ELECTRONS MAGNETIC FIELDS AND BACKGROUND RADIO EMISSION IN THE GALAXY

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ABSTRACT

Extensive data now available on the non-thermal background radio emission from different celestial directions, and recent measurements on the energy spectrum of cosmic ray electrons in the vicinity of the earth permit one to deduce information on the mean magnetic fields and cosmic electron spectra needed to exist in different regions of the Galaxy. It is found that in order to explain quantitatively the background radio brightness distributions from the Galaxy one needs (i) the same or nearly same electron spectrum that exists in the near interstellar space, to exist in almost all regions of Galactic space, (ii) a mean magnetic field close to 6×10^{-6} Gauss in the Disc in the direction of the Anti-centre, (iii) a mean magnetic field close to $2 \cdot 5 \times 10^{-6}$ Gauss in the radio Halo and (iv) a mean magnetic field probably close to $9 \cdot 5 \times 10^{-6}$ Gauss towards the Galactic Ridge in the direction of the Centre. Some inferences are also drawn on the confinement of cosmic rays in the Galaxy.

1. INTRODUCTION

EVEN before the discovery of the existence of electrons among the primary cosmic rays, it was recognised that the non-thermal nature of the Galactic background radio emission, could only be due to synchrotron radiation emitted by relativistic electrons spiralling along weak magnetic field lines; it was therefore necessary to postulate then, the existence of an appreciable flux of cosmic ray electrons in Galactic space. The first direct observation for a finite flux of electrons, roughly 1% of the nucleonic component, was made in 1960 [1, 2]; this was soon followed by very many experiments using more and more sophisticated experimental techniques. We now have sufficient data, from these experiments, to be able to construct a reliable electron energy spectrum observed in the neighbourhood of the earth in the energy region 100 MeV–50 BeV. Also, during the last decade or so, careful and extensive surveys of the Galactic background radio emission have been carried out using wide angle and narrow angle beams; from these, one finds that it is possible to construct the radio brightness distributions for different Galactic directions. Lastly, theoretical work carried out over a period of many years, has resulted in the formulation of a quantitative theory of synchrotron emission, to relate in a detailed manner the electron spectrum, the mean relevant magnetic fields and the resulting radio emission for different conditions that can exist in cosmic environments. It is thus seen that the present situation calls for a careful analysis to connect the radio and electron data, hoping that it would lead us to useful information on conditions existing in different parts of the Galaxy. It is true that many attempts have already been made in this general direction; of these the early ones were concerned primarily with the understanding of the gross features of the cosmic ray electron intensity or the radio brightness, assuming reasonable values for the relevant magnetic fields[3, 4]. The more recent ones are attempts to get information on the magnetic fields existing in Galactic space, in particular the Halo [5-9], through the simplified assumption that the observed radio emission and the radiating electrons have power law spectra connected by the relation $a = (\beta - 1)/2$ where a and β are the power indices of the radio brightness distribution and the electron energy spectrum respectively. However, it can easily be seen that this is only an approximation because even at the highest frequencies for which radio observations are available for the Galactic Halo and the Anti-centre, an appreciable part of the intensity arises from electrons which exhibit substantial departure from power law. To our knowledge, no attempt has yet been made to derive the complete energy spectrum of electrons in Galactic space by making use of the available experimental data.

The important advance made in the present treatment is that, unlike in earlier works, we have made more realistic and rigorous calculations to derive combinations of mean magnetic fields and energy spectra of radiating electrons that seem likely to exist in four favourable Galactic regions so that the observed radio brightness distributions from the corresponding directions can be accounted for. This is possible because the theory of synchrotron emission shows that the spectral shape of the radio brightness is essentially determined by the spectral shape of the radiating electrons. One also finds from the available literature, that information on the magnetic fields in different parts of the Galaxy is far from satisfactory[10, 11]. Under this situation, we believe that the present analysis adds to our knowledge in a very significant manner. Furthermore, the combined knowledge of cosmic ray particle intensities and magnetic fields required to exist in widely differing regions of Galactic space, such as the Disc and the Halo, has also been used to draw inferences on the confinement of cosmic ray particles in the Galaxy.

2. OBSERVATIONAL DATA

2.1. *Cosmic ray electrons observed in the neighbourhood of the earth*

In Figure 1 is summarised the data available on the differential flux of cosmic ray electrons measured in the neighbourhood of the earth during

