THE ABSORPTION BY THE INTERSTELLAR MEDIUM OF 80 MHz RADIO EMISSION FROM GALACTIC SUPERNOVA REMNANTS

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Abstract

High resolution 80 MHz observations of 20 galactic supernova remnants have been made with the Culgoora radioheliograph. More than half of the sources have an unexpectedly low flux density at 80 MHz, probably as a result of free–free absorption taking place in the inner arms of the Galaxy. The observations imply an r.m.s. electron density of about $0 \cdot 1$–$0 \cdot 5$ cm^{-3} along the line of sight. This large value for the electron density seems to require a greater ionizing flux than that which occurs in the solar vicinity.

I. Introduction

Observations at 80 MHz of galactic nonthermal radio sources reveal that the flux density is often much less than is expected from an extrapolation of higher frequency observations. The most dramatic example of this is Sgr A, whose flux density is less than 5 f.u.‡ as compared with an expected flux density of 350 f.u. (Dulk 1970; Brezgunov, Dagkesamansky, and Udaltsov 1971). Other discrete sources with reported absorption at low frequencies include W49 (Holden and Caswell 1969) and 3C 391 (Caswell *et al.* 1971), the flux densities of which are significantly reduced at 38 and 80 MHz respectively. A number of sources show signs of absorption at 10 MHz (Bridle 1969). Observations of the general background radiation by Shain, Komesaroff, and Higgins (1961), Ellis and Hamilton (1966), and Alexander *et al.* (1970) show a paucity of low frequency ($\leqslant$ 19 MHz) flux in the galactic plane. This is attributable to absorption of the background synchrotron emission by the interstellar medium within a few kiloparsecs of the Sun.

We report here on high resolution 80 MHz observations of 20 supernova remnants (SNR's), 10 to 12 of which are partially or totally absorbed.

II. Technique

The present observations of galactic SNR's were made in 1970 and 1971 with the 80 MHz radioheliograph at Culgoora, N.S.W. The 3 km diameter circle of 96 aerials, each 13 m in diameter, produces up to 48 pencil beams (Wild 1967).

All observations were made with the source near the meridian, where the beam size is then $3' \cdot 7$ in right ascension and $3' \cdot 7 \sec(30^\circ 18' + \delta)$ in declination. Adjacent beams are separated by $2' \cdot 1 \sec(30^\circ 18' + \delta)$ in declination. The eight beams used

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

Table 1

OBSERVED PARAMETERS FOR 20 NONTHERMAL SOURCES

(1) Galactic source number	(2) Position (1950) R.A. h m s	(3) Dec. ° ′	(4) 80 MHz	(5) S_{int} [Size] (f.u.) (min arc) 408 MHz	(6) 5000 MHz	(7) Spectral index α_{408}^{80}	(8) α_{5000}^{408}	(9) H 109α T_L/T_C	(10) τ_{80}	(11) Distance* (kpc)	(12) Map reliability	(13) Refs.*	(14) Notes†
G337·0−0·1	16 32 10	−47 30·0	23±5 [8×7]	36·8[6·1×6·1]	14·4[5·3×7·7]	+0·29	−0·37	0·074	1·08	4·4[1]	Low	1,2,3	1
G337·8−0·1	16 35 22	−46 51·9	20±5 [7×5]	31·5[5·5×5·0]	7·2 [5·9×5·0]	+0·28	−0·59	<0·013	1·41	6·7[1]	Mod.	1,2,3	
G338·3−0·1	16 37 27	−46 27·6	<10	12·5[6·0×5·5]	2·4 [6·7×6·0]	+0·14	−0·66	—	>1·30	5·8[1]	—	1	
G338·5+0·1	16 37 21	−46 12·6	<10	36·8[5·5×7·0]	16·1[6·2×7·5]	+0·80	−0·33	—	>1·84	5·3[1]	—	1	
G348·5+0·1	17 11 12	−38 26·7	120±30[9×6]	150 [8×3]	40 [9×6]	+0·14	−0·53	<0·007	1·08	4·5[2]	High	2,3,4,5,6	2
G348·7+0·3	17 10 47	−38 07·7	68±20 [4·5×7]	50 [2×5]	22 [5×4]	−0·19	−0·33	<0·008	0·23	6·1[2]	Mod.	2,3,4,5,6	3
G349·7+0·2	17 14 37	−37 23·3	30±10 [6×5]		13 [8×5]			<0·015		11·0[2]	Mod.	2,5,7	4
G357·7−0·1	17 37 05	−30 56·9	155±20[6×5]		16 [3×4]			<0·001		7·2[2]	High	2,5,7	5
G359·4−0·1	17 41 24	−29 24·0	<20	55 [5×6]	13 [3×3]	+0·62	−0·58	<0·015	>1·95	5·9[2]	—	2,5,7,8	
G04·5+6·8	17 27 43	−21 26·0	103±10[5×4]	41	7·4 [4·5×4·5]	−0·57	−0·68	<0·004	0·19	11·4[2]	High	2,4,7,9	6
G11·2−0·4	18 08 32	−19 26·9	44±10 [5×4]	35·9[4·3×4·2]	8·5 [4·7×4·8]	−0·12	−0·57	<0·015	0·73	7·6[1]	Mod.	1,2,7	
G18·9+0·3	18 21 21	−12 22·2	70±20 [7×12]	34 [6·6×?]	12 [7×15]	−0·44	−0·41	<0·030	—	4·4[2]	Mod.	2,5,6,7	7
G21·9−0·5	18 30 16	−10 13·0	150±30[13×7]	71 [11·3×5·7]	16 [10·5×6·5]	−0·45	−0·59	<0·015	0·22	2·6[1]	High	1,2,7	8
G25·3−0·1	18 35 11	−06 56·2	20±10 [4×5]	4·8 [2·8×3·3]	<0·5	−0·87	−0·90	—	—	—	Low	1	9
G29·7−0·2	18 43 49	−03 04·0	35±10 [4×4]	14·4[3·0×3·7]	3·3 [4×4]	−0·54	−0·59	—	—	13·8[1]	High	1,2,9	
G31·9+0·0	18 46 47	−00 58·7	34±5 [4·8×5·0]	35 [4·6×4·9]	10 [4·8×4·5]	+0·02	−0·50	<0·015	0·84	>8·5[10]	Mod.	7,10,14	10
G33·7+0·0	18 50 04	+00 35·7	70±20 [10×7]	34‡	5 [6×7]	−0·43	−0·78	<0·040	0·59	7·1[2]	High	2,5,7,11	11
G39·2−0·3	19 01 31	05 22·5	43±10 [5×7]	31·2[4·8×6·4]	9 [4×5]	−0·20	−0·50	<0·020	0·49	6·3[1]	High	1,2,5,7	12
G41·1−0·3	19 05 05	07 03·6	62±8 [5×6]	62‡	15 [10×5]	+0·35‡	−0·42‡	<0·015	0·16	5·3[2]	Mod.	4,7,11,12	13
G43·3−0·2	19 08 39	09 00·5	50±10 [6×5]	58·7[4·9×4·4]	16·7[5·1×4·6]	+0·10	−0·50	—	0·98	6·6[1]	Mod.	1,2,11,13	14

