

A New Look at Galactic Polar Radio Emission and the Local Interstellar Electron Spectrum

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Abstract

It is difficult to determine the local cosmic ray electron spectrum below ~ 10 GeV because of solar modulation effects. In the past the galactic polar radio spectrum has been used as a proxy to determine the electron spectrum.

New radio data and information on absorption effects at low frequencies make it worthwhile to re-examine this relationship. Above ~ 10 MHz where free-free absorption is negligible, the galactic radio spectrum can be determined accurately now up to ~ 2 GHz, giving a profile of the electron spectrum from ~ 0.4 to 6 GeV (for $B=5\mu\text{G}$). Below 10 MHz, where absorption becomes increasingly important, new information allows these absorption effects to be studied more accurately. This analysis leads to a radio emissivity spectrum down to ~ 0.3 MHz, extending the electron spectrum down to ~ 70 MeV. The local electron spectrum derived from these radio observations will be compared with that directly measured at the Earth.

1. Introduction

Below ~ 10 GeV solar modulation effects become increasingly important making it difficult to determine the local interstellar (IS) electron spectrum. These electrons, however, radiate synchrotron radiation, which from electrons of energy 0.1-6 GeV is observed in the radio range of ~ 0.5 MHz to ~ 2 GHz for a $5\mu\text{G}$ interstellar magnetic field. The spectral index of this radio emission, a , is related to the spectral index of the electron spectrum, s , by $s=2a+1$, so a measurement of the radio spectrum can be used to deduce the spectral index of the IS electron spectrum.

The radio spectrum in the direction of the galactic poles can be used to deduce a measure of the local electron spectrum (e.g., Webber, Simpson and Cane, 1980). Since these earlier studies, new radio data make it possible to more accurately determine this polar radio spectrum from ~ 10 MHz where free-free absorption is negligible, up to ~ 2 GHz where the 3K cosmic background radiation (CMB) dominates the spectrum. Below ~ 10 MHz, where absorption becomes important, new information on the IS thermal free electron density and spatial distribution that is responsible for the free-free absorption, allows these effects to be determined more accurately and the electron spectrum to be deduced down to ~ 0.1 GeV. In fact, from a study of the observed galactic radio spectrum in the range 0.1-10 MHz it is possible to obtain a self consistent measurement of the absolute local electron intensity in this low energy range.

2. Analysis and Interpretation of the Radio Data

In Table 1 we list the measurements of the polar radio intensities between 10 MHz and 2 GHz. These are the observed intensities with the 2.7K CMB and a 20% extra-galactic component subtracted, thus representing only the galactic component of the polar radio spectrum. The corresponding spectrum is shown in Figure 1. Earlier it was possible to approximate this polar spectrum with a simple spectral index ~ 0.62 (e.g., Webber, Simpson and Cane, 1980), but the latest analysis shows clearly that the spectral index is increasing with increasing frequency.

To illustrate this we derive the radio index between each frequency in Table 1. This index, as a function of frequency, is shown in Figure 2. It can be seen from both Figure 1 and Figure 2 that the radio spectrum slowly steepens with increasing frequency from an average index ~ 0.62 below a frequency of 178 MHz to an index approaching 1 at the highest frequencies. This corresponds to an electron spectral index increasing from ~ -2.24 at an equivalent energy ~ 0.4 GeV to an index ~ -2.90 at ~ 6 GeV ($B=5\mu\text{G}$).

TABLE 1
ELECTRON SPECTRUM DEDUCED FROM GALACTIC POLAR
RADIO SPECTRUM

ν (MHz)	E (elect)(GeV) $B_{ }=5\mu\text{G}$	t_{GNth} K	I_{GNth} (KJy sr $^{-1}$)	Ratio ($I_{\nu 1}/I_{\nu 2}$)	Radio Index	Elect Index	Elect Flux $^+$	$\times E^{3.0}$
10	0.408	2.65×10^5	820				1151	78.
20	0.577	4.2×10^4	520	1.577x	0.65	2.30	519	100
38	0.796	7.8×10^3	350	1.488x	0.62	2.24	243	122
85	1.19	1040	317	1.613x	0.60	2.20	95.8	161
178	1.72	146 ± 10	136	1.607x	0.64	2.28	39.2	200
408	2.61	14.5 ± 1.0	75.0	1.813x	0.71	2.42	13.6	240
820	3.70	2.55 ± 0.25	44.5	1.695x	0.75	2.50	5.60	295
1420	4.86	0.50 ± 0.05	30.0	1.594x	0.86	2.72	2.66	309
2000	5.77	0.18 ± 0.03	22.0	1.384x	0.95	2.90	1.63	313