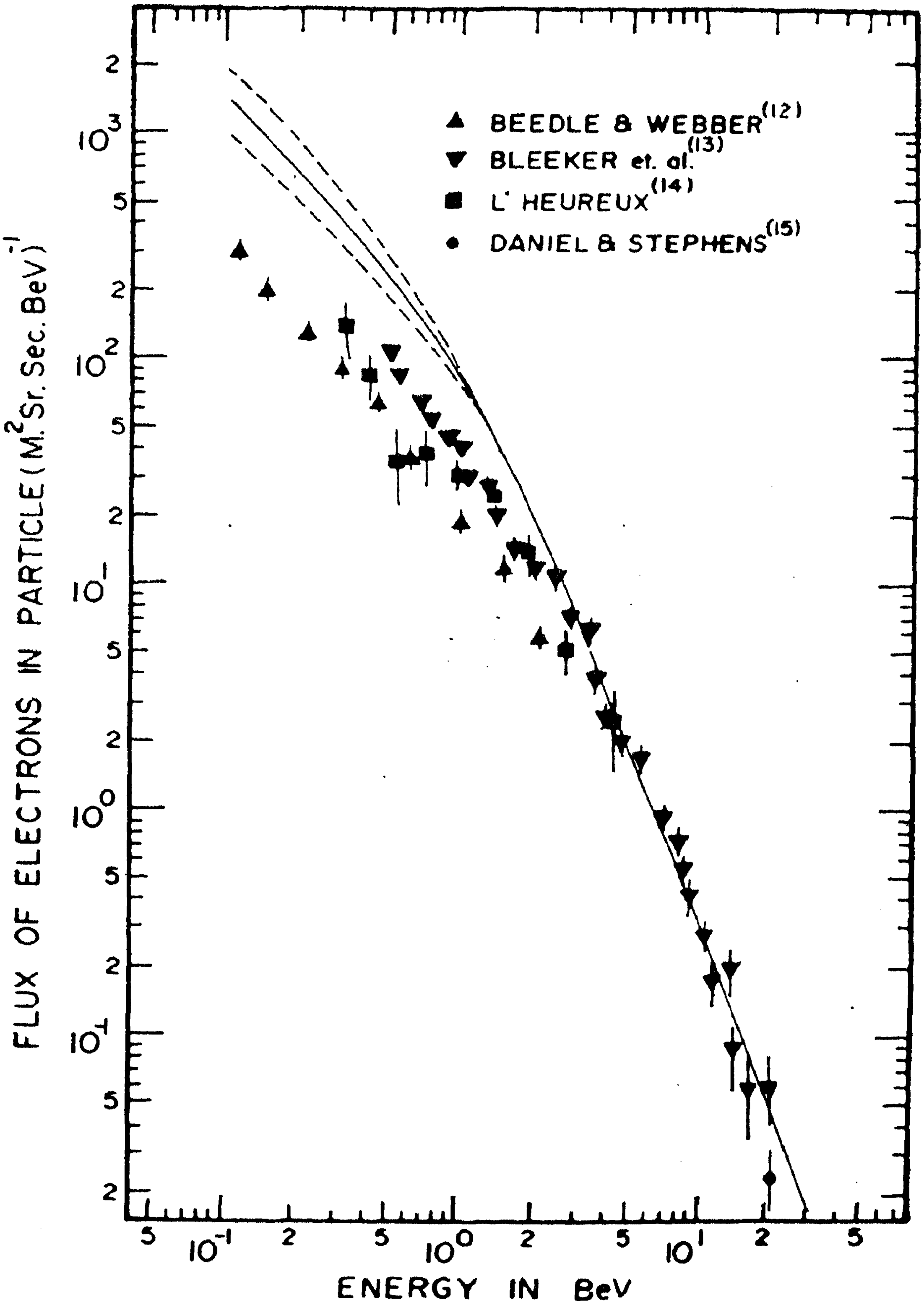

FIG. 1. Experimental determinations of the fluxes of primary electrons between 100 MeV and 20 BeV. The solid curve is the spectrum of interstellar electrons derived to account for the radio background emission in the direction of the Anti-centre. The dotted lines represents the electron spectra corresponding to the dotted lines in Fig. 4 *a* but with the same mean magnetic field and radiating distance.

1965–66, the period of minimum solar modulation[12–15]. It is seen from this figure that sufficient data exists for this period to construct a reliable energy spectrum from about 100 MeV to about 50 BeV; further the data above 5 BeV can be well fitted by the power law energy spectrum,

$$\frac{dJ(E)}{dE} = 126 \cdot E^{-2.6 \pm 0.1} \ (m^2 .\ \text{sec. sr. BeV})^{-1} \quad (1)$$

We would like to point out here that present evidence[16] strongly suggests that for rigidities in the range of 10–50 VB, the hydrogen, helium and heavy nuclei of the cosmic rays observed near the earth, have power spectra with exponents β close to 2·6.

2.2. *Non-thermal background radiation in the Galaxy*

Over a period of the last ten years or so, detailed and systematic radio surveys of the Galaxy have been carried out in a broad range of frequencies using wide angle and narrow angle beams. The surveys using wide angle beams were primarily meant for the background radiation at large, while those with narrow angle beams were meant for the study of discrete sources as well as the structure of the Galaxy. Making use of these surveys, we have constructed the nonthermal radio spectrum for four different regions of the Galaxy, namely (i) the Galactic Halo, (ii) the Halo Minimum, (iii) the Anti-centre and (iv) the Galactic Ridge; these four directions are schematically shown in Fig. 2.

(i) *The Galactic Halo.*—Since the solar system is situated at a Galactic latitude corresponding to $b'' = 1 \cdot 4°$ N, we have in this analysis considered only those surveys pertaining to the northern hemisphere in order to minimise the contribution from the Galactic Disc. The North Halo is generally defined over a wide region corresponding to right ascension R.A. $\approx$ 10–17 hrs. and declination $\delta \approx 20°–60°$. However, there is an enhancement of radiation due to the "North Galactic Spur" in the region R.A. $\approx$ 12–17 hrs. and $\delta \approx 20°$; hence this region of the sky has been excluded while evaluating the radiation from the Halo. The surveys with wide angle beams in the frequency range 10–400 MHz have been used[17–22] to deduce the spectrum in the Halo, and wherever necessary, relevant corrections have been made as indicated by the authors. Surveys below 10 MHs have not been considered here since it is thought that with further decrease of frequency, Galactic absorption and other effects might become increasingly important[23, 24]. In Fig. 3 *a*, we have plotted the brightness spectrum for the North