* References: 1, Goss and Shaver (1970) and Shaver and Goss (1970*a*, 1970*b*); 2, Milne (1970); 3, Wilson *et al.* (1970); 4, Lockhart (1971); 5, Altenhoff *et al.* (1970); 6, Kesteven (1968); 7, Reifenstein *et al.* (1970); 8, A. G. Little (personal communication); 9, Milne (1969); 10, Caswell *et al.* (1971); 11, Holden and Caswell (1969); 12, Fomalont (1968); 13, Mezger and Henderson (1967); 14, Bridle and Kesteven (1971).

† Notes on particular sources: 1. CTB 33; combined source, with nonthermal source 3′ north of thermal source (reported by Shaver and Goss 1970*b*). 2. CTB 37A, MSH 17−3*3*. 3. CTB 37B. 4. $\alpha_{5000}^{80} = -0{\cdot}20$; absorption possible. 5. MSH 17−3*9*; $\alpha_{5000}^{80} = -0{\cdot}55$; absorption improbable. 6. Kepler's SNR. 7. MSH 18−1*08*. 8. MSH 18−1*13*. 9. Extragalactic source? 10. 3C 391; 80 MHz flux is revision of 28 f.u. reported by Caswell *et al.* (1971). 11. Flux density in column 5 is for 430 MHz. 12. 3C 396. 13. 3C 397, CTB 67; flux density in column 5 is for 178 MHz and spectral indices in columns 7 and 8 are α_{178}^{26} and α_{5000}^{178} respectively; east component is not present at low frequencies (Wilson *et al.* 1970). 14. 3C 398, W49B.

‡ Refer to note in column 14.

for the present observations were positioned to straddle the source in declination and were repeatedly placed ahead of it to produce a series of drift scans, each of which was either 64 or 128 s long depending on the size of the source. The data were smoothed with a time constant of 2 s, sampled twice per second, and recorded on magnetic tape. Further processing on a digital computer produced averaged drift scans at each declination and a contour map of the source.

The r.m.s. fluctuations in the averaged drift scans amounted to ~ 2 f.u. These fluctuations are caused partly by the system responding to small diameter sources in the grating lobes of the radioheliograph. The radioheliograph does not respond to large scale galactic structure, so that the temperature of the baselevel underlying each discrete source is unknown. The flux density scale is based on observations of a number of calibration sources given by Kellermann, Pauliny-Toth, and Williams (1969). Errors in our calibration probably amount to $\sim 10\%$; for example, our values of flux density differ by $\sim 5\%$ from similar measurements of seven sources by Lockhart (1971), who used a different set of calibrators. The peak brightness temperature $T_{\rm p}$ assigned to the contour maps was obtained from the relationship $T_{\rm p} = S_{\rm p}\,\lambda^2/2k\Omega$, where $k = 1{\cdot}38\times10^{-23}$ J K^{-1}, $S_{\rm p}$ is the peak flux density (W m^{-2} Hz^{-1}), λ is the wavelength (m), and Ω is the solid angle (sr) subtended by each of the heliograph beams to half-power points.

Our source list is based on lists of probable SNR's given by Milne (1970) and Shaver and Goss (1970*b*). Limitations of the radioheliograph allowed us to observe only those sources within $-50° \lesssim \delta \lesssim 35°$ and our recording technique further limited the observations to sources whose size is $\leqslant 10'$ arc.