$^+j(1 \text{ GeV})_{\text{elect}} = 1.5 \times 10^2 \text{ particles}/(\text{m}^2\text{-s-sr-GeV})$

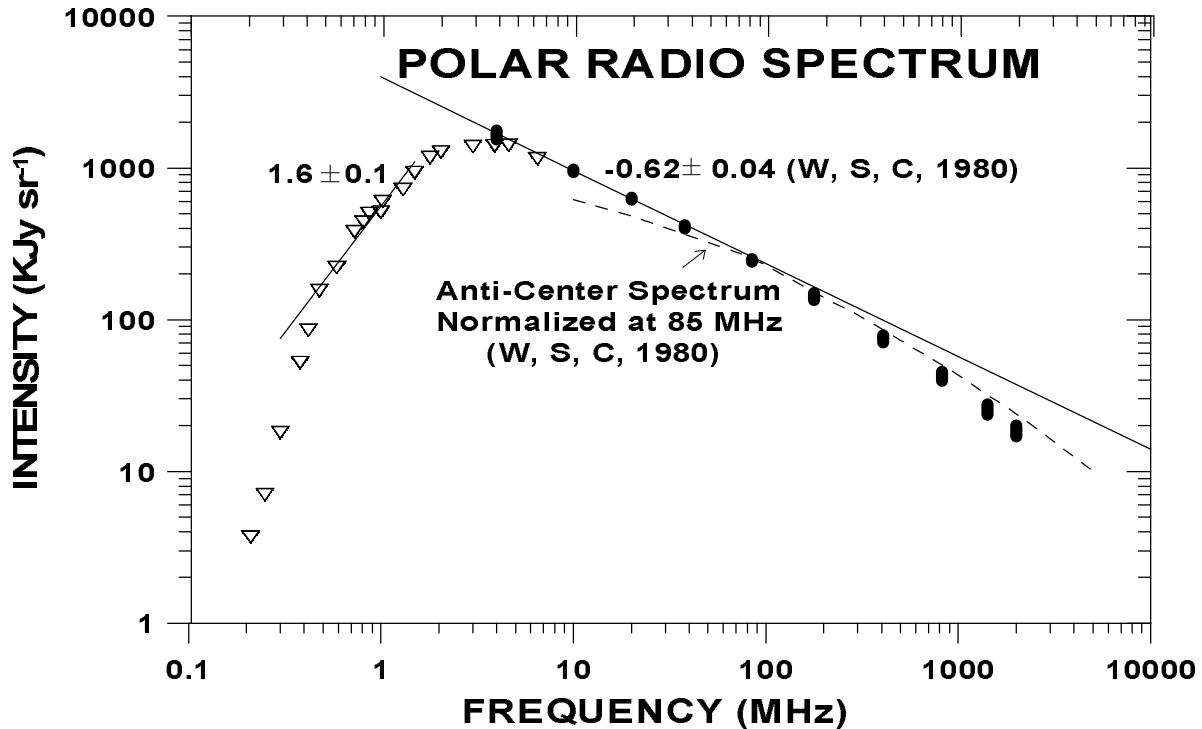


Figure 1: Galactic component of the polar radio spectrum as derived in this paper (Table 1) shown as solid vertical bars. Directly measured spectrum at low frequencies shown as open triangles.

If one normalizes the IS electron intensity to a value $=1.5 \times 10^2 \text{ e/m}^2 \text{ s sr GeV}$ at 1 GeV (~ 5 x the observed electron intensity at sunspot minimum, allowing for solar modulation). Then the IS electron spectrum derived from these radio measurements (shown in columns 8 and 9 of Table 1) is given in Figure 3. In this figure we also show the direct measurements at higher energies of the electron spectrum at the Earth taken from the paper by Rockstroh, et al., 1999. Also shown in Figure 3 are calculations of the electron spectrum, using source spectra with index $=-2.2$, -2.3 and -2.4 normalized to the same value at 1 GeV, made using a Monte Carlo propagation program (also described in Rockstroh, et al., 1999).

