A SOUTHERN MILKY WAY SURVEY AT 408 Mc/s

By M. M. Komesaroff*

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Summary

A survey of the galactic-plane emission at 408 Mc/s has been carried out over the range $280° < l^{\mathrm{II}} < 355°$, using the Australian 210 ft radio telescope which has a beamwidth of 47′·5 arc at this frequency. It is found that an abrupt increase in the emission which occurs near $l^{\mathrm{II}} = 326°$, and extends over several degrees of latitude, has a non-thermal spectrum. An estimate of the total radiated power is made, and it is suggested that this feature may be related to the expanding arm of neutral hydrogen whose existence has been demonstrated by H-line studies.

I. Introduction

Before 1962, only two surveys with pencil-beam resolution better than 1° had been made of the galactic-plane radio emission in the region south of the centre. These were the 85 Mc/s and 1440 Mc/s surveys of Hill, Slee, and Mills (1958) and Mathewson, Healey, and Rome (1962) respectively. By contrast, the region north of the centre had been studied at 85 Mc/s (Hill, Slee, and Mills 1958), 408 Mc/s (Large, Mathewson, and Haslam 1961), 960 Mc/s (Wilson and Bolton 1960), 1390 Mc/s (Westerhout 1958), and 2700 Mc/s (Altenhoff *et al.* 1960).

It was desirable to have at least one survey of the southern region at an intermediate frequency, both to provide additional spectral data about the discrete sources and to test the conclusions drawn by Mathewson, Healey, and Rome (1962) about the large-scale distribution of the thermal and non-thermal radiation components.

The present observations at 408 Mc/s were made with the 210 ft telescope of the Australian National Radio Astronomy Observatory, which at this frequency has a beamwidth of 47′·5 arc, very similar to the resolution of the earlier surveys. The 408 Mc/s studies were carried out simultaneously with higher resolution (14′ arc) observations at 1390 Mc/s by Hill. The area covered embraces approximately the region $-6° < b^{\mathrm{II}} < +6°$, $282° < l^{\mathrm{II}} < 356°$.

The present data generally confirm the spectral classification of discrete sources previously made by Mathewson, Healey, and Rome (1962), though in one or two cases there is evidence of spectral curvature which warrants further investigation.

An interesting result concerns a "step" in the brightness temperature contours near $l^{\mathrm{II}} = 326°$. The 408 Mc/s observations show that this contains two components. The first, which was discovered by Mathewson, Healey, and Rome, has a width in latitude of only 1°–2° and a thermal spectrum. Its longitude is symmetrical

* Division of Radiophysics, CSIRO, University Grounds, Chippendale, N.S.W.; present address: Department of Physics and Astronomy, University of Maryland.

with that of a similar thermal "step" north of the galactic centre, first described by Westerhout (1958) and attributed by him to a ring or disk of ionized hydrogen concentric with the Galaxy.

The second component, which occurs at the same longitude, has a non-thermal spectrum and extends at least over the range $-5°$ to $+5°$ in latitude. The coincidence in longitude and the fact that the non-thermal step represents more than 20% of the total galactic brightness suggest that it, too, is a large-scale galactic feature. An examination of radio surveys north of the galactic centre indicates that the step at the symmetrical longitude also contains a non-thermal component, although it is a considerably weaker one.

It is shown that the whole feature may be explained as synchrotron emission from a thin ring, containing an approximately tangential magnetic field, that is concentric with the Galaxy. In Section VII is discussed a possible connection with the expanding arm of neutral hydrogen discovered by Rougoor and Oort (1960). It is shown that the power outflows from the two features are of comparable magnitude, and it is suggested that they may draw their energy from a common source.

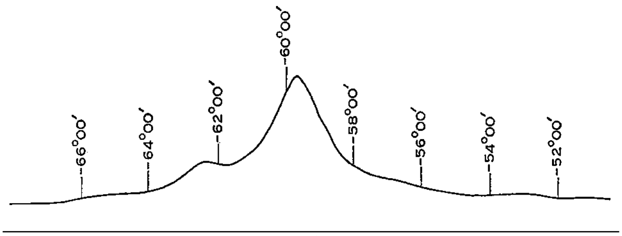


Fig. 1.—A typical scan in declination at R.A. $14^h 42^m 00^s$.

II. Equipment

The observations extended over three periods of 1–2 weeks in 1962. The receiver, previously described by Mackey (1964), was a double-sideband crystal mixer with a bandwidth of 8 Mc/s and was electronically switched between the feed dipoles and a low temperature reference load. The feeds consisted of a pair of parallel dipoles and reflector. The aerial beamwidth to half power was measured as $47' \cdot 5$ arc.

III. Observing Procedure and Data Reduction

Because the survey was strongly resolution-limited, and in order to minimize non-linearity effects due to the wide range of aerial temperatures, the normal sensitivity of the system was reduced by inserting an attenuator between the aerial feed and the receiver input. In this condition the minimum detectable flux was between 5 and 10 flux units (1 flux unit (f.u.) $= 10^{-26}\ \mathrm{W\,m^{-2}\,(c/s)^{-1}}$).

The observing procedure was determined by the 1390 Mc/s survey. Declination scans between $b = +6°$ and $b = -6°$ were made using a telescope drive rate of $2 \cdot 5°$/min, the interval in right ascension between scans being one-quarter to onethird of the 1390 Mc/s beamwidth (14′ arc). This produced a considerable redundancy at 408 Mc/s. An example of such a scan, at R.A. $= 14^{h}\,42^{m}\,00^{s}$, is shown in Figure 1. The markers appearing on this record are at declination intervals of 2°.

Hydra A was adopted as a standard of flux density. Its 408 Mc/s flux density was taken to be 137 f.u. (Kellermann 1964). The increment of "full beam brightness temperature" (see Seeger, Westerhout, and van de Hulst 1956) corresponding to Hydra A is 124 degK.

All temperatures were measured relative to the south celestial pole. To this end two procedures were adopted.

(1) Two series of long scans were made through the region to be surveyed, one a few degrees north and one a few degrees south of the galactic equator where the gradients are small. Immediately before and after each scan the aerial was pointed at the south celestial pole to establish the baseline.

(2) The aerial was also pointed at the pole a number of times during each night's observations.

Taken in conjunction with measured zenith angle effects derived from scans at a number of azimuths, (1) and (2) independently provided "baselines" for the survey scans. In general these agreed to better than half a contour interval.