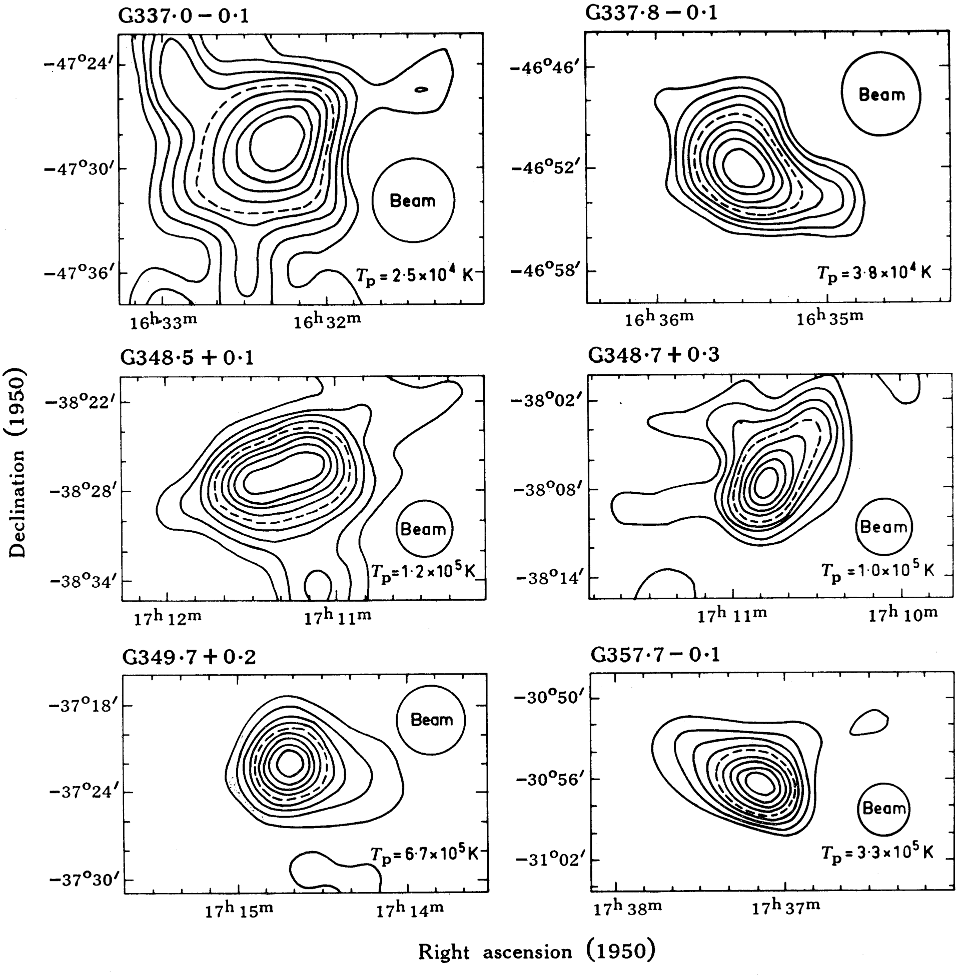
III. Observations

Table 1 lists the 20 sources observed, 17 of which were detected. The position given in columns 2 and 3 is based on higher frequency measurements; the measured position at 80 MHz may differ by 2–3′ arc owing to ionospheric refraction. Column 4 gives our measured flux density S_{80} and the observed source size at 80 MHz.

Wherever possible, our measurements have been compared with the 408 MHz results of Shaver and Goss (1970*a*) and the 5000 MHz results of Goss and Shaver (1970), who had comparable resolution ($\lesssim 4'$ arc). Columns 5 and 6 of Table 1 give the flux density and source size at 408 and 5000 MHz respectively. Columns 7 and 8 give the spectral index α (where $S \propto \nu^{\alpha}$) from 80 to 408 MHz and from 408 to 5000 MHz respectively. The remaining columns of Table 1 are discussed below.

Figures 1(*a*)–1(*c*) show contour maps of the 17 sources detected. The data for these maps were smoothed by eliminating all Fourier components with spatial frequencies higher than the spatial frequency cutoff of the aerial array. For weak sources, the data were further smoothed with a Gaussian function of half-width $0{\cdot}7$ times the beamwidth, a procedure which increased the effective beam size by $\sim 20\%$. The reliability of the contour maps, as determined by their reproducibility from one observation to another, is given in column 12 of Table 1.

Figure 2 shows the spectra of the 20 sources and includes our measurements at 80 MHz. A sharp break in the spectral slope occurs below 400 MHz for about half the sources.



Figs. 1(*a*)–1(*c*).—Contour diagrams of 17 nonthermal sources at 80 MHz. Contour levels are 10, 20, ..., 90% of T_p, the peak main beam brightness temperature; the dashed line is the 50% contour. The 10% contour often varies from one observation to another and has low reliability. Column 12 of Table 1 gives an evaluation of the reliability of the contour maps.

IV. Interpretation

The intrinsic spectrum of SNR's is almost always straight (e.g. Kellermann, Pauliny-Toth, and Williams 1969). When the SNR is sufficiently far from the galactic plane to preclude absorption by interstellar material, the spectrum remains straight to dekametric wavelengths. There is no observational or theoretical evidence for a low energy cutoff in the electron energy distribution, for appreciable synchrotron self-absorption, or for suppression of radiation by the Tsytovich–Razin effect. These possibilities have been discussed in detail by Ginzburg and Syrovatskii (1969), Dulk (1970), Caswell *et al.* (1971), and Bridle and Kesteven (1971). Therefore we attribute the observed break in the spectra of our low galactic latitude SNR's to absorption by the interstellar medium.