This IS electron spectrum may be extended to energies below ~ 0.4 GeV using the details of the measured radio spectrum below ~ 10 MHz as shown in Figure 1. In the low frequency range the radio intensity is given by the expression $I(\nu) = [\epsilon(\nu)/k(\nu)](1 - e^{-\tau(\nu)})$ where $\epsilon(\nu)$ is the local volume radio emissivity, $k(\nu)$ is the absorption coefficient and $\tau(\nu) = k(\nu)L$ is the optical depth. At frequencies below ~ 1 MHz, the optical depth is large and $I(\nu) \sim \epsilon(\nu)/k(\nu)$. At these frequencies the data in Figure 1 shows that $I(\nu) \sim \nu^{1.6}$ between ~ 0.3 -1.2 MHz and since $k(\nu) \sim \nu^{-2.1}$, this requires that the volume emissivity (radio spectrum) be $\sim \nu^{-0.5}$ or about the same as or slightly flatter than the index of -0.62 found in the frequency range 10-178 MHz

Thus, overall, the radio spectral index and the corresponding electron spectral index can be determined down to ~ 0.3 MHz (0.08 GeV). The absolute magnitude of this local electron spectrum can be deduced from the measured value of $I(\nu)$ at 1 MHz and determinations of the local volume radio emissivity in the direction of H_{II} regions as described by Webber and Rockstroh, 1978 and Fleishman and Tokarev, 1995 (but this analysis is beyond the scope of this paper).

3. Summary and Conclusions

New information relating to the polar radio spectrum from ~ 0.3 MHz to ~ 2 GHz allows an improved estimate of the local galactic electron spectrum from ~ 0.1 to 6 GeV. The radio data shows a spectrum with a steadily increasing exponent from ~ 0.5 at the lowest frequencies to ~ 1.0 at the highest frequencies. This corresponds to an electron spectrum with an exponent ~ -2.0 increasing to -3.0 over the corresponding energy range.

Using a Monte Carlo diffusion model for propagation, we find that this changing exponent can be well fit by an electron source spectrum of index -2.40 within quite narrow limits.

References

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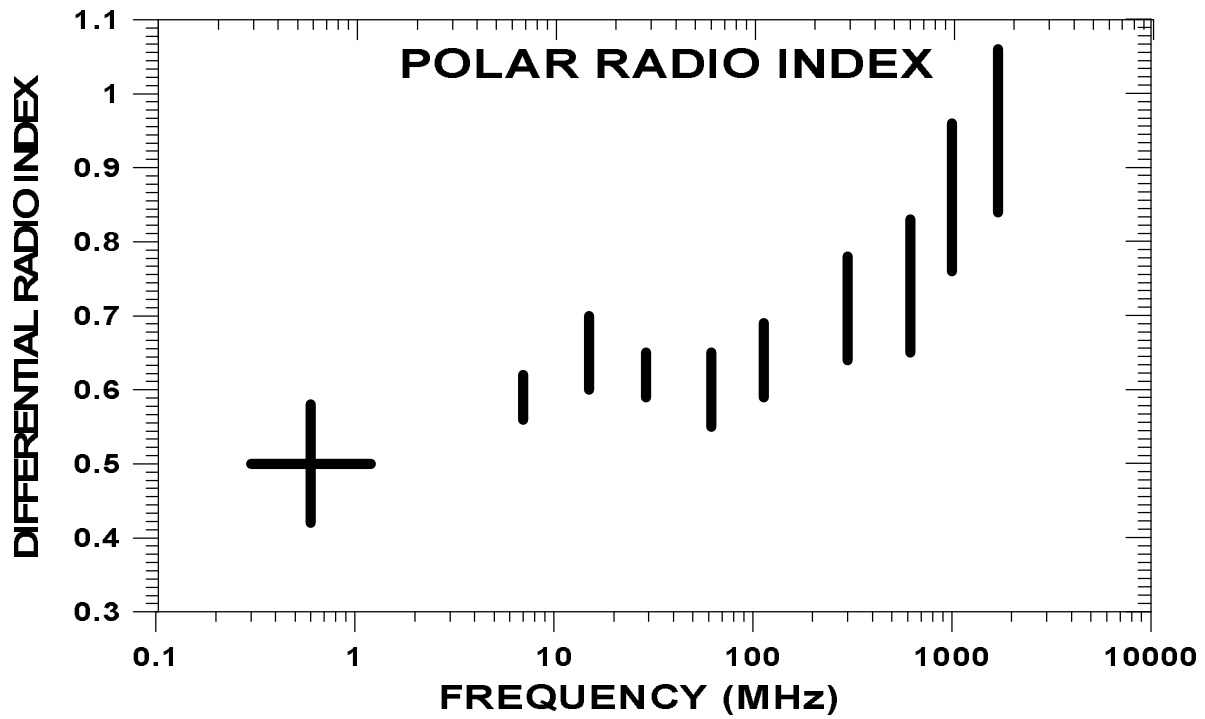