In constructing the isophotes the contour interval chosen was 25 degK aerial temperature, as determined from noise lamp calibrations. This is equivalent to 34·7 degK "full beam brightness temperature".

For each night's observations a scale was constructed consisting of parallel lines drawn on transparent paper, the spacing being equal to the deflection corresponding to one contour interval, with allowance for receiver non-linearities. The scale was laid over the record of each scan in turn, and the declination was noted of each contour level as measured above the previously determined baseline. These declinations were corrected for the effect of the 2 s receiver time constant at the scanning rate of 2·5°/min. The right ascensions and corrected declinations were then converted, using an IBM 7090 computer, to New Galactic Coordinates. The isophotes drawn from the resultant data are shown in Figure 2.

IV. The Discrete Sources

(a) *The Source List*

Table 1 lists the 49 sources that were observed; of these 39 have been catalogued by previous observers. It is believed that for the majority of sources the quoted positions are accurate to within $\pm 6'$ arc in each coordinate. Confusion was the major source of position error.

Angular sizes were not estimated, since resolution effects and residual receiver non-linearities could make such estimates quite misleading. Thus the figures quoted in column 6 are "peak" flux densities, designated by S'_{408} (in f.u.), and represent lower limits to the true flux densities.

Columns 7 and 8 contain "peak" flux densities for 85 and 1440 Mc/s respectively. The 85 Mc/s data are quoted directly from the Mills, Slee, and Hill (1958, 1960,

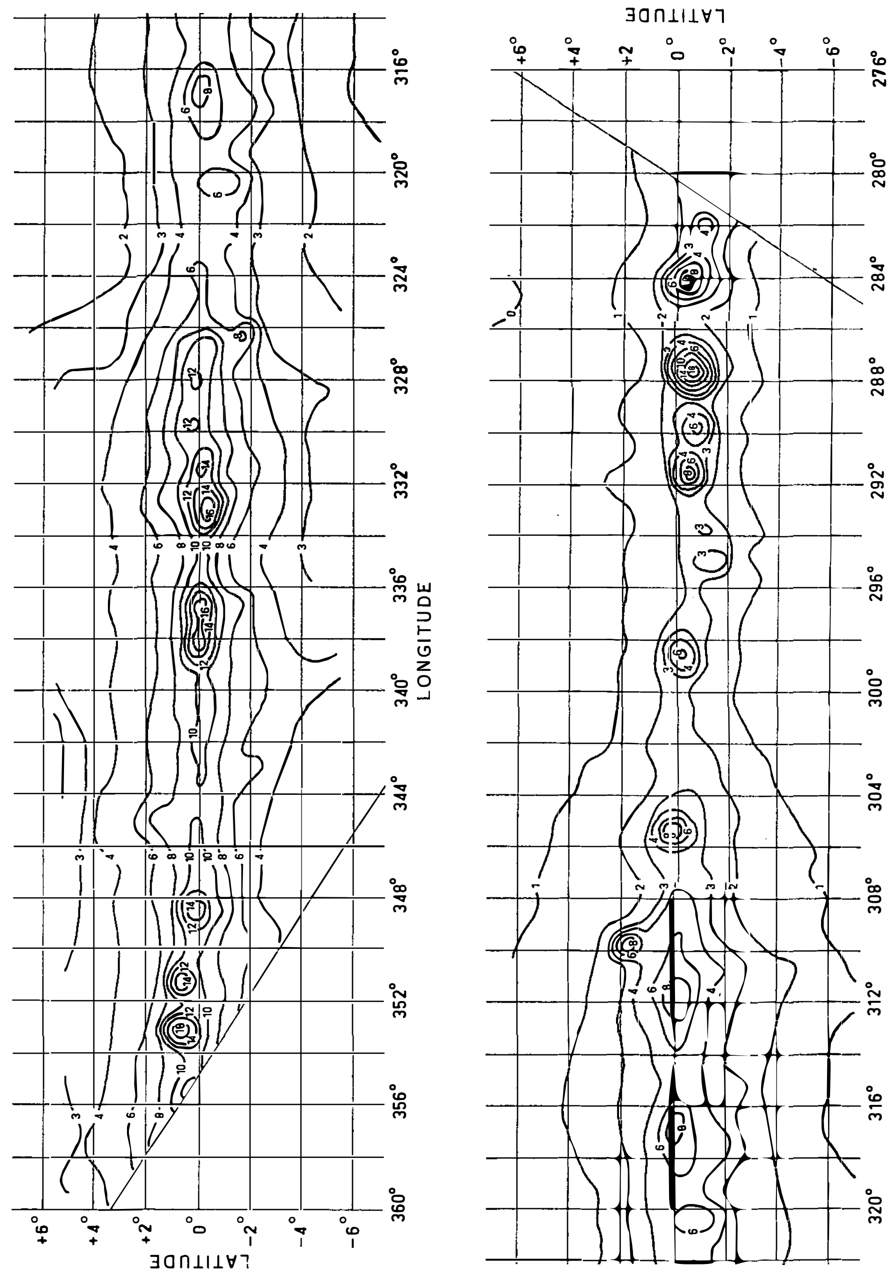


Fig. 2.—408 Mc/s isophotes. The contour interval is 25 degK aerial temperature or 34·7 degK "full beam brightness temperature".

1961) catalogue, while the 1440 Mc/s data are derived by multiplying the value of ΔT_{1440} due to Mathewson, Healey, and Rome (1962) by 15·3.

In calculating the spectral indices α_{85}^{408} and α_{408}^{1440} (columns 9 and 10), the quoted values of S'_{85} and S'_{1440} have been divided by 1·2 and 1·1 respectively in order to bring the flux scales at 85 and 1440 Mc/s into agreement with that of Conway, Kellermann, and Long (1963). This was done since the value for Hydra A used to determine the 408 Mc/s scale was based on the one due to those workers.

Columns 11, 12, and 13 of Table 1 contain source catalogue numbers used respectively by Mills, Slee, and Hill, by Mathewson, Healey, and Rome, and by Wilson and Bolton (1960).

The sources are classed as thermal or non-thermal in column 14, according to their spectral indices, and column 15 repeats identifications previously made by Mathewson, Healey, and Rome and, in the case of source 26, by Mills, Slee, and Hill. The abbreviations used in column 15 are:

RCW—Rodgers, Campbell, and Whiteoak (1960); G—Gum (1955);
BBW—Bok, Bester, and Wade (1955).