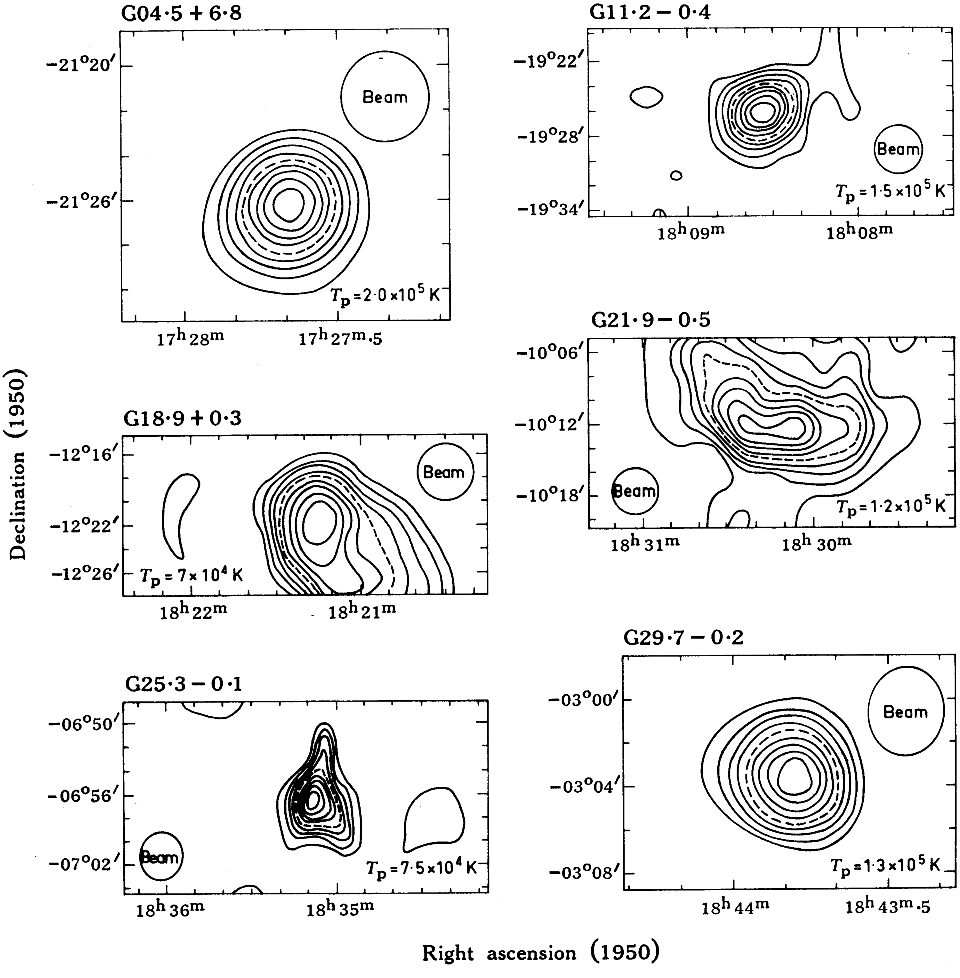


Fig. 1(*b*)

The absorption by the interstellar medium could be due to: (*a*) one or more HII regions along the line of sight, (*b*) the diffuse intercloud medium, (*c*) cold dense clouds, or (*d*) a mixture of emission and absorption regions within the source.

To investigate the cases (*a*)–(*c*), we require an estimate of the optical depth τ_{80} of the absorbing medium at 80 MHz. This may be obtained from the data in Table 1 by calculating the expected 80 MHz flux density S'_{80}, assuming a power law spectrum with spectral index determined by the 408 and 5000 MHz observations:

$$S'_{80} = S_{408}\,(80/408)^{\alpha}.$$

Then we calculate τ_{80} from the observed 80 MHz flux density S_{80} and the relation

$$S_{80} = S'_{80}\exp(-\tau_{80})\,. \tag{1}$$

The resulting values of τ_{80} are listed in column 10 of Table 1 and column 2 of Table 2.

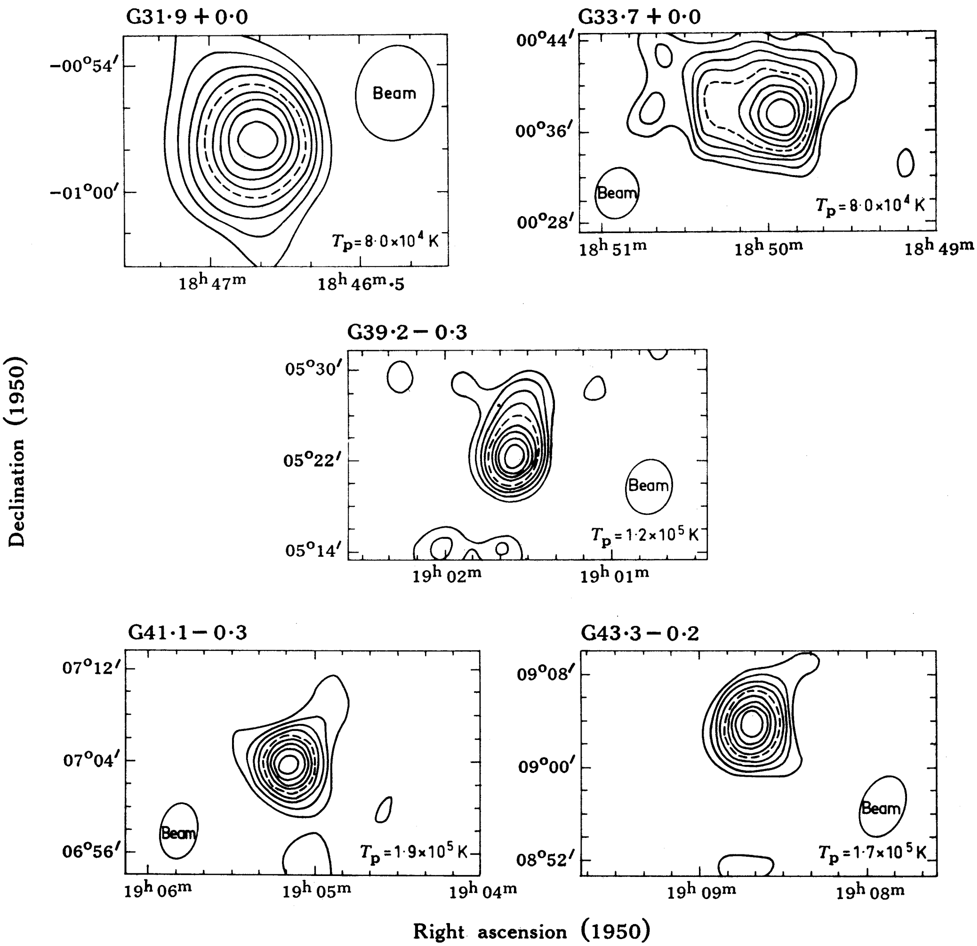


Fig. 1(c)

We estimate the uncertainty in τ_{80} to be $\sim 0\cdot3$ so that the values of τ_{80} given for G348·7+0·3, G04·5+6·8, and G21·9−0·5 are unreliable. The case of G41·1−0·3 is an exception in that the value $\tau_{80} = 0\cdot16$ was derived using a flux density measured at 26·3 MHz.

