.39
		H	-240 to 200	13.6	0.39
G32.0+0.0	3940	C	-70 to 350	16.5	0.28
		H	-230 to 200	16.5	0.28
G40.0+0.0	4105	C	-40 to 190	34.3	0.24
		H	-190 to 40	26.0	0.32
M16[3]	290	C[4]	-40 to 65	12.9	0.37[2]

[1]Line detected in absorption.
[2]Excluding velocities of the detected line.
[3]Observation near 325 MHz. All other observations are near 75 MHz.
[4]Line detected in emission.

Table 3. Arecibo observations[1].

Source	Position (ra, dec) 1950.0		Tsys (K)	Velocity Coverage[2] (km/s)	Effective Integ time (hours)	rms noise T_L/T_C*10^3	Peak HI Optical Depth
Crab	05h31m31s	21°59'17"	16000	-74 to 137	34.4	0.45	1.2
3C 123	04 33 55	29 34 14	12000	-78 to 133	13.3	0.74	2.5
G168.0-16.0	04 10 00	23 00 00	9000	-71 to 140	7.9	1.1	---
G180.0-0.0	05 42 26	28 55 12	10000	-72 to 139	7.0	1.2	---
Monoceros	06 24 50	06 13 00	9000	-61 to 150	5.9	1.0	---

[1]All observations were near 50 MHz.
[2]With respect to the carbon recombination line.

The observations with the 43-m telescope were made using a new 50–88 MHz broadband feed mounted at the prime focus. All of these observations were made near 75 MHz, where the HPBW is about 6°.7. The 1024-channel autocorrelator was split into four independent spectrometers of 256 channels each, providing a frequency resolution of 1.22 kHz. A total bandwidth of 156 kHz was used for each of the four spectrometers. We observed six positions in the galactic plane: from l=0° to l=40° in steps of 8°. These observations were aimed at determining whether the low-frequency carbon lines are easily detectable in absorption against the strong galactic non-thermal background.

M16 was also observed at 325 MHz with the 43-m telescope. These observations were made with a cavity-backed, crossed-dipole feed. An RF hybrid produced two circular polarizations. Reference spectra were obtained by frequency switching. Frequency resolution was 1.2 kHz or 1.1 km s^{-1}. At this frequency the carbon line was found to be in emission.

The Arecibo observations were made near 50 MHz using a crossed-dipole feed. The HPBW was about 80 arcmin. The spectrometer was configured to observe four transitions simultaneously with a frequency resolution of 0.3 kHz. Most of the positions observed at Arecibo were in the galactic anticentre direction; they include the Crab Nebula, which is a strong background source, and 3C123, which has a high H I optical depth in its direction. G168-16 corresponds to a position near the Taurus Molecular Cloud. The region near Monoceros was chosen because strong low-frequency continuum absorption has been observed at this position (Odegard 1986).

3 Results

Positive detections of lines in absorption were made towards the Galactic Centre at 75 MHz and towards M16 at 68 and 80 MHz. The line towards M16 was detected in emission at 325 MHz. A possible detection at 25 MHz was obtained towards G75.0+0.0. Fig. 1 shows the profile observed towards the Galactic Centre. Two transitions, C443α (75.4233 MHz) and C447α (73.4188 MHz), were observed simultaneously and both were detected. The spectrum in Fig. 1 is the average of these two transitions. The absorption feature occurs at a velocity of $-1\ \mathrm{km\,s^{-1}}$ and could arise anywhere along the line of sight to the Galactic Centre.