(b) *Accuracy of Flux Densities and Spectral Indices*

The accuracy with which the value of S'_{408} could be estimated was limited mainly by confusion. For the majority of cases where S'_{408} exceeds 30 f.u., it is believed that the error in the quoted value does not exceed about $\pm 20\%$. However, sources 1, 7, 8, 18, 22, 24, 28, 31, 38, and 39 are situated in highly confused regions, and for these the errors may be greater. Assuming that the errors in the other surveys also do not usually exceed $\pm 20\%$, the values of α_{85}^{408} and α_{408}^{1440} for the "strong" sources (except those mentioned above) are not in error by more than about $\pm 0 \cdot 25$.

(c) *Spectral Curvature*

The only sources, therefore, that show an apparently significant and "anomalous" spectral curvature are 4 and 46. The "background level" for source 4 is fairly indefinite and may have led to an unexpectedly large error. However, this does not seem to be so in the case of source 46, which is quite strong at all three frequencies, but a more careful investigation is required to determine if the spectral curvature is genuine. An exceedingly dense foreground HII region would be required if the effect is due to thermal absorption.

Two other interesting sources are 38 and 39. In neither case is the 408 Mc/s flux-density estimate considered very reliable, but since source 38 does not appear at 85 Mc/s, it has been classified as thermal. However, it is the only thermal source of such high flux density not identified with an optical object (unless it is part of RCW 108, whose position, however, is given as $l^{\mathrm{II}} = 336 \cdot 5°$, $b^{\mathrm{II}} = -1 \cdot 3°$).

Mathewson, Healey, and Rome have commented on 39, which, although it seems to have a thermal spectrum (between 1440 and 85 Mc/s), is seen in emission at 85 Mc/s against a background temperature greater than 13 000°K. If it is an HII region with electron temperature of 10^4 °K, and if the non-thermal emissivity of the Galaxy is roughly uniformly distributed along the line-of-sight, the distance of the

Table 1

LIST OF DISCRETE SOURCES

Serial No.	Position (1950·0) R.A. h	m	s	Dec. °	′	l^{II} °	b^{II} °	Peak Flux Density (10^{-26} W m^{-2} (c/s)$^{-1}$) 408	85	1440	Spectral Index α^{85}_{408}	α^{408}_{1440}	Catalogue No. MSH	MHR	WB	Spectrum	Source Identifications
1	10	04	14	−57	02	282·0	−1·3	60	47	110	+0·3	+0·4	10−*51*	9		th.	RCW 46
2	10	21	27	−57	31	284·2	−0·4	310	96	350	+0·8	0·0	10−*54*	10		th.	RCW 49; G 29
3	10	42	30	−59	34	287·6	−0·8	610	242	650	+0·7	0·0	10−*57*	11		th.	Carinae Nebula; RCW 53; NGC 3372
4	10	59	05	−60	34	289·9	−0·8	148	162	100	+0·1	−0·4	11−*61*	13		non-th.	NGC 3503
5	11	11	49	−61	01	291·5	−0·6	254	42	370	+1·3	+0·2	11−*62*	14		th.	RCW 57; G 38; NGC 3603
6	11	22	26	−58	56	292·0	+1·8	19	39	15	−0·4	−0·3	11−*54*	15		non-th.	
7	11	27	26	−62	08	293·6	−1·0	30		75		+0·7		17		th.	RCW 60; IC 2872
8	11	36	25	−63	05	294·9	−1·6	95	38	75	+0·7	−0·3	11−*65*	18		?	RCW 62; IC 2944
9	11	36	26	−67	51	296·2	−6·2	10	34		−0·7		11−*64*			non-th.	
10	12	09	47	−62	33	298·5	−0·3	166	112	165	+0·4	−0·1	12−*61*	20		th.	
11	12	18	42	−63	46	299·7	−1·4	10									
12	12	28	37	−66	55	301·0	−4·4	15									
13	13	09	44	−62	24	305·4	+0·1	230		260		0·0		25		th.	RCW 74
14	13	29	06	−66	56	306·9	−4·6	19									
15	13	43	19	−60	10	309·7	+1·7	242	795	130	−0·6	−0·6	13−*62*	29		non-th.	IAU 13S6A
16	13	57	32	−66	36	309·7	−4·9	10									
17	13	59	34	−63	46	310·7	−2·2	26	20		+0·3		13−*63*			th.	
18	14	06	00	−61	20	312·0	0·0	75	69	140	+0·2	+0·4	14−*61*	31		th.	RCW 83
19	13	58	08	−57	46	312·1	+3·6	10	35		−0·7		13−*52*			non-th.	
20	14	19	31	−64	07	312·7	−3·2	10									
21	14	14	07	−57	21	314·3	+3·4	10		15		+0·2		34		th.	
22	14	38	19	−62	22	315·3	−2·4	45	110	30	−0·5	−0·4	14−*63*	35		non-th.	
23	14	27	51	−56	57	316·2	+3·1	10									
24	14	43	10	−59	20	317·1	+0·1	132		120		−0·2		37		?	

25	14	52	31	−61	01	317·4	−1·9	19	84		−0·8		14—*61*			non-th.	
26	15	11	00	−59	03	320·4	−1·3	90	190		−0·4		15—*52*			non-th.	BBW 28802
27	15	27	58	−60	47	321·2	−3·9	10	55		−1·0		15—*61*			non-th.	
28	15	26	44	−56	00	323·8	+0·1	53	50	45	+0·2	−0·2	15—*54*	42		th.	
29	15	49	01	−56	01	326·3	−1·8	144	270	130	−0·3	−0·2	15—*56*	44		non-th.	
30	15	40	02	−54	14	326·4	+0·4										
31	15	51	03	−53	18	328·2	+0·2	49	146	90	−0·6	+0·4	15—*57*	46		?	
32	15	57	51	−52	13	329·7	+0·3	38	91	30	−0·4	−0·3	15—*58*	47		non-th.	
33	16	07	48	−51	21	331·5	0·0	75		110		+0·2		49		th.	
34	15	52	06	−48	18	331·6	+3·9	19		15		−0·3		50		?	
35	16	05	58	−49	19	332·6	+1·7	53									
36	16	16	18	−50	28	333·0	−0·3	197		260		+0·1		51		th.	RCW 106
37	16	37	52	−48	35	336·8	−1·6	53		45		−0·2		54		?	RCW 108; NGC 6193
38	16	31	22	−47	28	336·9	0·0	167		230		+0·2		55	33	th.	
39	16	36	31	−46	30	338·2	0·0	185	330	230	−0·3	+0·1	16—*47*	56	34	?	
40	16	16	07	−42	58	338·3	+5·1	15									
41	16	24	47	−42	08	340·0	+4·5	15	30		−0·3		16—*45*			non-th.	
42	16	57	05	−46	12	340·7	−2·5	23	30		−0·1		16—4*10*			?	
43	17	04	20	−44	15	343·1	−2·3	45	25		+0·5		17—*41*			th.	
44	16	45	49	−39	07	344·9	+3·6	26									
45	16	55	08	−40	19	345·1	+1·4	106		110		0·0		61	35	th.	
46	17	11	18	−38	24	348·5	+0·1	196	300	77	−0·2	−0·8	17—*33*	63	37	non-th.	
47	17	23	44	−38	33	349·8	−2·0	30	75		−0·5		17—*35*			non-th.	
48	17	16	59	−35	47	351·3	+0·7	276		323		+0·1		64	39	th.	RCW 127; NGC 6334
49	17	22	16	−34	14	353·2	+0·7	420		580		+0·2		65	40	th.	RCW 131; NGC 6357