To proceed further, we use the relation given by Mezger and Henderson (1967) (see also Oster 1970)

$$\tau = 8\cdot235\times10^{-2}\,a(T_e,\nu)\,\nu^{-2\cdot1}\,E T_e^{-1\cdot35}\,, \tag{2}$$

where

$$E = \int n_e^2\,\mathrm{d}s = n_e^2 L$$

is the emission measure (cm^{-6} pc), L being the thickness of the absorbing medium (pc), $a(T_e, \nu)$ is a correction factor of order unity, T_e is the electron temperature (K), and ν is the frequency (GHz). The quantity $E T_e^{-1\cdot35}$, which is listed in column 3 of Table 2, is found from equation (2) by putting $\nu = 0\cdot08$ GHz and $a(T_e, \nu) = 1$.

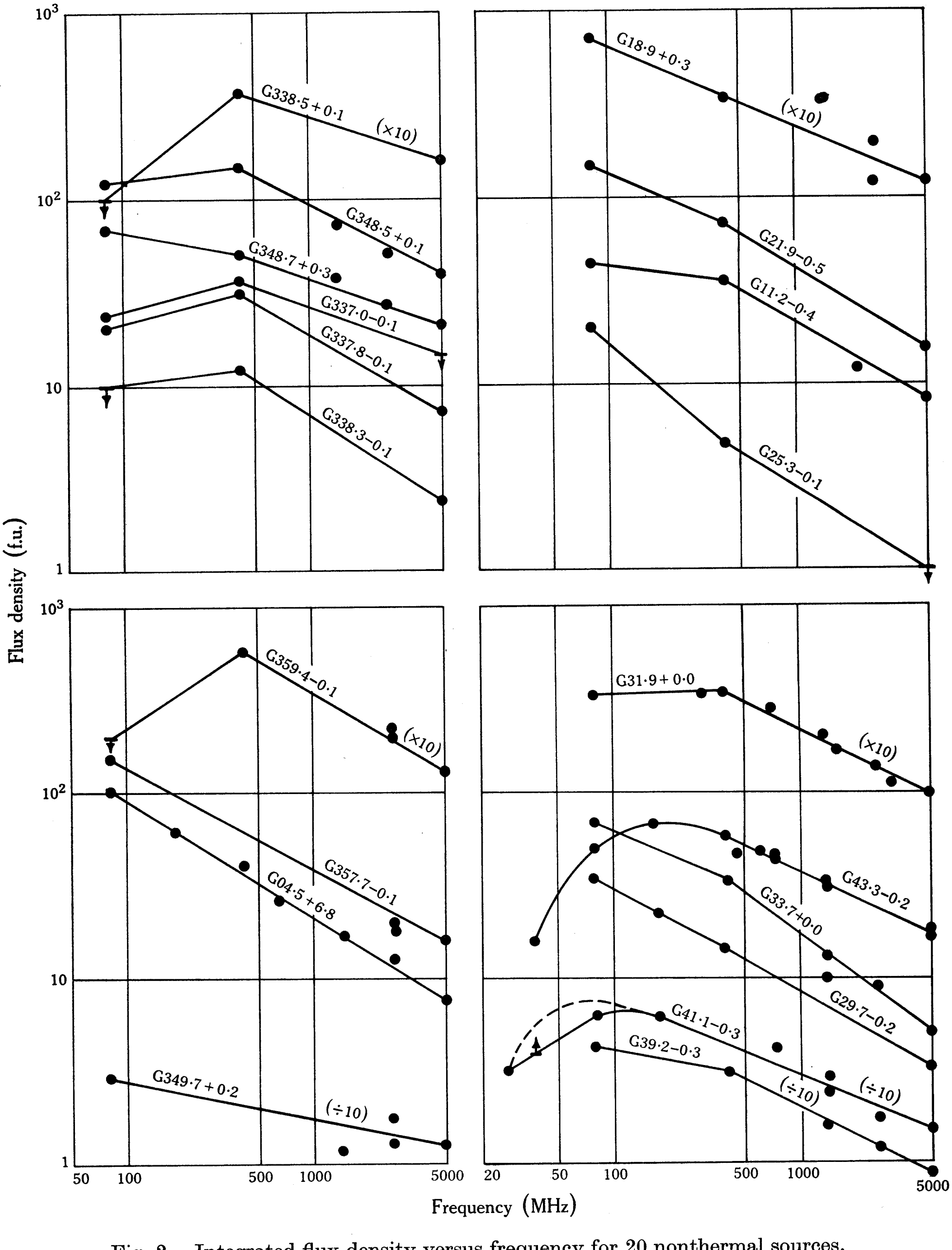


Fig. 2.—Integrated flux density versus frequency for 20 nonthermal sources.

It should be noted that, apart from the assumption that the intrinsic spectrum of SNR's is straight, $ET_e^{-1\cdot 35}$ is obtained directly from the observations.

