General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

X-615-70-22
PREPRINT

NASA TM X-63817

LOW FREQUENCY COSMIC NOISE OBSERVATIONS OF THE CONSTITUTION OF THE LOCAL SYSTEM

J. K. ALEXANDER
L. W. BROWN
T. A. CLARK
R. G. STONE

JANUARY 1970

N70-18641
(ACCESSION NUMBER) (THRU) 1
20 (PAGES) (CODE)
NASA TMX-63817 (NASA CR OR TMX OR AD NUMBER) 29 (CATEGORY)
FACILITY FORM 602

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

29

LOW FREQUENCY COSMIC NOISE OBSERVATIONS OF THE CONSTITUTION OF THE LOCAL SYSTEM

by

J. K. Alexander, L. W. Brown,
T. A. Clark and R.G. Stone
Laboratory for Extraterrestrial Physics
Goddard Space Flight Center
Greenbelt, Maryland

ABSTRACT

Based on measurements of the low frequency continuum radiation of the galaxy, estimates have been obtained for the gross distribution of thermal electrons, the synchrotron radiation emissivity, and the flux and spectrum of low energy cosmic ray electrons for the interstellar medium in the Local System. The volume emissivity of the synchrotron radiation at 1 MHz is 10^{-39} W/(m^{3}Hz sr). This value exceeds the emissivity deduced from measurements at higher frequencies over longer path lengths and in turn implies a low magnetic field between spiral arms ($\lesssim$ 1μG). For a mean interstellar magnetic field of 3 μG near the sun, the radio data indicate a cosmic ray electron intensity at 0.3 Gev of 10^4 el/(m^2 sec sr Gev). That this intensity exceeds the value obtained from direct measurements by a factor of ~100 suggests either a large residual solar modulation or gradients in the interstellar distribution of cosmic rays.

INTRODUCTION

From measurements obtained by the Radio Astronomy Explorer satellite (RAE-1) it has been possible to determine the average cosmic noise background spectrum down to about 0.4 MHz. The observed radio brightness reaches a peak near 3 MHz and then decreases at lower frequencies due to free-free absorption by thermal electrons in the interstellar medium. As a result, nearly all the radiation observed below 1 MHz originates from the vicinity of the local spiral arm. Through an analysis of the galactic background spectrum at very low frequencies, therefore, we can determine several important properties of the Local System. These include the volume emissivity of the background synchrotron radiation, the interstellar flux of cosmic ray electrons at low energies, and the gross distribution of interstellar thermal electrons.

Integrated background spectra obtained from the RAE satellite measurements for the general directions of the galactic poles, center and anti-center are shown in Figure 1. A summary of the experimental details and an analysis of the absolute accuracy of the measurements (±25%) has been published previously (Alexander et al. 1969). The relative accuracy of the different spectra is estimated to be ±15%. Since most of the measurements are from a 37-meter dipole antenna, the spectra are representative of the average features of broad regions on the order of 100 degrees in angular extent. Although measurements with such low resolution tell us nothing about the detailed brightness distribution across the sky, we will show that one can still determine a number of interesting points about the average properties of the galaxy in the vicinity of the Sun.

Early measurements of the low frequency background spectrum were found to be easily fit by a simple model assuming that the regions of galactic emission and absorption are uniformly mixed (Webber, 1968; Weber et al., 1969), and this assumption is strongly supported by the RAE observations. Under these conditions (ϵ/κ = constant) the observed brightness at a frequency ν is

$$\begin{aligned} I(\nu) &= \frac{\epsilon}{\kappa}\,(1-e^{-\tau}) + I_x(\nu)\,e^{-\tau} \\ &= \frac{<\epsilon L>}{\tau}\,(1-e^{-\tau}) + I_x(\nu)\,e^{-\tau} \end{aligned} \tag{1}$$

where ϵ is the volume emissivity of the nonthermal radiation, κ is the volume absorptivity due to ionized hydrogen, L is the path length over which the emission occurs, $\tau = <\kappa L>$ is the optical depth of the absorbing gas, and I_x is the brightness of those components of radiation coming from distances greater than L. Since the brightness temperature of the nonthermal radiation in the 1 MHz range is the order of 10^7 ^oK, the contribution to $I(\nu)$ due to thermal sources may be neglected. The absorptivity is given by (Ginzburg, 1964)