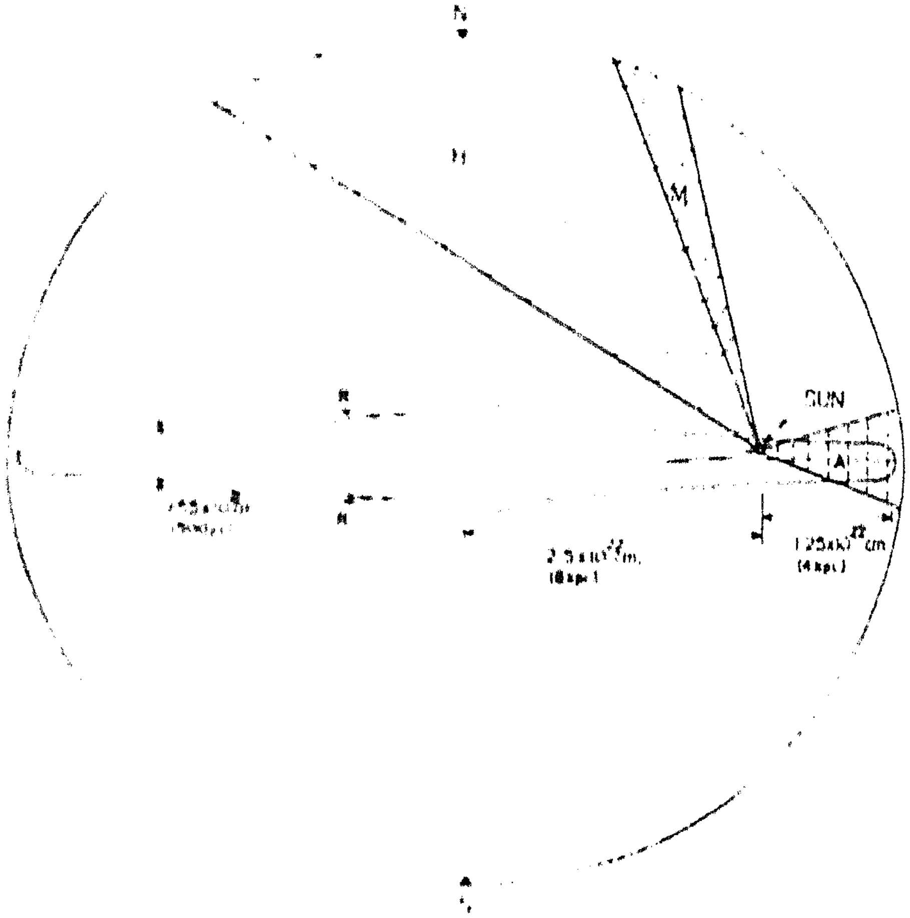

FIG. 2. Schematic drawing of the Galaxy showing different regions of space considered for analysis (not to scale).

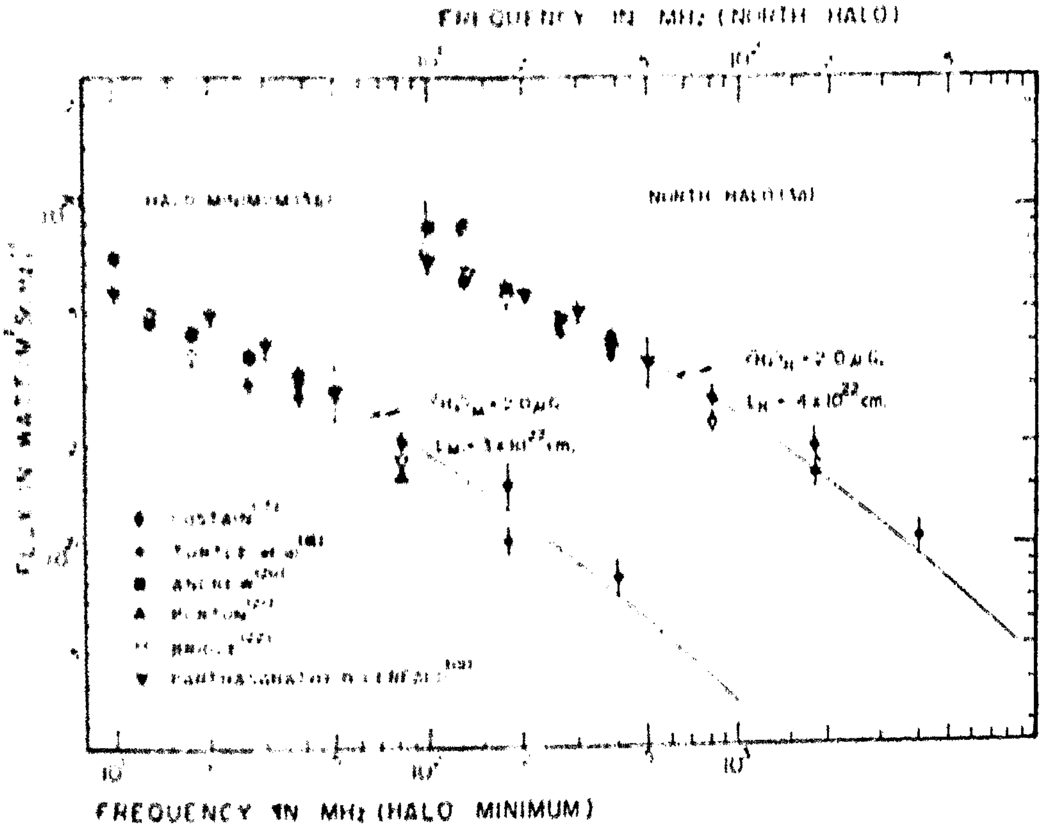

FIG. 3. Radio brightness distributions in the directions of the North Halo and Halo Minimum. The Curves in 3 *a* and 3 *b* were obtained using the electron spectrum given by the solid Curve in Fig. 1.