source must be at least about 4 kpc. In that case, according to the argument used by Komesaroff and Westerhout (1964), its flux is exceedingly large—more than 10 times greater than that from an HII region excited by an O5 star.

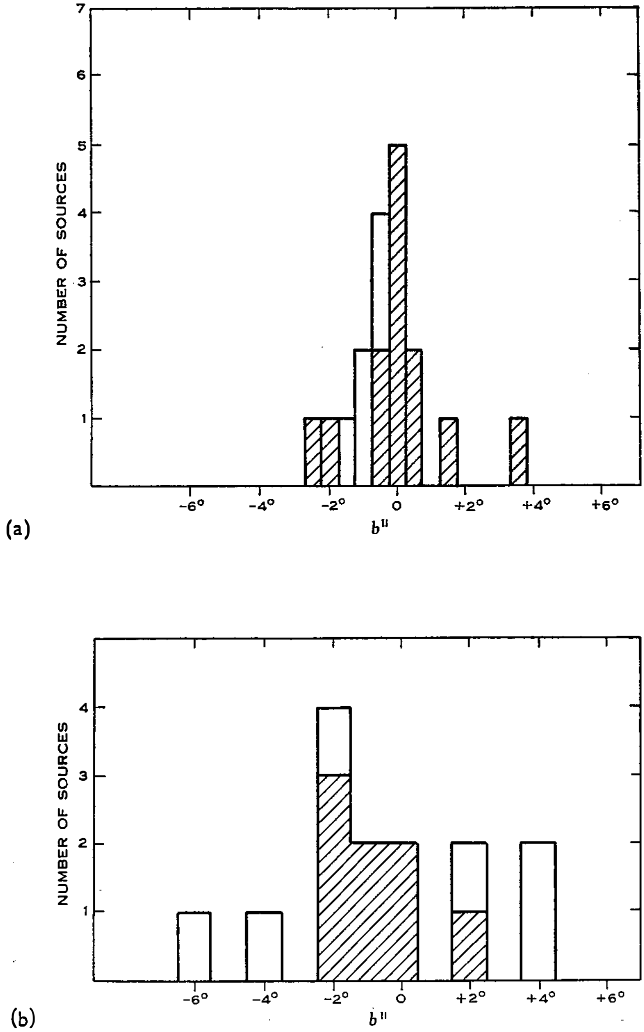


Fig. 3(*a*).—Number of thermal sources in each half-degree interval of galactic latitude. The shaded and unshaded areas refer to sources for which $298° < l^{II} < 355°$ and $282° < l^{II} < 298°$ respectively. Fig. 3(*b*).—Number of non-thermal sources in each one-degree interval of galactic latitude. The shaded area represents sources with flux densities greater than 20 f.u.

(*d*) *The Distribution with Galactic Latitude*

(i) *The Thermal Sources.*—Figure 3(*a*) shows the number of sources, classified as thermal in Table 1, that lie in each half-degree interval of b^{II}. The shaded part of the histogram is for $l^{II} > 298°$. For these longitudes the source number density is seen to have a sharply peaked distribution, falling by a factor of about 2 within one-quarter of a degree of the plane.

Taking into account that confusion probably prevents our "seeing" sources beyond a few kiloparsecs, this means that the majority of these thermal sources lie within less than 50 pc of the plane.

For $l^{\mathrm{II}} < 298°$ (unshaded part of histogram), the thermal sources are generally very intense and all lie south of the plane. Most of them evidently form part of a "local" feature.

(ii) *The Non-thermal Sources*.—Figure 3(*b*) is a similar histogram for the sources classified as non-thermal. In this case the shaded part of the histogram represents sources with 408 Mc/s flux densities greater than 20 f.u. This separation has been made because the survey of Bolton, Gardner, and Mackey (1964) has shown that, in high galactic latitudes, where presumably almost all sources are extragalactic, the number density corresponding to flux densities less than this limit and greater than 5 f.u. is about 0·03 per square degree. We, therefore, expect 20 to 30 extragalactic sources of between 5 and 20 f.u. within the 900 square degrees of our survey.

Because of the smaller number of sources, the interval of latitude is 1° for Figure 3(*b*), as compared with $\frac{1}{2}°$ for Figure 3(*a*). Nevertheless, it is clear on comparing the two figures that the non-thermal sources are more widely dispersed in latitude than the thermal. The non-thermal continuum distribution is similarly broader than the thermal, though of course both continuum distributions are very much broader than either source distribution. Large, Mathewson, and Haslam (1961) have obtained the same result for the region north of the galactic centre.

V. The "Continuum" Radiation

(*a*) *The Non-thermal Step near* $l^{II} = 325°$

A striking feature of the 408 Mc/s isophotes is the abrupt increase of brightness at all latitudes near $l^{\mathrm{II}} = 325°$. This is the longitude at which Mathewson, Healey, and Rome (1962) have noted an increase in the thermal component of galactic radiation, symmetrical in longitude with a similar increase observed by Westerhout (1958) north of the galactic centre. However, Westerhout has shown that the thermal emission extends over only about 1·5° of latitude, whereas the 408 Mc/s step extends over nearly the full range of latitudes covered by our survey.