$$\kappa = \frac{10^{-2}}{\nu^2}\,\frac{N_e^{\ 2}}{T_e^{\ 3/2}}\,(17.7 + \ln \frac{T_e^{\ 3/2}}{\nu}) \tag{2}$$

where N_e is the electron density of the absorbing medium in cm^{-3}, T_e is the electron temperature in ^oK, and ν is in Hz. For radiation from a homogeneous and isotropic distribution of electrons in a random magnetic field the emissivity is (Ginzburg and Syrovatskii, 1965)

$$\epsilon \cong 1.35x10^{-23} KB^{(\gamma+1)/2} \left(\frac{6.26x10^{18}}{\nu}\right)^{(\gamma-1)/2} \quad erg/(cm^3 sec\ sr\ Hz) \tag{3}$$

where B is the average magnetic field in the emitting region in Gauss, and K and γ determine the electron energy spectrum which is assumed to have the form

$$dN(E) = KE^{-\gamma}\ dE. \tag{4}$$

For large optical depths ($\tau >> 1$) equation (1) becomes

$$I(\nu) = \frac{\epsilon L}{\tau} \propto \nu^{2-\alpha} \tag{5}$$

where $\alpha = (\gamma-1)/2$ is the spectral index of the synchrotron radiation spectrum. From the shape of the spectra shown in figure 1 it appears that the optical depth has become sufficiently large at about 0.5 MHz to permit us to use equation (5) to determine α from the slope of the low frequency spectrum. All the curves are consistent with a value of $\alpha = 0.4 \pm 0.1$. There is some evidence that the synchrotron spectrum is becoming flatter in the galactic plane at the lowest frequencies, but the present measurements do not provide an unambiguous answer to this question.

ABSORPTION BY THERMAL ELECTRONS

Knowing α, we can then fit the observed spectra with a curve of the form given in equation (1) and thereby deduce τ. We find optical depths of approximately 1.5, 2.5, and 3.5 $\pm$50% at 1 MHz for spectra in the directions of the galactic poles, center, and anti-center, respectively.

The variation of optical depth with direction can be readily understood in terms of current concepts of galactic structure in the vicinity of the sun since it implies a higher electron density in the galactic plane and an increase in the radial distribution of N_e towards the anti-center direction in the Orion spiral arm. That is, the sun is located on the galactic center side of the electron distribution maximum in the local arm. If the volume emissivity is uniform in all directions in the local system, then the difference in the optical depths for center and anti-center region spectra can be interpreted as the result of the average N_e for the anti-center region being about 50% greater than towards the center. One must remember that these results apply to averages over angular regions of a few steradians in size and, as we shall subsequently show, over path lengths of several hundred parsecs.

If we take the average optical depth at 1 MHz to be $\sim$2, then we can estimate the average path length over which we are observing radiation at the low frequencies. In Table 1 we have tabulated the path length, L, corresponding to

$\tau = 2$ at 1 MHz for four different combinations of N_e and T_e for the interstellar medium. The cases with $N_e = 0.05\ cm^{-3}$ and $T_e = 50$ and $10^2\ ^oK$ correspond to possible cold clouds in the interstellar medium, while the cases with $N_e = 0.03\ cm^{-3}$ and $T_e = 10^3$ and $10^4\ ^oK$ correspond to recent models of the intercloud medium (Field et al., 1969; Hjellming et al., 1969).

	$T_e(^oK)$	$N_e(cm^{-3})$	$L_{\tau=2}(pc)$
Cold clouds	50	0.05	0.95
	10^2	0.05	2.5
Intercloud Medium	10^3	0.03	170
	10^4	0.03	$4.2x10^3$

Table 1

From Table 1 we can see that the observed absorption can be easily explained if the average line of sight intersects a few parsecs of cold clouds. Likewise, the absorption can arise within a distance comparable to the thickness of the galactic disk if we assume that the absorption occurs in a more or less continuous distribution of inter-cloud gas at an average T_e of $10^3\ ^oK$. On the other hand, if the interstellar medium is at a temperature of $10^4\ ^oK$, then it does not make any appreciable contribution to the observed optical depth, and the absorption must be due to cold clouds along the line of sight.