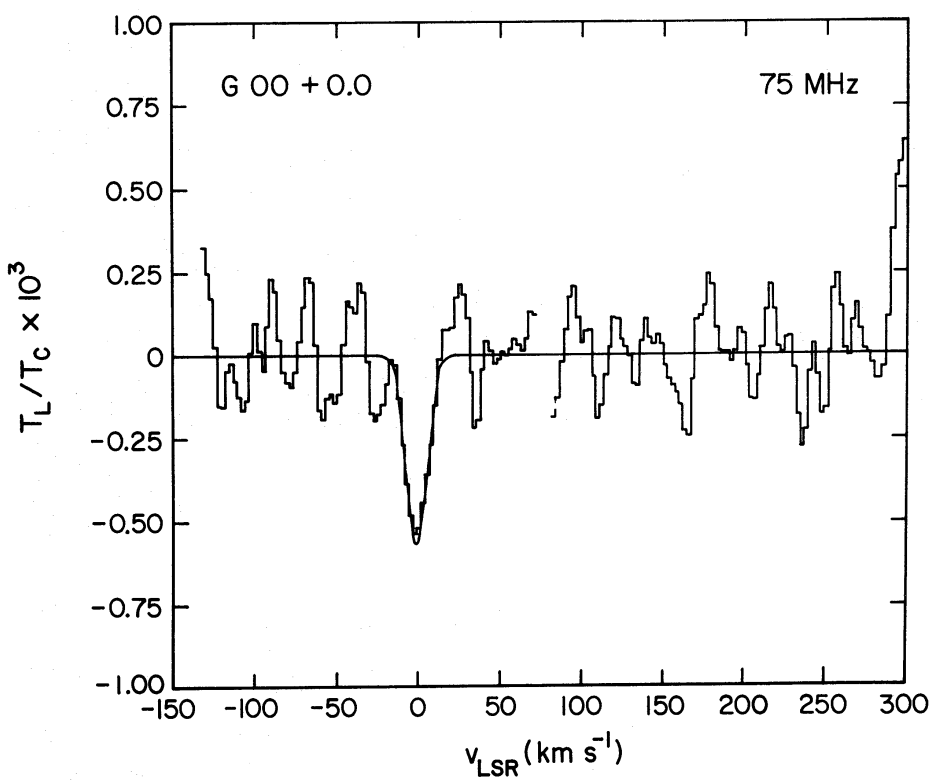

Figure 1. Averaged spectrum observed towards the Galactic Centre at 75 MHz. The velocity scale is with respect to the carbon recombination line. Points to the left of the break at $75\ \mathrm{km\,s^{-1}}$ are an average of all of the data. Points to the right of the break are an average over that half of the data not contaminated by interference. These data span the hydrogen recombination line frequency ($+149\ \mathrm{km\,s^{-1}}$ with respect to the carbon line velocity). A Gaussian fit to the absorption feature is shown as the smooth curve.

Fig. 2 shows the average of two transitions observed near 68 MHz and four transitions observed near 80 MHz towards M16. Also shown is the emission profile that was observed at 325 MHz. Within the errors, the observed velocities of these features agree with that of a strong H I absorption feature in this direction (Radhakrishnan *et al.* 1972).