Columns 5, 8, and 11 of Table 2 give respectively the emission measure for $T_e = 5000$ K (possibly pertaining to HII regions and/or the intercloud medium), $T_e = 100$ K (possibly pertaining to some intercloud regions), and $T_e = 50$ K (possibly pertaining to cold dense clouds). We now consider these possibilities in more detail.

TABLE 2

DERIVED PARAMETERS FOR 13 NONTHERMAL SOURCES AND SGR A

The emission measure E is given in units of cm^{-6} pc, the r.m.s. electron density $\langle n_e^2 \rangle^{\frac{1}{2}}$ in cm^{-3}, and the quantity ζn_{HI} in $10^{-14}\ cm^{-3}\ s^{-1}$

(1) Source	(2) τ_{80}*	(3) $ET_e^{-1\cdot 35}$ (a=1)	(4) Dist.* (kpc)	(5) $T_e = 5000$ K E	(6) $\langle n_e^2 \rangle^{\frac{1}{2}}$ [$L=D$]	(7) ζn_{HI}	(8) $T_e = 100$ K E	(9) $\langle n_e^2 \rangle^{\frac{1}{2}}$ [$L=0\cdot 3D$]	(10) ζn_{HI}	(11) $T_e = 50$ K E	(12) $\langle n_e^2 \rangle^{\frac{1}{2}}$ [$L=0\cdot 02D$]	(13) ζn_{HI}
G337·0−0·1	1·08	0·065	4·4[1]	6600	1·22	67	36	0·16	18	15	0·41	180
G337·8−0·1	1·41	0·085	6·7[1]	8600	1·13	57	47	0·15	16	20	0·38	160
G338·3−0·1	>1·30	>0·078	5·8[1]	>7900	>1·17	>62	>43	>0·16	>18	>18	>0·39	>160
G338·5+0·1	>1·84	>0·111	5·3[1]	>11200	>1·45	>94	>61	>0·20	>28	>26	>0·49	>260
G348·5+0·1	1·08	0·065	4·5[2]	6600	1·21	66	36	0·16	18	15	0·41	180
G359·4−0·1	>1·95	>0·118	5·9[2]	>11900	>1·42	>90	>64	>0·19	>25	>27	>0·48	>250
Sgr A	>4·0[3]	>0·243	10	>24400	>1·56	>110	>132	>0·21	>31	>56	>0·53	>300
G11·2−0·4	0·73	0·044	7·6[1]	4400	0·76	26	24	0·10	6·9	10	0·26	73
G21·9+0·5	0·22	0·013	2·6[1]	1300	0·72	23	7·3	0·10	6·9	3·1	0·24	62
G31·9+0·0	0·84	0·051	>8·5[4]	5100	<0·78	<27	28	<0·11	<7·3	11·7	<0·26	<73
G33·7+0·0	0·59	0·036	7·1[2]	3600	0·71	23	19	0·10	6·9	8·2	0·24	62
G39·2−0·3	0·49	0·030	6·3[1]	3000	0·69	21	16	0·10	7·0	6·8	0·23	57
G41·1−0·3	0·16	0·010	5·3[2]	980	0·43	8·3	5·3	0·06	2·5	2·2	0·14	21
G43·3−0·2	0·98	0·059	6·6[1]	6000	0·95	40	32	0·13	11·7	13·6	0·32	110
Average	1·19	0·072	6·2	7300	1·08	52	39	0·15	15·6	17	0·36	140

* References: 1, Goss and Shaver (1970) and Shaver and Goss (1970*a*, 1970*b*); 2, Milne (1970); 3, Dulk (1970); 4, Caswell *et al.* (1971).

(*a*) *Absorption by HII Regions*

An HII region dense enough or deep enough to absorb the 80 MHz radiation might be detectable by, for example, its hydrogen recombination lines. Column 9 of Table 1 lists the observed line–continuum temperature ratio of the H 109α line. This line was detected for only one source, G337·0−0·1, and in this case there is evidence for a near coincidence of two separate sources, with the line-emitting source displaced by 3′ arc from, and more distant than, the SNR (Shaver and Goss 1970*b*). However, because of the high contributions made by these nonthermal sources to the continuum temperatures, the measured T_L/T_C limits do not place very stringent limits on the amount of ionized hydrogen present in front of the sources (Bridle and Kesteven 1971). The emission measures derived from our observations on the assumption that $T_e = 5000$ K range from about 10^3 to $3 \times 10^4\ cm^{-6}$ pc. These are small to moderate values for HII regions, although recombination lines might be detectable if studies were made with special care.

The distances to supernova remnants can be estimated from measurements of their angular diameters and surface brightnesses (Kesteven 1968; Milne 1970).

Column 11 of Table 1 gives these distances, which are probably good to about $\pm 50\%$ (Shaver and Goss 1970*b*). In Figure 3 the estimated positions of the SNR's are shown on a map of the HI spiral structure of the Galaxy. We see that at least two unabsorbed SNR's (G357·7−0·1 and G348·7+0·3) lie in the same general direction of, and possibly at larger distances than, a half-dozen absorbed SNR's. This suggests that the absorption is spotty, as would be expected if it results from discrete HII regions. On the other hand, it seems extraordinary that more than half of our 20 SNR's would lie behind HII regions (for estimates of the spatial distribution of HII regions see Mezger 1970 and Shaver and Goss 1970*b*).