SYNCHROTRON EMISSIVITY

As we have indicated above, the effect of free-free absorption in the interstellar medium is to restrict our observations of the background intensity below 1 MHz to radiation originating within the Local System. If we can estimate the path length to $\tau = 1$, therefore, we can calculate the volume emissivity of the synchrotron radiation in the region of the local arm. To determine $L(\tau = 1)$ we can either assume a model for the composition of the interstellar medium and calculate the path length from equation (2), or we can assume a scale size for the Local System and deduce $L(\tau = 1)$ from the measured optical depths. On the basis of the former approach, we can see from Table 1 that both the concept of cold clouds intercepting, on the average, 1% of the total line of sight, or an intercloud medium with $< T_e > = 10^3$ °K leads to $\tau = 1$ at 1 MHz for a path length of the order of 100-200 pc. Alternatively, if we assume a semi-major axis of 500 pc and a disk semi-thickness of 200 pc for the Local System, the value of 2 for the average optical depth at 1 MHz leads to an average path length of $\sim$ 150 pc for $\tau = 1$. Using a disk semi-thickness of $\sim$ 400 pc as suggested by Bridle and Venugopal (1969) leads to an average value of $L(\tau = 1)$ of 220 pc. In the calculations that follow we have taken the average distance to $\tau = 1$ at 1 MHz to be 200 $\pm$ 100 pc.

Taking the average brightness at 1 MHz to be $\sim 6 \times 10^{-21}$ W/(m^2 Hz sr), $<\tau> = 2$, and $<L> = 200$ pc, we calculate the volume emissivity in the Local System to be $1(^{+1.0}_{-0.5}) \times 10^{-39}$ $W/(m^3\ Hz\ sr)$. Measurements of the emissivity in particular directions have been made by Roger (1969) at 22 MHz, Andrew (1969) at 13 MHz, and Bridle (1968) and Purton (1966) at 10 MHz, and when their results are scaled to 1 MHz assuming $\alpha \approx 0.4$ one gets an emissivity of about one third our value. The values for all four of the higher frequency measurements represent averages over the order of 2 kpc lines of sight, and except for Purton's observations towards the Cygnus X region all of those lines of sight included inter-arm regions between the Orion and Perseus spiral arms. We would ascribe the difference of a factor of three between the ground based observations and our value of emissivity, therefore, to a lower volume emissivity in the inter-arm region which results in a lower average emissivity when measured over a 2 kpc distance than when determined for the region within 200 pc of the sun. If we assume that one fourth of the line of sight to sources in the Perseus arm lies in spiral arm regions and three fourths in the inter-arm region, then this interpretation leads to an estimate of an inter-arm emissivity not greater than one tenth the volume emissivity in spiral arms. The likelihood of a lower inter-arm emissivity has also been discussed by Baldwin (1967).

A lower emissivity between spiral arms could result from a lower inter-arm magnetic field and/or a lower flux of cosmic ray electrons. Cosmic ray electrons with energies below 1 Gev, corresponding to radiation at frequencies below 20 MHz, can be contained by quite low fields, and therefore a lower magnetic field seems to be the more probable explanation. Since the emissivity is proportional to $B^{\alpha+1}$, an inter-arm emissivity 1/10 the arm emissivity leads to an inter-arm magnetic field on the order of 1/5 the magnetic field in the local arm. If the average interstellar magnetic field in the Local System is $\sim 3\mu G$ (Verschuur, 1969; Jokopii and Lerche, 1969), then the magnetic field outside the arm must be less than $1\mu G$.

COSMIC RAY ELECTRON SPECTRUM

The principal electron energy contributing to synchrotron radiation at a frequency ν can be estimated by

$$\nu = 4.6\ BE^2 \tag{6}$$

where ν is in MHz, B is in μG, and E is in Gev. For a $3\mu G$ magnetic field, our observations at 1 MHz correspond to 0.27 Gev electrons. Using our measured emissivity we can calculate the coefficient K of the cosmic ray energy spectrum (equation 4) and number of cosmic ray electrons in the energy range of a few hundred Mev. Again using $\epsilon = 10^{-39}$ W/(m^3 Hz sr), $B = 3\mu G$ and $\gamma \simeq 1.8$, we get $K = 2.6 \times 10^{-13}\ \mathrm{erg}^{\gamma-1}\ \mathrm{cm}^{-3}$. The differential electron flux in interstellar space at 0.27 Gev is found to be the order of 10^4 el/(m^2 sec sr Gev) and is compared with direct measurements of cosmic ray electrons in figure 2. This value is a factor of 170 greater than the measured electron flux at solar minimum obtained from balloon experiments