Halo and it can be seen that it has a shape with $\alpha \approx 0 \cdot 4$ at low frequencies increasing to about 0·8 at the highest frequencies.

(ii) *The Halo Minimum.*—The brightness distribution in the coldest part of the Galaxy has been obtained from the surveys used for the North Halo. The minimum intensity occurs around RA $\approx$ 10 hrs. and $\delta \approx$ 20–60°. The spectrum thus constructed is shown in Fig. 3 *b*. Within errors of measurement, this spectrum has a shape identical to the one obtained for the Halo but with an absolute intensity about three-fourth of that in the Halo.

(iii) *The Anti-centre.*—From the same sky surveys employed in (i) and (ii), we have been able to choose the aerial temperatures corresponding to regions close to the Anti-centre, *i.e.*, $l'' \approx$ 140°–190° and $b'' \approx$ 10° N.–10° S. (l'' and b'' are the new Galactic longitude and latitude). The flux values thus deduced from these surveys have been plotted in Fig. 4 *a* and it can be seen that this spectrum is slightly, though noticeably, flatter than that in the

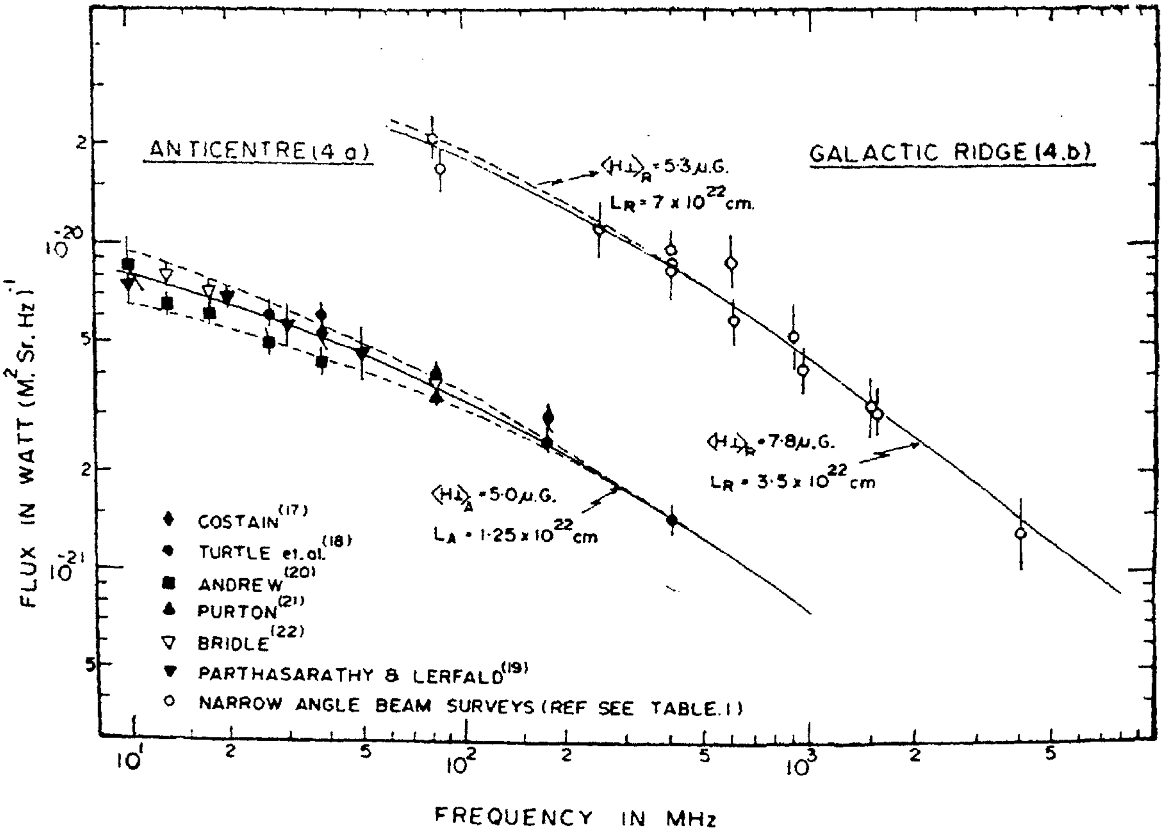

FIG. 4. Radio brightness distributions in the directions of the Anti-centre and the Galactic Ridge. The solid Curves in 4 *a* and 4 *b* were obtained by using the solid Curve in Fig. 1 while the dotted lines in 4 *a* correspond to the dotted lines in Fig. 1.