A similar feature, also extended in latitude, appears at 85 Mc/s, as shown by the observations of Hill, Slee, and Mills (1958). In order to determine its spectral index by comparing the two surveys, we need to estimate the brightness temperature corresponding to the zero contour of the 408 Mc/s survey. This has been done by calculating the "expected" temperatures at 408 Mc/s from the 85 Mc/s temperature for the latitudes +4° and −4°, on the assumption that the spectral index is −0·6 (Komesaroff 1961). The calculation has been carried out for every 5° of longitude and the results averaged, yielding a mean "baseline" brightness temperature of 16(±3)°K with, however, an apparent variation with longitude, which could be the result of spectral changes. The variation may in places be as large as the mean value (i.e. 16°K), but since the temperatures we will be dealing with in the subsequent argument are generally greater than 100°K, this will not affect the validity of our conclusions.

Table 2 lists "lower envelope brightness temperatures" on each side of the step near $l^{\mathrm{II}} = 325°$ for $b^{\mathrm{II}} = +2°$, 0°, and −2°, for both 408 and 85 Mc/s, as well as the temperature ratios; in addition, it gives the incremental ratio $\Delta T_{\mathrm{b}}(85)/\Delta T_{\mathrm{b}}(408)$ corresponding to the step. For $b^{\mathrm{II}} = +2°$, 0°, and −2°, this ratio has the approximate values 40, 29, and 36, corresponding to spectral indices of −0·35, −0·15, and −0·28 respectively. For $b^{\mathrm{II}} = +2°$ and −2°, the spectrum of the step is distinctly non-thermal, and it represents a 30–80% increase over the temperature on the low longitude side. For $b^{\mathrm{II}} = 0°$ the spectrum of the step is flatter, because of the accompanying rise in the thermal emission. However, the following argument, which is based mainly on the 85 Mc/s results, and which makes no assumptions about the essentially unobservable spectral index along the galactic equator, shows that for this latitude also there is a very substantial non-thermal increase near $l^{\mathrm{II}} = 325°$.

Table 2

"LOWER ENVELOPE" BRIGHTNESS TEMPERATURES

l^{II}	$b^{\mathrm{II}} = +2°$			$b^{\mathrm{II}} = 0°$			$b^{\mathrm{II}} = -2°$		
	$T_{\mathrm{b}}(85)$ (°K)	$T_{\mathrm{b}}(408)$ (°K)	$\frac{T_{\mathrm{b}}(85)}{T_{\mathrm{b}}(408)}$	$T_{\mathrm{b}}(85)$ (°K)	$T_{\mathrm{b}}(408)$ (°K)	$\frac{T_{\mathrm{b}}(85)}{T_{\mathrm{b}}(408)}$	$T_{\mathrm{b}}(85)$ (°K)	$T_{\mathrm{b}}(408)$ (°K)	$\frac{T_{\mathrm{b}}(85)}{T_{\mathrm{b}}(408)}$
310°–320°	6000	120	50	8500	200	43	6000	120	50
330°–340°	10 000	220	45·5	14 000	390	36	8000	175	45·7
	$\frac{\Delta T_{\mathrm{b}}(85)}{\Delta T_{\mathrm{b}}(408)} = 40$			$\frac{\Delta T_{\mathrm{b}}(85)}{\Delta T_{\mathrm{b}}(408)} = 29$			$\frac{\Delta T_{\mathrm{b}}(85)}{\Delta T_{\mathrm{b}}(408)} = 36$		

Westerhout (1958) has shown that for a medium that emits non-thermal radiation and also contains ionized hydrogen, a good approximation to the resulting brightness temperature for the frequencies we are interested in is given by

$$T_{\mathrm{b}} = (10^4 + T_{\mathrm{n}}/\tau)(1 - \mathrm{e}^{-\tau}). \tag{1}$$

Here T_{n} is the non-thermal brightness temperature which would be observed in the absence of absorption, and τ is the optical depth of the ionized hydrogen, whose electron temperature is assumed to be 10^4 °K.

It can be shown from equation (1) that if T_{b} is less than 10^4 °K, then T_{n} must be less than T_{b}. Now the Hill, Slee, and Mills isophotes show that, for $l^{\mathrm{II}} < 320°$, $T_{\mathrm{b}}(85)$ is always less than 9000°K except on what are obviously discrete sources. It follows that, for these longitudes, the "lower envelope" non-thermal brightness temperature is less than 9000°K.

On the other hand, for $l^{\mathrm{II}} > 330°$, the value of $T_{\mathrm{b}}(85)$ scarcely falls below 14 000°K, and in only one region, extended over less than 0·5° in longitude, does it fall as low as 13 000°K. If we accept 13 000°K as the "lower envelope" value of

$T_b(85)$, we can set a lower limit to $T_n(85)$ in this region. To do this we refer to the results of Mathewson, Healey, and Rome. These show that the value of $T_b(1440)$ does not exceed $17 \cdot 5$°K except on discrete sources. Clearly, the thermal component alone of brightness temperature at 1440 Mc/s must be less than this, and this leads to an upper limit of $0 \cdot 7$ for $\tau(85)$. From equation (1) we can then show, using 13 000°K as the "lower envelope" value of $T_b(85)$, that $T_n(85)$ is greater than 11 000°K.

Thus, for l^{II} between 320° and 330°, $T_n(85)$ increases from less than 9000°K to more than 11 000°K, or by more than 20%. Assuming a non-thermal spectral index of $-0 \cdot 6$, the corresponding increase at 408 Mc/s is greater than 34 degK. The variations of $T_b(408)$ at $b^{\text{II}} = +2°$ and $-2°$ suggest, however, that this is a very conservative lower limit.

(b) *The Step near* $l^{II} = 34°$

Considering the magnitude of the non-thermal step and its coincidence in longitude with the thermal step, it seems that we are dealing with a large-scale feature of the Galaxy. Is there a corresponding feature north of the galactic centre?

Figure 4 is a composite diagram, using data from the present survey and others, showing the variation of brightness temperature with longitude for the three latitudes that we have been discussing and for a number of frequencies. The brightness temperature scale is logarithmic, and the heights of the scales for the various frequencies have been adjusted to bring the profiles into approximate coincidence. For $b^{\text{II}} = +2°$, 0°, and $-2°$, the adjustments of the 408 Mc/s scale relative to 85 Mc/s are equivalent to multiplying the 408 Mc/s temperature by the factors 49, 48, and 45, corresponding to spectral indices of $-0 \cdot 48$, $-0 \cdot 46$, and $-0 \cdot 42$ respectively.