Figure 2: Index of radio spectrum derived between measurement frequencies listed in Table 1.

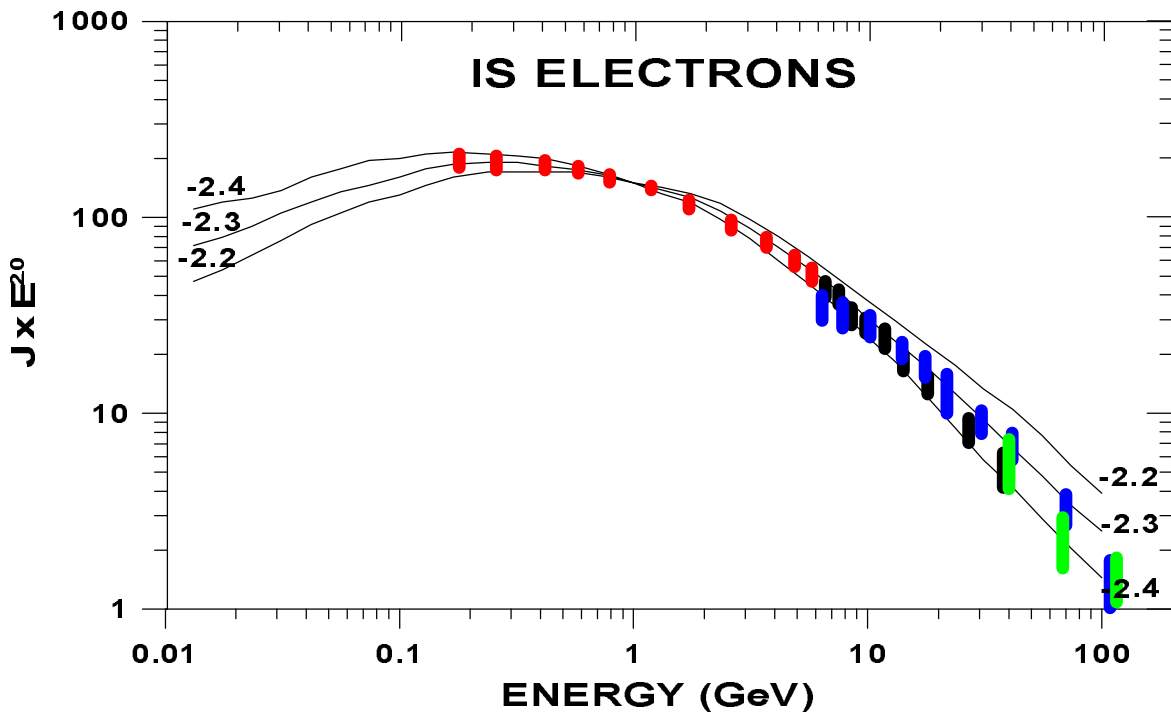


Figure 3: IS electron spectrum (shown as red bars) derived from the polar radio spectrum as listed in Table 1. Direct measurements at the Earth from the summary by Rockstroh, et al., 1999, shown as solid colored bars.