TABLE I

Radio flux data used in the present analysis for the galactic ridge

Frequency in MHz	Beam width	Flux (Watt. $m^{-2}.sr^{-1}.Hz^{-1}) \times 10^{21}$	Reference	Remarks
81·5	2°×15°	21·0	Baldwin[25]	Uncorrected
86	0°·8×0°·8	17·0	Hill *et al.*[26]	,,
250	1°×8°	11·2	Kraus and Ko[27]	,,
400	2°×2°	8·7	Seeger *et al.*[28]	,,
400	2°·2×1°·7	9·7	Seeger *et al.*[29]	Corrected by the authors
408	0°·7×0	8·35	Large *et al.*[30]	Corrected according to Penzias and Wilson
600	3°×3°	8·9	Piddington and Trent[31]	Uncorrected
610	0·5°×0·5°	5·9	Moron[32]	Corrected by the authors
900	0°·8×0°·8	5–35	Denisse *et al.*[33]	Uncorrected
960	0°·8×0°·8	4·2	Wilson and Bolton[34]	Corrections according to Penzias and Wilson
1390	0°·6×0°·6	3·2	Westerhout[35]	,,
1440	1°×1°	3·04	Mathewson *et al.*[36]	Uncorrected
4080	0°·7×0°·7	1·28	Penzias and Wilson[37]	Corrected by the authors

* The large beam width is in the celestial east-west plane.

Halo, but has comparable absolute intensities. Here too the slope varies from about 0·3 at the lowest frequencies to about 0·8 at the highest frequencies.

(iv) *The Galactic Ridge.*—Surveys of the Galactic Ridge, made with narrow angle beams in the frequency range 80–4,080 MHz are of relevance here [25–37] and are summarised in Table I. The values in Table I, denoted as uncorrected are those in which no normalisation has been made with any standard radio source in the Galaxy (such as Virgo A and Cygnus A). From these surveys, we have plotted in Fig. 4 *b* the mean flux values corresponding to the two directions $l'' = 0$ and $b'' = 3\cdot6^{\circ}$ N. and $3\cdot6^{\circ}$ S.; these directions have been chosen in order to avoid the Galactic nucleus and any possible thermal radiation from the corona, which are confined within $b'' = \pm 2^{\circ}$. At 4,080 MHz [38] the flux value shown is for $l'' \approx 5^{\circ}$ E. ($\delta = -25\cdot5$) and $b'' = \pm 3^{\circ}\cdot6$, and may slightly be small compared to that at $l'' = 0$. It can be seen from Fig. 4 *b* that, within experimental uncertainties. this spectrum has a shape same as that for the Anti-centre in the common frequency range, but with an intensity about 6 times larger; further the shape is consistent with a constant slope of $\approx 0 \cdot 8$ beyond 400 MHz.

3. THE THEORY OF SYNCHROTRON RADIATION

It is now well recognised that the background radio emission in the Galaxy is due to synchrotron radiation emitted by high energy electrons spiralling along magnetic field lines existing in Galactic space. The spectral shape of this radiation would therefore depend on the energy spectrum of the radiating electrons as they exist in the relevant space. Thus from a knowledge of the radio spectrum corresponding to a particular direction in the Galaxy and the appropriate dimension of the radiating region, one could in principle, uniquely determine the energy spectrum of electrons and the mean magnetic field for that region of space. While for radio emission with a simple power law this can be achieved without difficulty (since the electrons responsible for such a spectrum also have a power law), for other spectral shapes this is not so. Since our objective here is to derive a detailed electron energy spectrum corresponding to a radio spectrum which is not a power law spectrum, we have made use of the following rigorous formulation of the theory of synchrotron radiation summarised by Ginzburg and Syrovatsky[38]. The spectral distribution of the power radiated by a single electron of energy E is

$$p(\nu) = \frac{\sqrt{3}\, e^3 H_{\perp}}{mc^2} \frac{\nu}{\nu_c} \int_{\nu/\nu_c}^{\infty} K_{5/3}(\eta)\, d\eta \tag{2}$$

where

$$\nu_c = \frac{3eH_{\perp}}{4\pi mc} \left(\frac{E}{mc^2}\right)^2 . \tag{3}$$

The function

$$F(x) = x \int_{x}^{\infty} K_{5/3}(\eta)\, d\eta,$$

has been evaluated and tabulated [38] for different values of $x = \nu/\nu_c$ with the maximum value of $F(x)$ occurring around $x \approx 0 \cdot 29$. When we consider electrons with a spectrum of energies, the power radiated at a given frequency would come from electrons with a wide range of energies. Further since $F(x)$ is a function of E through equation 3, we shall define $G_\nu(E) = F(x)$ for a given frequency ν. When the radiating electrons have a spectrum of energies and are isotropically distributed, the intensity of radiation can be evaluated from the relation

$$I_\nu = \frac{L}{4\pi}\int_{E_1}^{E_2} p(\nu)\, N(E)\, dE$$

$$= \frac{\sqrt{3}\, e^3 \langle H_\perp \rangle}{4\pi\, mc^2}\, L \int_{E_1}^{E_2} G_\nu(E)\, N(E)\, dE \qquad (4)$$

where $(H_\perp)$ is the mean component of the magnetic field perpendicular to the line of sight, L is the dimension of the radiating region along the line of sight and $N(E)\,dE$ is the number of electrons per unit volume having random directions of motion with energies in the interval E and $E + dE$ (other notations used here are same as in reference 38). The integration is carried out numerically choosing for the limits, values of E_1 and E_2 such that

$$G_\nu(E_1)\, N(E_1)\, dE \approx G_\nu(E_2)\, N(E_2)\, dE \ll [G_\nu(E)\, N(E)\, dE]_{\max.} \qquad (5)$$

The value of $[G_\nu(E)\, N(E)\, dE]_{\max.}$ would depend upon the spectral shape of the electrons and can be estimated suitably.