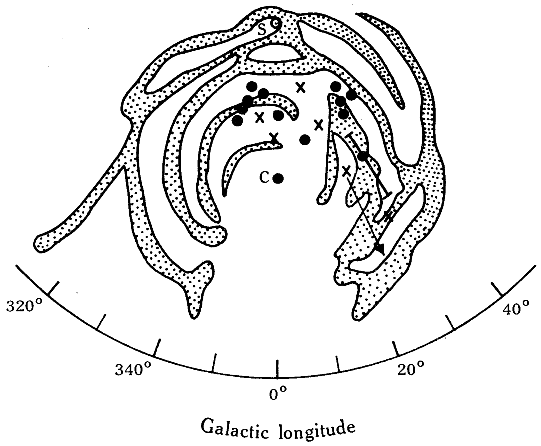


Fig. 3.—Schematic outline of the HI structure of the Galaxy with the estimated positions of observed SNR's. The filled circles and crosses represent absorbed and unabsorbed SNR's respectively. The galactic centre source Sgr Å (marked C) is also absorbed at 80 MHz. The Sun's position is marked S. (Diagram after Kerr and Westerhout 1965.)

(*b*) *Absorption by Intercloud Medium*

Models of the general interstellar medium have been calculated by Field, Goldsmith, and Habing (1969), Hjellming, Gordon, and Gordon (1969), and Spitzer and Scott (1969). The predicted temperature of this intercloud medium lies between 10^3 K (Hjellming, Gordon, and Gordon 1969) and 10^4 K (Field, Goldsmith, and Habing 1969). The absorption coefficient at 80 MHz is correspondingly low. Assuming $T_e = 5000$ K, the emission measures required by the observed absorption are between 10^3 and 3×10^4 cm^{-6} pc. If we now assume that the absorption occurs along the entire path, we may put $L = D$ and derive the r.m.s. electron densities given in column 6 of Table 2. (These values would be reduced by a factor of 2·5 if we put $T_e = 1000$ K.) They range from about 0·4 to $> 1\cdot5$ cm^{-3}, about an order of magnitude greater than is predicted by theoretical models or is observed near the Sun by pulsar dispersion measurements (Radhakrishnan and Murray 1969; Van de Hulst 1970).

Gordon and Gottesman (1971) and Jackson and Kerr (1971) measured recombination line emission from regions away from known sources. Assuming local thermodynamic equilibrium and a uniform medium, they found that the temperature was between 10^3 and 2×10^3 K, and the r.m.s. electron density, (or more properly, $\langle n_e n_{HII}\rangle^{\frac{1}{2}}$) was between 0·15 and 0·3 cm^{-3}. Our data in Table 2 imply $0\cdot15 \lesssim \langle n_e^2\rangle^{\frac{1}{2}} \lesssim 0\cdot5$ if $T_e = 1000$ K. (We measured no absorption near galactic longitude

25° where the recombination lines of Gordon and Gottesman (1971) were observed, and so our lower value, $0 \cdot 15$ cm^{-3}, should be representative there.) Therefore the recombination line emission and 80 MHz absorption give similar electron densities, and both imply higher electron densities in the inner regions of the Galaxy than are found to occur in the solar vicinity (Bridle and Venugopal 1969; Alexander *et al.* 1970).

An especially interesting comparison involves the source G31·9+0·0 (3C 391) which lies only 0°·7 from G31·2+0·0, the location at which Jackson and Kerr (1971) observed a recombination line. Emission and absorption measurements at 21 cm reported by Caswell *et al.* (1971) and Bridle and Kesteven (1971) have established that the distance to G31·9+0·0 is between 8·5 and 13 kpc. (The distance derived from the flux density–angular size relation is 9·1 kpc.) Thus the path lengths for the 80 MHz absorption and recombination line emission ($\approx$ 13 kpc) are similar. Taking $T_e = 1000$ K, $L_{80} = 10^4$ pc, and $\tau_{80} = 0 \cdot 84$, we find from equation (2) that $\langle n_e^2 \rangle^{\frac{1}{2}} = 0 \cdot 24$. For the recombination line we use the relation of Dupree and Goldberg (1970)

$$T_L \Delta\nu_L = 1980\, E T_e^{-1\cdot 5} \exp(13\cdot 3/T_e)\,, \tag{3}$$

where T_L (K) is the line temperature, $\Delta\nu_L$ (kHz) is the full linewidth at half-power, T_e (K) is the electron temperature, and E (cm^{-6} pc) is the emission measure. Using Jackson and Kerr's (1971) values of $T_L \Delta\nu_L = 60$ K kHz and $L_L = 13$ kpc, we find $\langle n_e n_{HII} \rangle^{\frac{1}{2}} = 0 \cdot 28$. The agreement is very good, probably because the same regions which emit the recombination lines also absorb 80 MHz flux. The recombination line profile indicates that the emission occurs mainly in the Scutum and Sagittarius arms; the 21 cm absorption line profile of G31·9+0·0 also shows strong absorption features from these arms. These factors suggest that most of the recombination line emission, the 80 MHz absorption, and the 21 cm absorption occurs in extended regions (the general interstellar medium or possibly a number of small clouds) within spiral arms.

If we assume a steady state, we can estimate the ionization rate from the ionization equilibrium equation

$$\zeta n_{HI} = n_e n_{HII} \alpha^{(2)}\,, \tag{4}$$

where $\alpha^{(2)}$ is the hydrogen recombination coefficient to the second level (s^{-1} cm^3) and ζ is the ionization rate (s^{-1}) (Spitzer 1968). Putting $n_e = n_{HII}$ and using the expression for $\alpha^{(2)}$ from Spitzer (1968), we obtain the quantity ζn_{HI} listed in column 7 of Table 2. In the general interstellar medium we expect $n_H \lesssim 1$ cm^{-3} (Van Woerden 1967). Therefore ζ must be 10^{-12}–10^{-13}, which is a factor of 100–1000 greater than is estimated for the solar vicinity (Field, Goldsmith, and Habing 1969). The required ionization fraction x is high ($\gtrsim 0 \cdot 5$) and the total density $n_H = n_{HI} + n_{HII}$ must be greater than n_e, and hence $\gtrsim 1$ cm^{-3}.