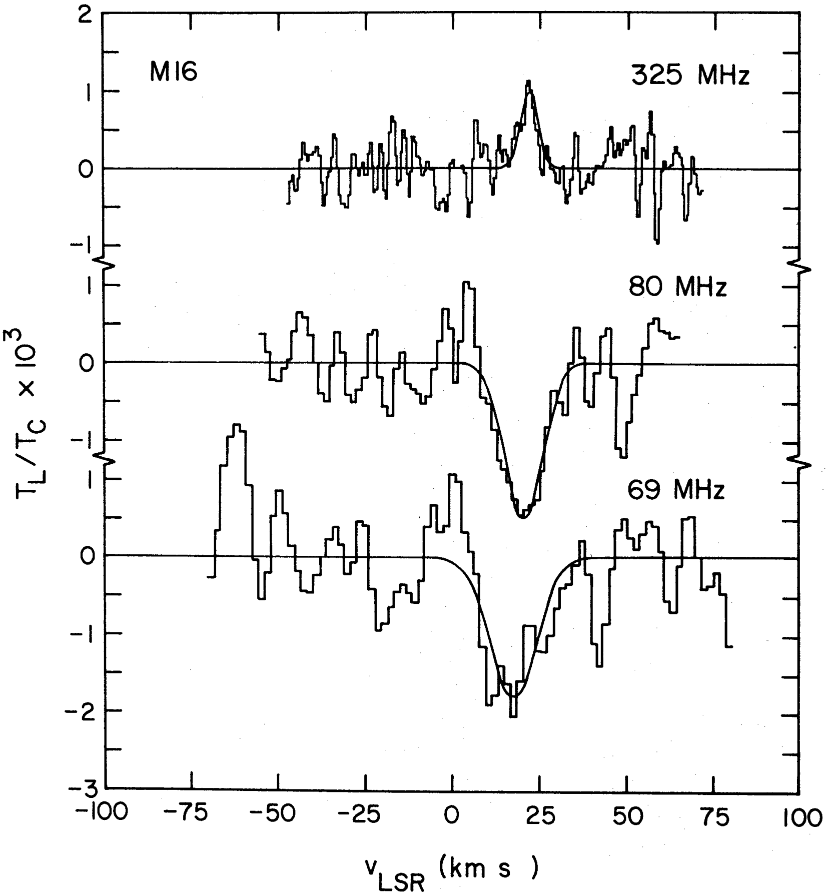

Figure 2. Spectra observed towards M16. The upper spectrum is the C272α transition observed at 325 MHz. The middle spectrum is the average of four transitions observed near 80 MHz. The lower spectrum is the average of two transitions observed near 68 MHz. The velocity scale is with respect to the carbon recombination lines.

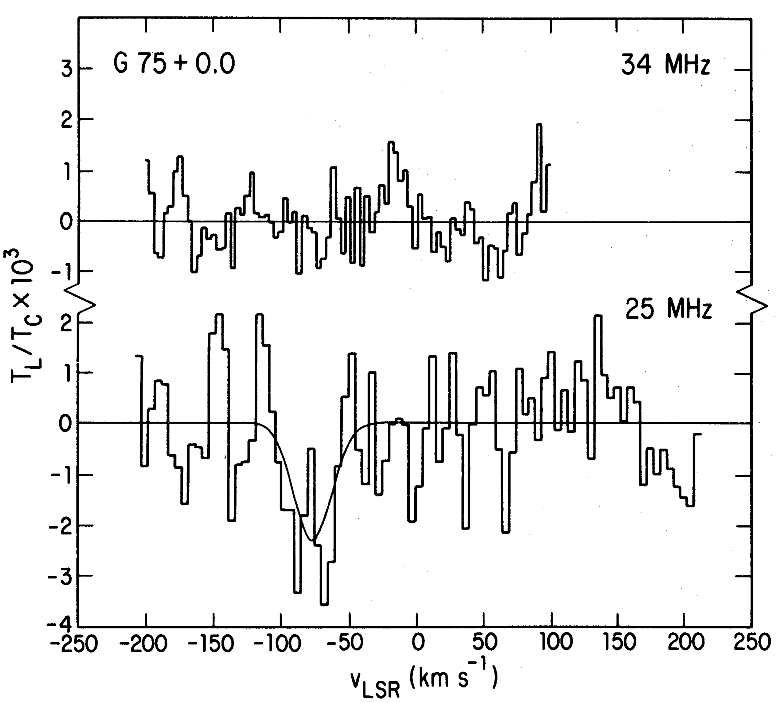

Figure 3. Spectra observed towards G75.0+0.0.

Fig. 3 contains the spectra observed towards G75.0+0.0 near 25 and 34 MHz. If the feature near $-77\,\mathrm{km\,s^{-1}}$ at 25 MHz is real, then this spectrum is not consistent with that reported by Konovalenko (1984b) for the same direction but observed with a different beam size (4°×15°). In the spectrum reported by Konovalenko there is an absorption feature near $+10\,\mathrm{km\,s^{-1}}$ with an optical depth of 1×10^{-3}. This feature would be just below the detection line of our spectrum near 25 MHz in Fig. 3. On the other hand, the feature at $-77\,\mathrm{km\,s^{-1}}$ ($T_L/T_c\approx2.3\times10^{-3}$) should easily have been seen in the spectrum reported by Konovalenko. If we exclude the possibility that this feature is not real then the only explanation for the discrepancy is that the telescope beams used for the two observations have non-overlapping regions. We note here that the H I emission in this region peaks near $0\,\mathrm{km\,s^{-1}}$ and extends all the way to $-80\,\mathrm{km\,s^{-1}}$ (Weaver & Williams 1973). The spectrum taken towards the same direction near 34 MHz (Fig. 3) shows no features.