Given a radio spectrum which is not a simple power law, as is evident from Figs. 3 and 4, the electron spectrum responsible for the same, can best be obtained by trial and error. Though the spectral shape of the radio emission essentially depends on the spectral shape of the electrons contributing to the corresponding frequencies, a change of the magnetic field does influence the radio spectral shape through the electron spectrum. It can be seen from equation 3 that such a change would result in a small change in the limits of integration; however, if the electron spectrum does not appreciably vary in this region, this effect would be small.

4. THE METAGALACTIC RADIO COMPONENT

Before one proceeds to connect, in a quantitative manner, the observed background radio spectrum with an appropriate combination of electron spectrum and mean magnetic field in the radiating region within the Galaxy, it is necessary to enquire whether there exists any appreciable amount of isotropic radio emission of metagalactic origin. So far only one attempt has been made to determine directly the metagalactic intensity by making use of the radio absorption in the Large Magellanic cloud[39]; all others are indirect and depend on the assumption that the spectral shape of the isotropic metagalactic component, if any, is steeper and different from that of the Galactic background emission[17, 22, 40]. In all these works it can be noticed that the estimated value of the metagalactic radiation is quite sensitive to the assumed spectral index for this radiation. Though the uncertainties involved in these estimates are rather large, we have examined the consequences, in our analysis, of the existence of a metagalactic component under two assumptions:

(*a*) The metagalactic radiation has a spectral shape similar to the observed radiation in the direction of the Halo; such a situation seems possible if this component mainly arises due to integrated radiation from discrete metagalactic sources along the line of sight. Under this assumption, only Shain's[39] work is of relevance since the estimated value of the metagalactic radiation at 19·7 MHz depends only on the spectral index of this radiation at this frequency. The spectral index α of the brightness distribution in the direction of the Halo at 19·7 MHz is 0·5 and the corresponding metagalactic radiation according to Shain is about 19%. Thus by assuming a value of $\approx 20\%$ for the metagalactic radiation, it can be easily shown that the required electron spectrum would be the same as that without this radiation but with either marginally reduced (6%) magnetic field or a 20% decrease of the radiating distance or an appropriate combination of both.

(*b*) If, however, the metagalactic component contributes 20% of the Halo intensity at 10 MHz and has a spectral index $\alpha = 1 \cdot 3$, as is likely to be the case if this radiation is due to synchrotron radiation by the equilibrium electrons in the metagalactic space, it can be shown that (i) the electron spectrum calculated by us to exist in the Galaxy will be unaffected for energies $\gtrsim 500$ MeV, and (ii) the spectrum below this energy would become increasingly flatter than in the corresponding energy range of the spectrum observed near the earth. If however one demands, as seems reasonable, that the electron spectrum in Galactic space cannot be, in general, flatter than that in the vicinity of the earth, it becomes possible to say that the magnitude of the metagalactic component at 10 MHz should be less than 20% of the observed background radiation in the direction of the Halo.

Thus we have reason to believe that the existence of any metagalactic component of the type (*a*) or (*b*) or any combination of these will not materially affect any of our conclusions; hence this effect has been neglected in the present analysis.

5. THE ELECTRON SPECTRUM OUTSIDE THE SOLAR SYSTEM

Of the four Galactic directions for which the radio brightness distributions have been compiled in Sec. 2.2, the Radio Disc in the direction of the Anti-centre resembles closest to our near-interstellar space. We would, therefore, attempt to derive first, the electron spectrum in this region of the Galaxy. Later we will show that if the same or nearly same spectrum also exists in the other Galactic directions, we will be able to explain satisfactorily the relevant radio spectra.

(*a*) *The Galactic Anti-centre.*—Extensive investigations on the nucleonic component of the cosmic radiation made during the last solar cycle indicate that particles with rigidities $\gtrsim 10$ BV undergo little or no solar modulation. Further, present evidence[15] strongly indicates that for rigidities of 10–50 GV, the cosmic ray hydrogen, helium and heavy nuclei observed near the earth, all have power spectra with $\beta \approx 2 \cdot 6$, same as that determined for electrons (equation 1). It therefore seems reasonable to expect that the shape and intensity of electrons of energy $\gtrsim 5$ BeV are well preserved in interstellar space, as is known to be in the case of the nucleonic component.

In order to evaluate the energy spectrum of electrons existing in the radiating region, one has to fix the value of L and the corresponding mean magnetic field $\langle H_\perp \rangle$. The value of L in the direction of the Anti-centre has been taken to be $L_A = 1 \cdot 25 \times 10^{22}$ cm. Since it has already been pointed out that electrons with energy $\gtrsim 5$ BeV in the direction of the Anti-centre are expected to have the same spectrum as those in the vicinity of the earth, it is possible to set quite meaningful constraints on $\langle H_\perp \rangle_A$, because the deduced electron spectrum at lower energies should smoothly join with that at energy $\gtrsim 5$ BeV near the earth. It is then possible to fix by trial a single value of $\langle H_\perp \rangle_A$ and an unique, smoothly varying electron spectrum, to match the observed radio spectrum. It may be pertinent to point out here that the curve fitting in the high frequency end of Fig. 4 *a* depends primarily on the assumed magnetic field because in this frequency region $I_\nu \;\alpha\; L.\, \langle H_\perp \rangle^y$ where $y > 1$. The electron spectrum shown by the solid curve in Fig. 1 and a value of $\langle H_\perp \rangle_A = 5 \times 10^{-6}$ Gauss are found to give the best fit to the radio brightness distribution, namely the solid curve in Fig. 4 *a*.