(Fanselow et al., 1969). If we lower the emissivity by a factor of two on the assumption that the path length to $\tau = 1$ at 1 MHz was underestimated and raise the magnetic field to $5 \mu G$, then the calculated electron flux can be reduced by a factor of four. This is the lower limit that the radio data will permit, however. The remaining difference of a factor of 40 or more between the electron flux predicted by the radio measurements and the directly measured flux at a few hundred Mev is probably due to residual solar modulation effects. If the electron flux measured at the earth is reduced from the interstellar value by a factor $\exp(-\eta/R_o)$ where R_o is the rigidity below which the modulation is rigidity-independent, then for $R_o = 0.3$ GV our measurements give a residual modulation parameter $\eta \gtrsim 1$ GV. Alternatively, if the sun were located in a region of atypically low electron flux in the galaxy, then even after correcting for solar modulation the directly measured fluxes would be lower than the mean interstellar flux deduced from radio measurements over distances of several hundred parsecs. We feel that the possibility of a large scale gradient in the cosmic ray electron distribution deserves further study. This possibility has also been raised by Rees and Silk (1969).

SUMMARY

New integrated spectra of the galactic background continuum radiation at low frequencies show that free-free absorption by thermal electrons in the interstellar medium

results in large optical depths for frequencies below 1 MHz. Consequently, since the measurements in this frequency range correspond to observations over lines of sight only a few hundred parsecs in extent, the low frequency spectra may be used to determine the properties of the Local System. Even on a large angular scale (i.e. a few steradians), the ionized component of the interstellar medium does not appear to be uniform but shows a concentration in the galactic plane and a maximum towards the anti-center direction. This is to be expected since the sun is thought to be located on the inside edge of the local spiral arm with the maximum gas concentration of the arm towards the anti-center.

The volume emissivity of the synchrotron radiation in the Local System at 1 MHz is 1 $(^{+1.0}_{-0.5})$ x 10^{-39} W/(m^3Hz sr). When scaled to 1 MHz, high frequency measurements of the emissivity obtained over longer effective path lengths are lower by about a factor of three. This difference can be interpreted as evidence for a lower emissivity by a factor of the order of ten in inter-arm regions than in spiral arms. Such a variation in emissivity could arise if inter-arm magnetic fields were the order of one fifth the interstellar magnetic fields in spiral arms (i.e., $<1\mu G$).

For a mean interstellar field of $3\mu G$ in the local system, the synchrotron radiation at 1 MHz is due to cosmic ray electrons at energies of about 0.27 Gev. From our measurement of emissivity the calculated interstellar cosmic ray intensity at this energy is $1(^{+3.0}_{-0.75}) \times 10^4$ el /(m ^{2}sec sr Gev). Direct measurements of low energy cosmic rays have yielded lower intensities by factors of the order of 100. Since the radio measurements provide an estimate of the mean interstellar electron flux, a larger solar modulation factor in this energy range than has been predicted in earlier calculations is required. The solar modulation factor may be reduced if we suppose that there are gradients in the large scale distribution of cosmic rays and that the intensity in the solar neighborhood is lower than the mean interstellar value in the Local System.

The authors gratefully acknowledge discussions with Dr. Reuven Ramaty.

REFERENCES

Alexander, J.K., Brown, L.W., Clark, T.A., Stone, R G., Weber, R.R 1969, Astrophys. J. Lett. 157, L163.

Andrew, B.H. 1969, Mon. Not. R. Astr. Soc. 143, 17.

Baldwin, J.E. 1967, Radio Astronomy and the Galactic System, I.A.U. Symposium No. 31, ed. H. van Woerden (London and New York: Academic Press) p. 337.

Bridle, A.H. 1968, Mon. Not. R. Astr. Soc. 138, 251.

Bridle, A.H., Venugopal, V.R. 1969, Nature 224, 545.

Fanselow, J.L., Hartman, R.C., Hildebrand, R.H., Meyer, Peter 1969, Astrophys. J. 158, 771.

Field, G.B., Goldsmith, D.W., Habing, H.J. 1969, Astrophys. J. Lett. 157, L163.

Ginzburg, V.L. 1964, The Propagation of Electromagnetic Waves in Plasmas (London: Pergamon Press).

Ginzburg, V.L. Syrovatskii, S.I. 1965, Ann. Rev. Astron. & Astrophys. 3, 297.

Hjellming, R.M., Gordon, C.P., Gordon, K.J. 1969, Astron. & Astrophys. 2, 202.