The parameters obtained from Gaussian fits to the detected lines are listed in Table 4.

Table 4. Parameters of detected carbon lines.

Source	Frequency (MHz)	Transitions Averaged	$T_L/T_C\times10^3$	V_{LSR} (km/s)	Width FWHM (km/s)	$N_{e,max}$ (cm-3)	Telescope	Beam Size
G00.0+0.0	75	C443α,C447α	-0.57±0.04	-1.0±0.5	14.8±1.2	0.8?	43m	6.7°
M16	68	C456α,C457α	-1.8 ± 0.3	17.6±2.0	16 ± 3	0.8	91m	3.7°
	80	C431α,C435α, C437α,C438α	-2.0 ± 0.3	20.5±1.0	13 ± 2	0.9?	91m	3.1°
	325	C272α	+0.96±0.17	22.1±0.5	5.7±1.2			
G75.0+0.0	24	C635α,C643α C645α,C646α, C650α	-2.3 ± 0.4	-77 ± 3	33 ± 6	0.1	91m	10.4°

All the other directions observed yielded only upper limits. These can be inferred from the rms noise in the observed spectra given in Tables 1, 2 and 3. In many cases the observed spectra included the frequency of the corresponding hydrogen recombination lines, which occur at a velocity of $+150\,\mathrm{km\,s^{-1}}$ with respect to the carbon lines. No lines due to hydrogen were detected.

4 Discussion

From considerations of pressure broadening at a temperature near 100 K, the widths of the absorption lines detected towards the Galactic Centre at 75 MHz and towards M16 at 68 MHz imply upper limits to the electron densities in the absorbing clouds of $0.8\,\mathrm{cm^{-3}}$. If the feature towards G75.0+0.0 is real, the upper limit is $0.1\,\mathrm{cm^{-3}}$. If these lines are measured at even lower frequencies and the pressure broadening is determined, then the actual electron density of the gas can be measured.

At these densities, the calculations of Walmsley & Watson (1982b) show that a pure hydrogenic-type population of high principal quantum number states would result in the lines being in emission. In order to account for lines in absorption a dielectronic recombination-like process has to be invoked. This process, first described by Watson, Western & Christensen (1980), has a considerable influence on the level populations. The process involves the capture of an electron with positive energy with the simultaneous excitation of the ground-state fine structure transition. Although the total energy of the system is positive, the atom is temporarily stabilized against autoionization by collisions, which change the angular momentum of the outer electron and make radiative transitions unlikely. The process requires incident electrons with thermal energies near the energy-splitting of the ground state, 92 K, which is close to the typical temperature for H I absorbing clouds (e.g. Payne, Salpeter & Terzian 1982, 1983). Detailed calculations of level populations based on this process (e.g. Walmsley & Watson 1982b) can predict the variation of line strength with frequency for different electron densities and temperatures in the clouds. If these lines are observed over a range of frequencies then the properties of the absorbing clouds can be determined.

From simple theoretical considerations these lines are expected to be in absorption at low frequencies. This is because at higher n values the atoms are larger and undergo collisions more frequently, driving level populations toward their thermodynamic equilibrium values; the upper levels are less populated than the lower ones and the recombination lines are in absorption. At lower n, radiative processes are the dominant populating mechanism. This tends to invert the level populations, since downward transitions out of a given level are more rapid than the transitions into it from higher levels; stimulated emission results. The turnover frequency between absorption and emission is again a function of the electron densities and temperatures of the clouds. For example, the turnover frequency is about 150 MHz when the electron density is $0.1\,\mathrm{cm}^{-3}$ and the temperature is 100 K (Walmsley & Watson 1982b). Such an effect has, in fact, been observed towards Cas A (Payne *et al.* 1988) where the carbon lines are in absorption below 100 MHz and go into emission above 200 MHz. We may also have observed this phenomenon here in the case M16 where the lines observed in absorption at 68 and 80 MHz have apparently gone into emission at 325 MHz.