In Table II we have shown the regions of the electron energy spectrum which contribute about 80% of the observed radiation at different frequencies. It can be easily shown that reasonable adjustments in the values of L_A and $\langle H_\perp \rangle_A$ would still demand almost the same electron spectrum to exist in this region. Further, to demonstrate the sensitivity of the method on the electron spectrum used, we have shown by dotted lines in Fig. 4 *a* the radio spectra that would result from two slightly different electron spectra indicated by dotted lines in Fig. 1, but for the same value of L_A and $\langle H_1 \rangle_A$. Thus we infer that the electron spectrum inferred for the Anti-centre direction is quite reliable between the energy region of about 200 MeV–5 BeV.

TABLE II

Parameters used and derived in the present analysis

Region of space	Electron spectrum (used)	Length L $10^{\cdot 2}$ cm. (assumed)	$\langle H_\perp \rangle$ 10^{-6} Gauss (deduced)	Energy range in BeV of electrons contributing 80% of the radio flux at			
				10 MHz	100 MHz	400 MHz	4000 MHz
1. Anticentre ..	Deduced (solid curve of Fig. 1)	1·25	5·0	0·2–1·2	0·5–2·6	1·1–4·3	..
2. Gelactic Ridge ..	,,	3·5	7·8	..	0·5–2·2	0·9–3·8	2·5–10·5
3. North Halo ..	,,	4·0	2·0	0·3–1·6	0·9–3·7	1·7–6·5	..
4. Halo Minimum ..	,	3·0	2·0	0·3–1·6	0·9–3·7	1·7–6·5	..

Now we proceed to see whether the electron spectrum derived for the Anti-centre region could also explain the observed radio emissions from the other three directions.

(*b*) *The Galactic Ridge.*—The selection of the two directions in the Galactic Ridge has been made to permit us to probe the Disc towards the Galactic Centre. However, since the Disc is rather thin compared to its diameter, the directions chosen lead to large uncertainties in the radiating distance L_R within the Disc. In spite of this, we can first set an supper limit for L_R which corresponds to the dimension of the Galaxy itself and is 7×10^{22} cm. On the other hand if the radio Disc has a thickness close to 500 pc,[41] then $L_R \approx 3 \cdot 5 \times 10^{22}$ cm. (Fig. 2). On the basis of the existing data we are inclined to think that the true value is closer to the latter one; this leads to a value of $\langle H_\perp \rangle_R \approx 7 \cdot 8 \times 10^{-6}$ Gauss in order to give a good fit for the radio observation (Fig. 4 *b*) using the same electron spectrum as given by the solid curve in Fig. 1. The true value of $\langle H_\perp \rangle$, relevant to the Disc in the direction of the Ridge is likely to be somewhat lower than $7 \cdot 8 \times 10^{-6}$ Gauss since part of the radio contribution from this direction would come from the Halo. On the other hand, if we use $L_R \approx 7 \times 10^{22}$ cm. it will result in a value of $\langle H_\perp \rangle \approx 5 \cdot 3 \times 10^{-6}$ Gauss. It can be noticed from

Table II that the major part of the radiation in this direction comes from electrons of energy $\gtrsim 1$ GeV.

(*c*) *The Galactic Halo and Halo Minimum.*—Since the region of space in the direction of the Halo Minimum is part of the North Halo, these two regions could be discussed together. The radio Disc is only about 500 p.c. in thickness and the solar system is situated at a Galactic latitude $b'' = 1{\cdot}4°$. Thus in the North Halo direction, the contribution of radio emission comes mainly from the Halo. Assuming, therefore, a value $L_H = 4 \times 10^{22}$ cm. for the Halo towards the North Galactic pole, we obtain a magnetic field $(H_\perp)_H = 2 \times 10^{-6}$ Gauss to get the best fit to the radio brightness distribution (Fig. 3 *a*) using the electron spectrum as it exists in the Anti-centre region. Since, as mentioned earlier, the radio spectra in the direction of the Galactic Halo and Minimum are identical, it seems reasonable to suppose that the mean magnetic field as well as the electron spectrum in the different regions of the Halo are also the same. One can, therefore, obtain for the Halo Minimum the dimension of the radiating region as $L_M = 3 \times 10^{22}$ cm. It may also be relevant to recall here the noticeable, though small, difference in the shape of the radio spectra for the Anti-centre and the Halo mentioned in Sec. 2·2. This too is to be expected, if the same electron spectrum exists in all Galactic space but the mean magnetic fields differ as in Table II.

6. CONCLUSIONS AND INFERENCES

6·1 *The electron spectrum in Galactic space*

Using the observational data on the cosmic ray electron spectrum near the earth and the radio brightness distribution, we have been able to derive reliably the relevant interstellar electron energy spectrum in the energy region of about 200 MeV–5 BeV in the direction of the Galactic Anti-centre. It is then found that the same interstellar electron spectrum can well account for the radio spectra observed in the direction of the Galactic Ridge and the North Galactic Halo, if one uses reasonable values for the dimensions of the respective radio emitting regions. Further, in the case of the Ridge, it becomes possible to extend the deduced electron spectrum upto about 10 BeV because of the availability of radio data upto about 4,000 MHz. It is then found that the interstellar electron spectrum between 5 and 10 BeV is consistent with our idea that the spectrum observed near the earth at energies $\gtrsim 5$ BeV is well preserved in interstellar space.