Jokopii, J.R., Lerche, I. 1969, Astrophys. J. 157, 1137.

Purton, C.R. 1966, Ph.D. Thesis, University of Cambridge.

Rees, M.J., Silk, J., 1969, Astron. & Astrophys. 3, 452.

Roger, R.S. 1969, Astrophys. J. 155, 831.

Verschuur, G.L. 1969, I.A.U. Symposium No. 39 on Gas Dynamics of the Interstellar Medium.

Webber, W.R. 1968, Aust. J. Phys. 21, 845.

Weber, R.R., Stone, R.G., Somerlock, C.R. 1969, Astron. & Astrophys. 1, 44.

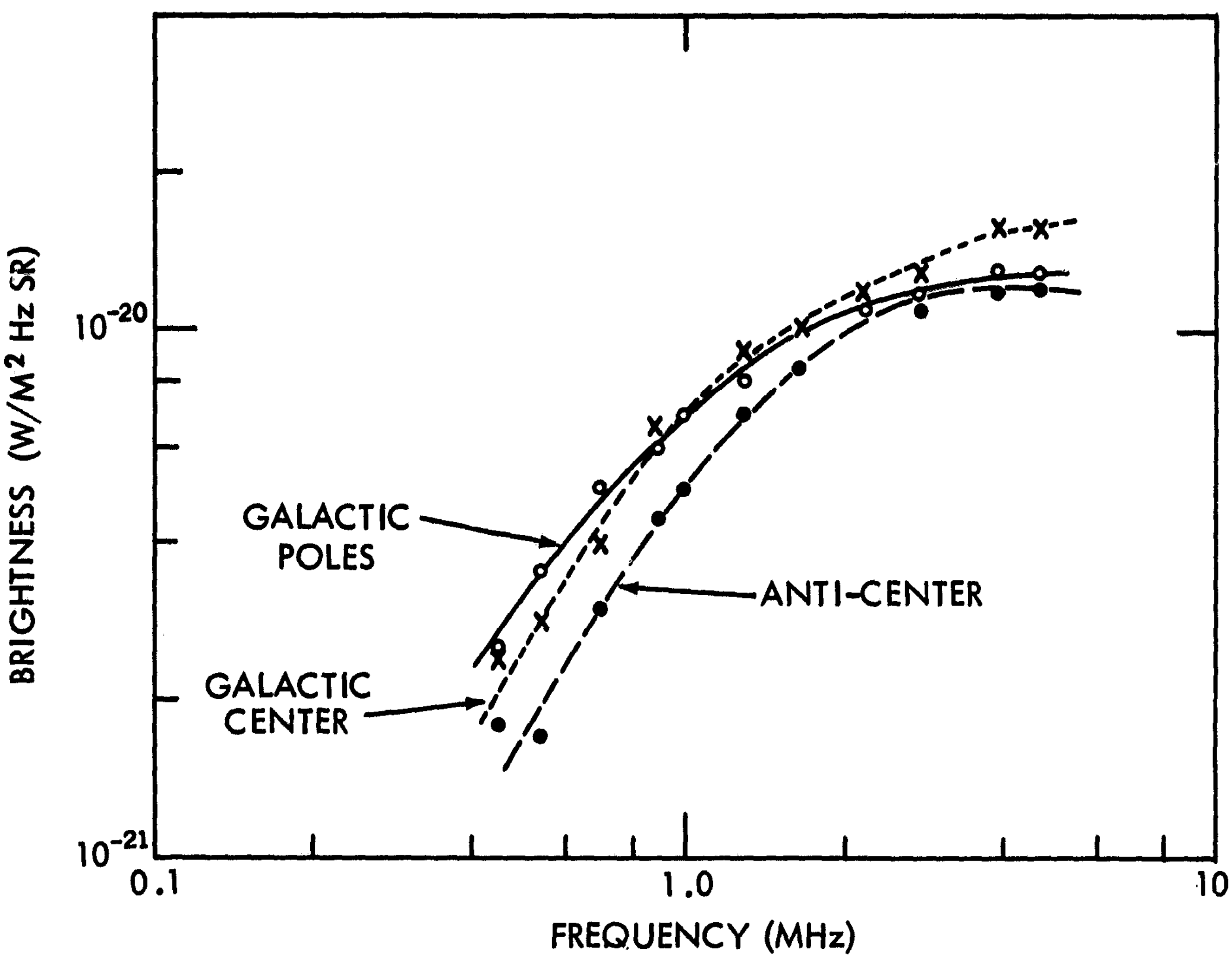

Figure 1 - Integrated cosmic noise background spectra for the general regions of the galactic poles, center and anticenter from measurements with the RAE-I diple antenna.