In M16 the lines increase in width from $5\,\mathrm{km\,s^{-1}}$ at 325 MHz to $16\,\mathrm{km\,s^{-1}}$ at 68 MHz. If this increase in width is interpreted as being caused by pressure broadening, some difficulties are encountered. The best fit to the observed width based upon pressure broadening implies an electron density in the gas of $0.8\,\mathrm{cm}^{-3}$. If all the electrons come from carbon with cosmic abundance ($\mathrm{C/H} \approx 3\times10^{-4}$) then a neutral hydrogen density of $2400\,\mathrm{cm}^{-3}$ is implied. This density is unusually high for a typical H I cloud. Radiation broadening can account for less than one third of the width observed at 68 MHz. From the 150-MHz all-sky map of Landeker & Wielebinski (1970) we estimate the average galactic background temperature in the vicinity of M16 to be about five times higher than it is in the vicinity of the Earth, i.e. about 3000–5000 K at 100 MHz. Using the formula in Shaver (1975) we get ≈ 1 kHz ($4.4\,\mathrm{km\,s^{-1}}$) for the width of the line due to radiation broadening. Alternatively, the linewidth variation may be caused by angular size effects as discussed below.

Towards the Galactic Centre, a carbon recombination line near $0\,\mathrm{km\,s^{-1}}$ has been observed in emission near 325 MHz (Anantharamaiah & Bhattacharya 1986). The observed width of this line is $26\pm2\,\mathrm{km\,s^{-1}}$ at 325 MHz compared to an absorption line width of $14.8\pm2\,\mathrm{km\,s^{-1}}$ at 75 MHz. This makes it difficult to assert that the absorption and emission lines arise in the same gas. It is possible that the 325-MHz emission line is a blend of more than one component. It would be interesting to observe the Galactic Centre lines at frequencies above 200 MHz with higher spectral resolution.

Another aim of these observations was to determine whether or not low-frequency (<100 MHz) recombination lines of carbon are commonly detectable. In particular, are these lines easily detectable against the strong galactic non-thermal background and in directions with high H I optical depth? Of the 19 directions observed, lines were detected in only two, or possibly three directions. The line-to-continuum ratios of these detections are in the range of 0.0006–0.002. The mean of the upper limits (3σ) for the other directions is 0.0016. It is clear that these lines are not widely detectable with presently available telescopes.

One possible reason for the lack of detections is the angular resolution of the telescopes used. These observations have been made with angular resolutions of 1°.5–10°. In typical single-dish absorption measurements, a background source that is small compared to the beam dominates the continuum emission within the beam. Although the continuum emission from the source is reduced by beam dilution, the line-to-continuum ratio is not. At low frequencies, however, the non-thermal galactic background is generally strong, and there is no relatively small angular diameter background source which dominates the system temperature in most of the directions observed here (except for the Crab Nebula and Cyg A). Because the angular size of the absorbing cloud is likely to be much smaller than the telescope beam, the line-to-continuum ratio for a single cloud will be severely beam-diluted.