We note here that if large parts of the general interstellar medium have temperatures of only $\sim$100 K then the electron density required to produce the 80 MHz absorption is only $\sim 0 \cdot 15$ (see column 9 of Table 2). Although this low temperature is not a feature of theoretical models based on cosmic ray or X-ray heating, it could occur in the nonsteady-state model discussed in Section V.

(c) *Absorption by Cold Dense Clouds*

We now consider the third possibility, absorption by cold dense clouds. The low temperature of such clouds ($T_e \approx 50$ K) increases the absorption coefficient to the extent that $\langle n_e^2 \rangle^{\frac{1}{2}} \approx 0 \cdot 05$ is sufficient to produce the observed absorption if the clouds occupy the entire line of sight. However, if the clouds occupy only a few per cent of the line of sight (Van Woerden 1967) then $0 \cdot 14 \lesssim \langle n_e^2 \rangle^{\frac{1}{2}} \lesssim 0 \cdot 5$ is required (column 12 of Table 2).

Cesarsky and Cesarsky (1971) showed that the data of Gottesman and Gordon (1970) can be explained by a two-phase medium in which the cold dense clouds produce most of the recombination line emission. Assuming that the clouds occupy 2% of the line of sight and have $T_e \approx 50$ K, they find $\langle n_e n_{\rm HII} \rangle^{\frac{1}{2}} \approx 0 \cdot 1$. Our data in column 12 of Table 2 show that, with the same cloud temperature and filling factor, the required electron density is $0 \cdot 14 \lesssim \langle n_e^2 \rangle^{\frac{1}{2}} \lesssim 0 \cdot 5$. (Again, the lower value, $0 \cdot 14$ cm^{-3}, should pertain to the longitude of Gottesman and Gordon's (1970) observations.) The agreement here is not quite as good but is still well within the limits of the observations.

If we again assume ionization equilibrium and use equation (4) to estimate $\zeta n_{\rm HI}$, we obtain the values in column 13 of Table 2. Putting $n_{\rm HI} = 100$ cm^{-3} in these cold clouds, we find $2 \times 10^{-15} \lesssim \zeta \lesssim 3 \times 10^{-14}$, which is a factor of 10–100 greater than is estimated for the solar vicinity. The ionization fraction is $1 \cdot 5 \times 10^{-3} \lesssim x \lesssim 5 \times 10^{-3}$.

(d) *Absorption by Regions in the Source*

We now turn to the fourth possibility: that the source consists of a mixture of emission and absorption regions. In this case, the turnover in the spectrum is rather gradual with a power law, rather than an exponential, decrease in flux at low frequencies. One of the sources G41·1—0·3 has a spectrum which seems to be better fitted by a power law decrease of flux (see Fig. 2), while four others (G338·5+0·1, G359·4—0·1, Sgr A, and G43·3—02) are better fitted by an exponential decrease. The data on the remaining sources are too sparse to decide between the two models.

V. Discussion

The r.m.s. electron density in the absorbing medium is seen from Table 2 to be about 0·1–1·5 cm^{-3}, depending on the assumed temperature and filling factor. On the other hand, 0·1 cm^{-3} is an upper limit to the average electron density $\langle n_e \rangle$ in the solar neighbourhood, as determined by pulsar observations (Bridle 1969; Radhakrishnan 1969). Also, theoretical investigations predict $n_e < 0 \cdot 1$ both in the warm intercloud region and in cold dense regions (Hjellming, Gordon, and Gordon 1969; Spitzer and Scott 1969; Field 1970).

If our high values for $\langle n_e^2 \rangle^{\frac{1}{2}}$ are correct, these high electron densities must be maintained in the cold dense clouds by an enhanced ionization rate or a depressed recombination rate (see e.g. Spitzer 1968). The cosmic ray or X-ray intensity must then be 10–1000 times higher in the inner arms of the Galaxy (where most of the absorption presumably occurs) than in the solar vicinity. Local sources of soft X-rays may dominate in these regions (Silk and Werner 1969).

Schwarz, McCray, and Stein (1972) have developed a time-dependent model of the interstellar medium in which most of the heating and ionization comes from occasional supernovae. In their model, small cold clouds condense from density perturbations and the remaining interstellar material cools slowly with a cooling time $\tau_c \approx 10^5$ yr. In the 10^6 yr preceding the next supernova in the vicinity, the material may cool to < 100 K, while remaining largely ionized. Therefore, according to this model, a large portion of the interstellar medium may be in a cool, partially ionized state. The radio wave absorption may occur in the small cold clouds or, perhaps as likely, in extended cool intercloud regions within the spiral arms. Our data in Table 2 show that if $T_e \approx 100$ K and if the absorbing regions occupy 30% of the line of sight, then $\langle n_e^2 \rangle^{\frac{1}{2}} \approx 0 \cdot 2$ will suffice to explain the absorption.

VI. Conclusions

The present observations suggest that large HII regions of low surface brightness can probably be eliminated as significant sources of 80 MHz absorption, purely on account of the improbability of so many of the sources lying behind such regions. We cannot, however, decide between absorption by distributed ionized hydrogen with a temperature of a few hundred to a few thousand kelvins and absorption in cold dense clouds which occupy a few per cent of the line of sight. Our data, together with recombination line observations, suggest that the absorption occurs within spiral arms in the inner parts of the Galaxy. Compared with the solar vicinity, the absorbing regions must be unusally highly ionized by a continuous cosmic ray or X-ray flux, or possibly by ultraviolet and soft X-rays from occasional supernovae.

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