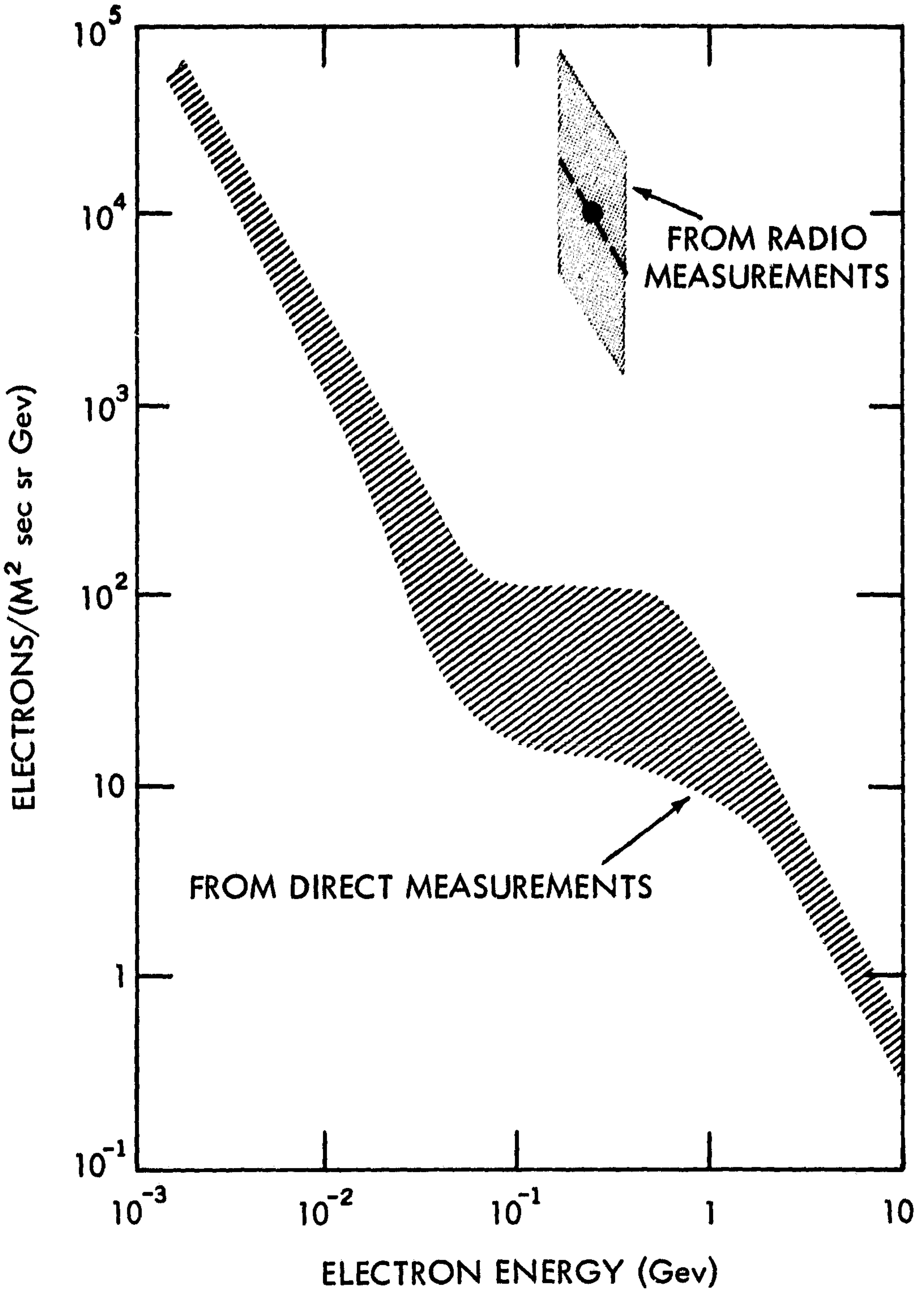

Figure 2 - Interstellar intensity of cosmic ray electrons deduced from the low frequency radio measurements compared with the electron spectrum determined from direct measurements on balloons and satellites.