One indication of filling-factor effects is provided by the M16 observations, where an absorption line was detected with the 93-m telescope but not with the 43-m telescope. M16 falls within the 43-m telescope beam when pointed to G16.0+0.0 and should have been detected in this direction except for filling-factor effects. The electron temperature of M16 is approximately equal to the 10 000 K background temperature observed in this direction in the 68–80 MHz range. Little contrast between M16 and the background should be expected at these frequencies. If the filling factor for the larger 43-m beam were the same as for the 93-m beam, then the line would have been detected at about the 10σ level, and yet no line was detected. However, if we are observing a single cloud that just fills the 93-m beam, the line would be near the 2σ level and could escape detection with the 43-m telescope. If the cloud is smaller than the 93-m beam, its optical depth must be proportionately higher. Note that the angular size of M16 itself is about 30 arcmin, *very* much smaller than the $\approx$200 arcmin beam of the 93-m telescope at 68 and 80 MHz. It is unlikely that the cloud which causes the absorption lines has such a high optical depth that it would be observable if it covered only M16 itself. It must cover most of the $\approx$200 arcmin beam of the telescope. At 325 MHz, on the other hand, M16 is much brighter than the background and M16 nearly fills the 45 arcmin beam of the 43-m telescope. The observed emission feature would thus be generated by stimulated emission in front of M16 itself and would have an intrinsically smaller angular size of $\approx$30 arcmin. This may explain the fact that the emission feature is much narrower than the absorption feature without invoking pressure broadening.

5 Conclusions

We have observed carbon recombination lines at frequencies less than 100 MHz towards 19 directions in the galactic plane. Positive detections of lines in absorption were made towards the Galactic Centre at 75 MHz and towards M16 at 68 and 80 MHz. The widths of these lines imply electron densities less than 0.8 cm^{-3} in the absorbing clouds. The line towards M16 is observed in emission at 325 MHz as expected from simple theoretical considerations.

The low frequency recombination lines of the type detected towards Cas A (Konovalenko & Sodin 1980, 1981; Ershov *et al.* 1984; Anantharamaiah *et al.* 1985) are not easily detectable in many other directions with presently available telescopes.

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References

Anantharamaiah, K. R. & Bhattacharya, D., 1986. *J. Astr. Astrophys.*, **7**, 141.
Anantharamaiah, K. R., Erickson, W. C. & Radhakrishnan, V., 1985. *Nature*, **315**, 647.
Blake, D. H., Crutcher, R. M. & Watson, W. D., 1980. *Nature*, **287**, 707.

Ershov, A. A., Ilyasov, Yu. P., Lekht, E. E., Smirnov, G. T., Solodkov, V. T. & Sorochenko, R. L., 1984. *Soviet Astr. Lett.,* **10,** 348.

Ershov, A. A., Lekht, E. E., Smirnov, G. T. & Sorochenko, R. L., 1987. *Soviet Astr. Lett.,* **13,** 8.

Konovalenko, A. A., 1984a. *Soviet Astr. Lett.,* **10,** 353.

Konovalenko, A. A., 1984b. *Soviet Astr. Lett.,* **10,** 384.

Konovalenko, A. A. & Sodin, L. G., 1980. *Nature,* **283,** 360.

Konovalenko, A. A. & Sodin, L. G., 1981. *Nature,* **294,** 135.

Landeker, T. L. & Wielebinski, R., 1970. *Aust. J. Phys. Astrophys. Suppl.,* **16,** 1.

Odegard, N., 1986. *Astrophys. J.,* **301,** 813.

Payne, H. E., Anantharamaiah, K. R. & Erickson, W. C., 1988. *Astrophys. J.*, in press.

Payne, H. E., Salpeter, E. E. & Terzian, Y., 1982. *Astrophys. J. Suppl.,* **48,** 199.

Payne, H. E., Salpeter, E. E. & Terzian, Y., 1983. *Astrophys. J.,* **272,** 540.

Radhakrishnan, V., Goss, W. M., Murray, J. D. & Brooks, J. W., 1972. *Astrophys. J. Suppl.,* **24,** 49.

Shaver, P. A., 1975. *Pramana,* **5,** 1.

Walmsley, C. M. & Watson, W. D., 1982a. *Astrophys. J.,* **255,** L123.

Walmsley, C. M. & Watson, W. D., 1982b. *Astrophys. J.,* **260,** 317.

Watson, W. D., Western, L. R. & Christensen, R. B., 1980. *Astrophys. J.,* **240,** 956.

Weaver, H. & Williams, D. R. W., 1973. *Astr. Astrophys. Suppl.,* **8,** 1.