6.2. *The Solar modulation of cosmic ray electrons*

It is evident from Fig. 1 that the electron energy spectrum observed in the neighbourhood of the earth during the period of minimum solar modulation is quite different from that derived for interstellar space at energies < 3 BeV. This clearly shows that there is a finite residual solar modulation in the case of electrons as in the case of the nucleonic component. A detailed discussion of this topic has been dealt with separately.[42]

6.3. *Magnetic fields in the Galaxy*

Estimates of magnetic fields made in the present analysis correspond to the mean perpendicular component in the relevant region of space along the line of sight. While the magnetic fields in the Galactic Halo are likely to be highly randomised, in the Disc, they are mainly oriented along the spiral arms. However, since the radiating regions considered here have linear dimensions very large compared to the thickness of spiral arms, we may assume that the magnetic fields are randomly oriented in all directions; we then get $\langle H \rangle = 1 \cdot 23 \langle H_{\perp} \rangle$. This leads to a mean magnetic field in the Disc towards the Anti-centre region of $\langle H \rangle_A \approx 6 \times 10^{-6}$ Gauss. From considerations described in Sec. 5 *a*, it can be seen that the uncertainties in this value, arising from the uncertainty in the value of L_A and the errors in the fitting of the radio spectrum are expected to be $\lesssim 20\%$. Further uncertainties, in the value of the magnetic field deduced, could arise from the following: (*a*) Since for the Anti-centre we have considered radiation from a region with $b'' \pm 10°$, a small part of the radiation ($\lesssim 10\%$) from the Halo might have also been included, thus leading to a small underestimation of the value of $\langle H \rangle_A$. (*b*) A contribution of metagalactic component, if it exists, would lead to an overestimation of this magnetic field. These two effects are small and have a tendency to cancel each other.

The mean magnetic field $\langle H \rangle_R$ in the Disc in the direction of the Galactic Ridge as obtained from the present analysis is $\langle H \rangle_R \approx 9 \cdot 5 \times 10^{-6}$ Gauss. Recently Okuda and Tanaka[9] have derived a mean magnetic field of $(1 \cdot 2 - 2 \cdot 4) \times 10^{-5}$ Gauss from somewhat similar consideration for explaining the radio emission straight in the direction of the Galactic nucleus. The value derived by these authors cannot be compared with our value because it is now known that the Galactic nucleus is an intense source of radio emission of thermal and non-thermal origin.

The value of the mean magnetic field derived for the Halo is $\langle H \rangle_H \approx 2 \cdot 5 \times 10^{-6}$ Gauss; this value is consistent with those obtained by various authors in the past. The uncertainty in $\langle H \rangle_H$ depends both on the possible metagalactic component present in the Halo radiation as well as on the uncertainty in the dimension of the Halo. It may be worth mentioning here that with more detailed measurements of the radio spectrum from different directions of the Halo, using narrower beam widths, it may be possible to throw more light on the dimensions and shape of the radio Halo.

6.4. *Confinement of cosmic rays in the Galaxy*

Though we have shown that a consistent picture can be built up to explain the observed non-thermal radiations from different regions of the Galaxy by assuming that the energy spectrum of electrons is the same in all regions of the Galaxy, it would be instructive to see how much variation in this intensity can be tolerated. Since we are of the opinion that the electron spectrum derived for the Galactic Anti-centre (*i.e.*, the near interstellar space) cannot be in serious error for the reasons given in Sec. 5, we would now enquire about the situation in the Halo. Let us for the same of argument reduce the electron intensity in the Halo by a factor of 2, then one finds that in order that the observed radio spectrum at high frequencies be explained, one requires a mean magnetic field $\langle H\rangle_H$ of 4×10^{-6} Gauss. If in addition the value of L used is too large, the effect would be to demand a still larger value of the magnetic field. With such high magnetic fields, the effective energy of the radio emitting electrons will be shifted towards lower energies, thus requiring an electron spectrum steeper than that in the Disc for the same energy region. This would again be difficult to understand if the confinement volume for the electrons observed near the earth, is the Galactic Disc as deduced from a study of the electron intensities above 50 BeV.[43] From these arguments it seems unlikely that there could exist any large (> 2) lowering of the mean intensity of cosmic rays in the Halo compared to the Disc. However, one cannot at this stage rule out the possibility that there exists a finite gradient in the intensity of the cosmic rays from the Disc towards the periphery of the Halo.

Even in the plane of the Galactic Disc, it is not possible to rule out at this stage the existence of a gradient in the cosmic ray intensity from the centre outwards. The fact that the mean magnetic field obtained for the Galactic Ridge towards the Galactic Centre, of close to $9{\cdot}5\times10^{-6}$ Gauss, is rather large compared to that in the Anti-centre, and the possibility of a higher concentration of cosmic ray sources near the Galactic nucleus, makes the existence of such a gradient possible. However, here too, it would be difficult to allow for a difference in the cosmic ray intensity in the central region of the Galaxy and the Anti-centre by a value > 2 because it would then demand a magnetic field at the centre comparable to that in the direction of the Anti-centre.

From the foregoing discussions it can be realised that the cosmic ray intensity cannot be very different from region to region in the whole Galaxy. Observations also indicate that the spectra of electrons, protons, helium and heavier nuclei at high energies are quite similar to one another. In spite of all this understanding, there is still no satisfactory explanation as to why the electron component is only about 1% of the nucleonic component.

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