The step near $l^{\text{II}} = 325°$ is obvious at all three longitudes, but its spectrum is clearly flatter at $b^{\text{II}} = 0°$ than for $b^{\text{II}} = +2°$ or $-2°$.

Near $l^{\text{II}} = 34°$ there is also a step in the contours, but for $b^{\text{II}} = 0°$ this only appears at the higher frequencies. (It was from this high-frequency increase that Westerhout deduced the sudden enhancement in the thermal component of emission.) On the other hand, at $b^{\text{II}} = +2°$ and $-2°$ the step appears at both 408 and 85 Mc/s, and the appearance of the profiles suggests that the spectrum of the increase is non-thermal. However, the magnitude of the increase is clearly less than for $l^{\text{II}} = 325°$, and the picture is slightly complicated by the fact that T_b rises between 35° and 30°, then falls very slightly, and rises again towards the galactic centre.

Table 3 lists values of $T_b(408)$ and $T_b(85)$ at $l^{\text{II}} = 30°$ and 33° derived by interpolating between the isophotes of the surveys of Large, Mathewson, and Haslam, and Hill, Slee, and Mills. The values of the ratio $\Delta T_b(85)/\Delta T_b(408)$ and corresponding values of the spectral index are also given. These indicate that for $b^{\text{II}} = +2°$ and $-2°$ the step has a non-thermal spectrum. It is reasonable to suppose that the non-thermal step extends through $b^{\text{II}} = 0°$ also but is masked here by the thermal step.

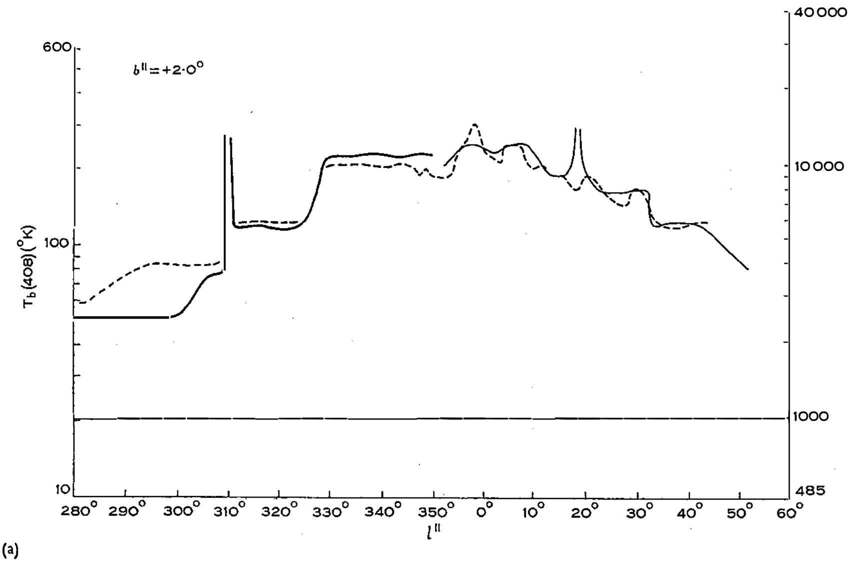


Fig. 4(*a*).—Variation of brightness temperature with l^{II}, at $b^{II} = +2°$, for 85 and 408 Mc/s. Identical logarithmic scales of brightness temperature have been used for both frequencies, but their relative heights have been adjusted (see Section V). Where the results of other surveys are shown, the curves have been derived from the published isophotes. 408 Mc/s: —— present survey, —— Large, Mathewson, and Haslam (1961); 85·5 Mc/s: - - - - Hill, Slee, and Mills (1958).

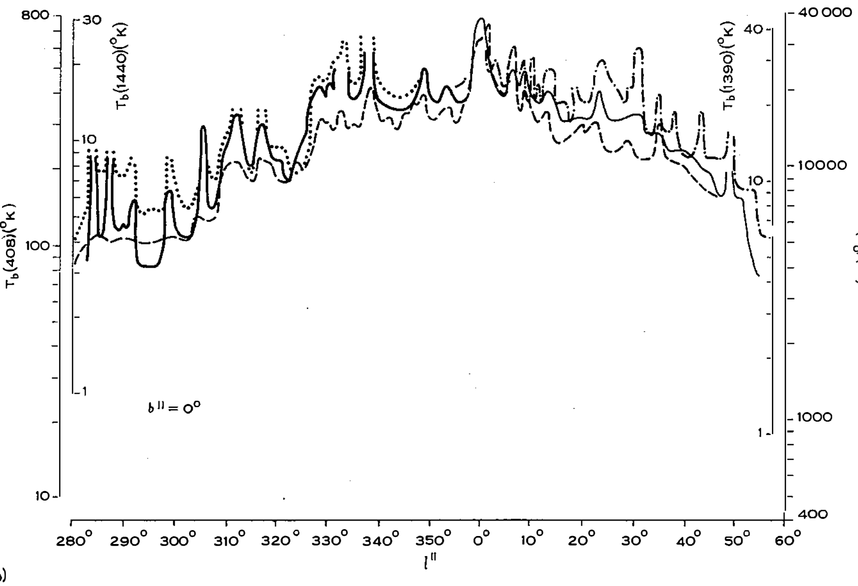
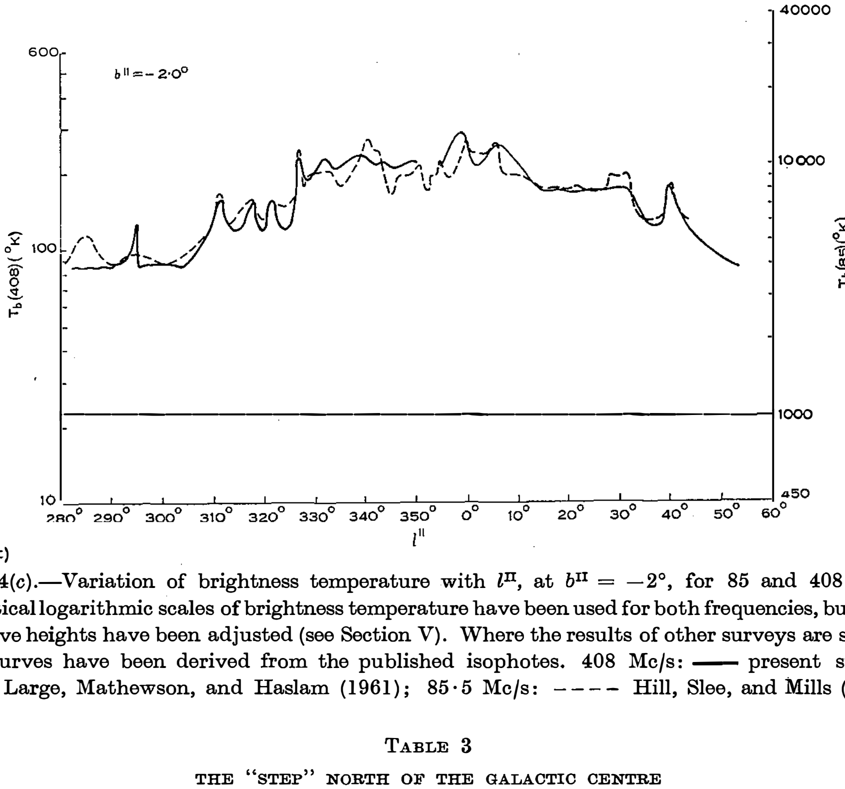


Fig. 4(*b*).—Variation of brightness temperature with l^{II}, at $b^{II} = 0°$, for 85, 408, and 1400 Mc/s. Identical logarithmic scales of brightness temperatures have been used for all frequencies, but their relative heights have been adjusted (see Section V). Where the results of other surveys are shown, the curves have been derived from the published isophotes. 408 Mc/s: —— present survey, —— Large, Mathewson, and Haslam (1961); 1400 Mc/s: · · · · · · Mathewson, Healey, and Rome (1962), –·–·– Westerhout (1958); 85·5 Mc/s: - - - - Hill, Slee, and Mills (1958).

(c) *Form of the Non-thermal Emitting Region*

The symmetry in the longitudes of the steps strongly suggests that the non-thermal emitting region, like the thermal, is radially symmetrical about the galactic centre. If the emission is isotropic and confined to a thin cylindrical shell, the resulting brightness temperature should be greatest where the line-of-sight is tangential



(c)

Fig. 4(c).—Variation of brightness temperature with l^{II}, at $b^{II} = -2°$, for 85 and 408 Mc/s. Identical logarithmic scales of brightness temperature have been used for both frequencies, but their relative heights have been adjusted (see Section V). Where the results of other surveys are shown, the curves have been derived from the published isophotes. 408 Mc/s: —— present survey, —— Large, Mathewson, and Haslam (1961); 85·5 Mc/s: – – – – Hill, Slee, and Mills (1958).

Table 3

THE "STEP" NORTH OF THE GALACTIC CENTRE

l^{II}	$T_b(85)$ (°K)	$T_b(408)$ (°K)	$T_b(85)$ (°K)	$T_b(408)$ (°K)
30°	9000	166	9000	166
33°	6000	123	6500	130
	$\dfrac{\Delta T_b(85)}{\Delta T_b(408)} = 70$		$\dfrac{\Delta T_b(85)}{\Delta T_b(408)} = 70$	
	$\alpha_{85}^{408} = -0{\cdot}7$		$\alpha_{85}^{408} = -0{\cdot}7$	

to the shell, that is, the distribution should be "limb brightened". If, on the other hand, isotropic emission occurs within a disk-like structure, the brightness temperature will increase smoothly to a maximum near longitude zero. In fact, neither model fits the observed distribution shown in Figures 4(*a*) and 4(*b*). For l^{II} between 310°

and 325°, T_b remains substantially constant. At $l^{II} = 325°$, T_b rises abruptly to a maximum and then remains close to that level between $l^{II} = 330°$ and $l^{II} = 360°$. Beyond 360° the distribution is more complicated and shows some evidence of limb brightening near $l^{II} = 30°$.

We can, however, fit the observations if we take into account the non-isotropic nature of synchrotron radiation. For the case of a uniform magnetic field, and an

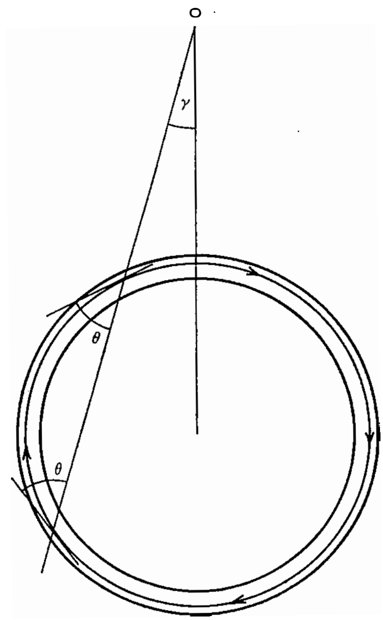


Fig. 5.—A thin cylindrical shell seen edge-on by an observer at O. The assumed direction of the magnetic field is indicated by an arrow.

assembly of emitting electrons having an energy spectral index of γ and an isotropic velocity distribution, we have

$$I(\theta) \propto (\sin\theta)^{\frac{1}{2}(1+\gamma)} \qquad \text{(Westfold 1959).} \tag{2}$$

Here $I(\theta)$ is the intensity emitted in a direction making an angle θ with the magnetic field. The radio-frequency spectral index α is related to γ by

$$\alpha = \tfrac{1}{2}(1-\gamma). \tag{3}$$

Figure 5 represents a thin cylindrical shell of emission viewed edge-on. The magnetic field is assumed to be everywhere tangential to the shell. For such a model it is easily shown that, for an observer at O,

$$T_b \propto \frac{I(\theta)}{\sin\theta}.$$

That is, by (2) and (3),

$$T_b \propto \sin^{|\alpha|}\theta.$$

Figure 6 shows the variation of brightness temperature with longitude l for a shell whose radius subtends an angle of 35° at the observer. The maximum brightness temperature due to the shell is assumed to be 103°K, and the shell is superimposed on a uniform background of 120°K. The full curve was computed for $\alpha = -0 \cdot 3$, and the dashed curve for $\alpha = -0 \cdot 6$. The crosses indicate observed values of $T_b(408)$ from the present survey at $b^{II} = +2°$, and the squares indicate observed values at $b^{II} = -2°$. Clearly, both models predict greater rounding of the shoulder of the curve than is actually observed. Good agreement could be secured if we let $\alpha = 0$, but this conflicts with our previous measurements. Increasing the assumed thickness of the shell would only increase the disagreement.

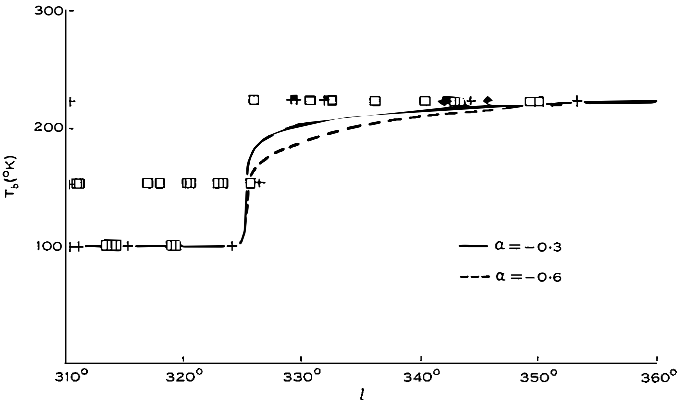


Fig. 6.—Variation of brightness temperature with longitude l for the model of Figure 5 assuming the parameters given in Section V(c). + Observed values of $T_b(408)$ at $b^{II} = +2°$; □ observed values at $b^{II} = -2°$.

However, good agreement between prediction and observation would be achieved if we relaxed the assumed condition that the magnetic field is everywhere strictly tangential to the shell. If, instead, the magnetic field shows random fluctuations about this preferred direction, the degree of beaming is reduced, and this has a similar effect to reducing the value of $|\alpha|$. Hanbury Brown and Hazard (1960) have shown that quite small fluctuations have a marked effect on the observed brightness distribution.

One could explain the difference between the region for which $l^{II} < 360°$ and that for which $l^{II} > 360°$ by assuming that beyond $l^{II} \simeq 10°$ the fluctuations in magnetic field direction increase. This would explain the generally lower values of T_b and also the suggestion of limb brightening near $l^{II} = 30°$.

VI. The Band of Polarized Radiation

Mathewson and Milne (1964) have shown that at 408 Mc/s the regions having a high percentage of linearly polarized radiation lie within a fairly narrow band approximately perpendicular to the galactic plane. They attribute this effect to the beaming of synchrotron radiation perpendicular to the magnetic field of the local spiral arm.

Since the band of polarized emission is approximately 50° wide and intersects the galactic equator near $l^{\mathrm{II}} = 350°$, one edge of it must coincide with the non-thermal step on the southern side of the galactic centre and presumably contributes to it. However, there are two indications that the total contribution is small.

First, the observations of Pauliny-Toth and Shakeshaft (1962), at 404 Mc/s, show that in the vicinity of the anticentre the step in the brightness contours corresponding to the polarized band is only about 10 degK, or an order of magnitude less than the step we find near $l^{\mathrm{II}} = 325°$ at $b^{\mathrm{II}} = +2°$. Secondly, the contribution due to the polarized band vanishes near $l^{\mathrm{II}} = 15°$, but the 408 Mc/s isophotes of Large, Mathewson, and Haslam (1961) are quite smooth to within less than 2° of the galactic plane near this longitude.

VII. A Possible Energy Source for the Non-thermal Feature

It has been shown that the enhanced non-thermal radiation extends over the range of longitude +35° to −35°. Taking the Sun's distance from the galactic centre as 10 kpc, this corresponds to a radius of 5·7 kpc. The 21 cm observations of Rougoor and Oort (1960) demonstated an outwardly expanding ring of neutral hydrogen at a somewhat smaller distance from the centre. One is tempted to speculate that this may be the energy source for the continuum feature.

Table 2 shows that near $l^{\mathrm{II}} = 325°$ and for $b^{\mathrm{II}} = +2°$ and −2° the 408 Mc/s non-thermal brightness temperature increase is between 75 and 100 degK. Near $l^{\mathrm{II}} = 30°$ and for the same latitudes the increase is smaller but probably between 20 and 40 degK. For $b^{\mathrm{II}} = 0°$, the non-thermal component of the increase is more difficult to estimate, but it has been shown that for $l^{\mathrm{II}} \simeq 325°$ this cannot be less than 34 degK. Figure 2 shows that near $l^{\mathrm{II}} = 325°$ the step continues out to about $b^{\mathrm{II}} = +5°$ and $b^{\mathrm{II}} = -5°$ with an amplitude of at least about 30 degK. The isophotes of Large, Mathewson, and Haslam show that near $l^{\mathrm{II}} = 35°$ the step continues out to $b^{\mathrm{II}} \simeq +3°$ and −3°.

Thus we can set a fairly conservative lower limit to the total power radiated by considering a cylindrical surface having a uniform 408 Mc/s brightness temperature of 30°K, extending over the range +35° to −35° in longitude and +4° to −4° in latitude, corresponding to a radius of 5·7 kpc and a width of 1·4 kpc. Assuming that the spectral index is −0·6, the total power radiated between 0 and 10^4 Mc/s is about 2×10^{30} W. If the spectrum extends to optical wavelengths (say 5000 Å), this must be increased by a factor of about 80.

Now, according to Oort (1964), the total mass of gas streaming out from the galactic centre in 1 yr is equivalent to one solar mass, and its velocity is about 50 km/s. This corresponds to an outward flow of kinetic energy of $2\cdot5\times10^{39}$ J/yr or 8×10^{31} W, which is only 40 times larger than the lower limit on the radiation from the non-thermal "ring".

Thus it seems that an explanation of the non-thermal feature in terms of a conversion of expansion kinetic energy into synchrotron radiation is ruled out, as this would require an exceedingly efficient conversion process. However, the foregoing does suggest that the expanding arm and the continuum feature may draw their energy from a common source.

In Section V(*c*) it was shown that the observed characteristics of the continuum feature can be explained as synchrotron radiation from a thin cylindrical shell containing an approximately tangential magnetic field. If now it is assumed that the radiating electrons, like the neutral hydrogen, originate in a source near the galactic centre, whence they are emitted radially outward, three effects will occur when they reach the "tangential field" region.

(1) The electrons will begin to gyrate and emit synchrotron radiation.

(2) As a result of the conversion of translational momentum into rotational, the electrons will accumulate at this distance.

(3) The rate of collisional excitation will increase, leading to increased thermal emission.

Thus the main observational features would be qualitatively explained. The validity of our assumption that relativistic electrons and neutral hydrogen originate in a common source could perhaps be tested by a detailed comparison of continuum and 21 cm data.

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