1968, *Bull. Astr. Inst. Netherlands* **19** 352–354; *Communication from the Observatory at Leiden*

THE SPECTRUM OF THE GALACTIC RADIO EMISSION DERIVED FROM THE OBSERVED SPECTRUM OF COSMIC-RAY ELECTRONS

H. OKUDA*

Received 19 September 1967

Using recent observations of the cosmic-ray electrons, the spectrum of the galactic radio emission is calculated in detail by synchrotron theory. It agrees well in shape with the observed radio spectrum. A slight discrepancy between the calculated and the observed spectra may be due to solar modulation.

1. Introduction

Since EARL (1961) obtained a positive result for the existence of cosmic-ray electrons, many observations of cosmic-ray electrons have been made (MEYER and VOGT, 1962; AGRINIER *et al.*, 1964; BLEEKER *et al.*, 1965; DANIEL and STEPHENS, 1966). The quality of the observations has also been improved appreciably and a reliable energy spectrum of the cosmic-ray electrons is now available (BLEEKER *et al.*, 1967; L'HEUREUX and MEYER, 1967; WEBBER and CHOTKOWSKI, 1967).

The theory that these electrons emit the non-thermal radio emission in the galactic magnetic field by synchoton radiation (see, e.g., SHKLOVSKY, 1960) is strongly supported by the detection of linear polarization in the galactic radio emission (WESTERHOUT *et al.*, 1962; WIELEBINSKI *et al.*, 1962).

Our knowledge of the spectrum of the galactic radio emission has also been greatly improved by adopting new techniques (TURTLE *et al.*, 1962; PURTON, 1966; YATES and WIELEBINSKI, 1966; BRIDLE, 1967).

These improvements have made it possible now to compare the spectrum of the cosmic-ray electrons and that of the galactic radio emission in greater detail than before.

2. Calculation of the radio spectrum

Applying synchrotron theory (see, e.g., OORT and WALRAVEN, 1956), we can calculate the volume emissivity in the radio spectrum, $\varepsilon(\nu)$, by

$$\varepsilon(\nu) = \int_0^\infty P(\nu, E) N(E)\,\mathrm{d}E \qquad (1)$$

if the energy spectrum of electrons $N(E)$ is known. Here $P(\nu, E)$ is the radio power emitted by a single electron with energy E in a magnetic field $H_\perp$ and given by

$$P(\nu, E) = \frac{3^{\frac{1}{2}} e^3}{mc^2} H_\perp (\nu/\nu_c) \int_{\nu-\nu_c}^\infty K_{\frac{5}{3}}(\eta)\,\mathrm{d}\eta \qquad (2)$$

$$= C H_\perp F(\nu/\nu_c) \quad \mathrm{erg} \cdot \mathrm{sec}^{-1} \cdot (\mathrm{c/s})^{-1},$$

where $C = 2.343 \times 10^{-22}$, if $H_\perp$ is measured in Gauss, $K_{\frac{5}{3}}(\eta)$ is the modified Hankel function of the order 5/3, and ν_c is defined by

$$\nu_c = (3/4\pi)(eH_\perp/mc)(E/mc^2)^2 = LH_\perp E^2 \text{ c/s}, \qquad (3)$$

where $L = 1.608 \times 10^{13}$ if E is measured in GeV.

We adopt a variable α defined by

$$\alpha = E/E_\nu, \qquad (4)$$

where E_ν is also defined by

$$LH_\perp E_\nu^2 = \nu, \qquad (5)$$

and therefore

$$\nu/\nu_c = \alpha^{-2}. \qquad (6)$$

Eq. (1) can then be written as

$$\varepsilon(\nu) = CL^{-\frac{1}{2}} H_\perp^{\frac{1}{2}} \nu^{\frac{1}{2}} \int_0^\infty N(\alpha E_\nu) F(\alpha^{-2})\,\mathrm{d}\alpha. \qquad (7)$$

The quantity E_ν denotes the energy at which the critical frequency is equal to ν, and $F(\alpha^{-2})$ represents the relative contribution by an electron with energy αE_ν to the emission between ν and $\nu+\mathrm{d}\nu$. Figure 1, where $F(\alpha^{-2})$ as given by Oort and Walraven has been plotted

---

* On leave of absence from Nagoya University, Nagoya, Japan.

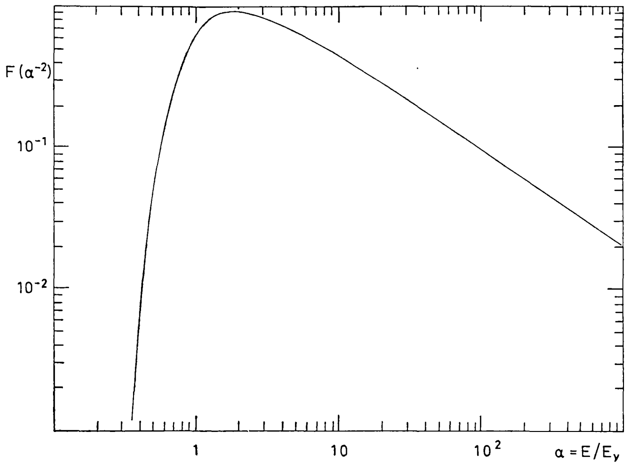

Figure 1. Relative contribution of electrons of different energy to the radio emission at one frequency.

against α, shows that the electron spectrum in the high-energy part ($E > E_\nu$) is far more effective for the emission of a certain frequency than the low-energy part ($E < E_\nu$). This means that any uncertainties in the low-energy part of the electron spectrum do not strongly influence the following calculation of the radio spectrum.

The calculations were based on the energy spectrum of the cosmic-ray electrons compiled in figure 2 from the observations by Bleeker *et al.* (1967). The spectrum covers an energy range between 0.5 and 70 GeV. Some flattening of the spectrum is clearly seen in the energy region below about 6 GeV. This flattening may be due either to some solar modulation or to interstellar modulation or to both of them. However, the observations of the cosmic-ray electrons in the last few years have not shown any apparent time variation with solar activity (Bleeker *et al.*, 1967; L'Heureux *et al.*, 1967). This might indicate that the solar modulation of the electron component is considerably smaller than that of protons and heavier cosmic-ray components.

Hence, we shall calculate the galactic radio spectrum on the basis of the observed electron spectrum. The comparison of the calculated radio spectrum with the observations will then show whether any modulation is present between the galactic electrons and the cosmic-ray electrons observed near the Earth. The calculations were made by eq. (7) using an electronic computer. For simplicity, we adopted constant values of $H_\perp$, namely 1.5×10^{-5} G in the disk and 2.5×10^{-6} G in the halo. The resulting volume emissivities are shown in figure 3.

3. Comparison with the observations

The spectrum of the galactic radio emission has recently been measured with great care by several authors (Purton, 1966; Yates and Wielebinski, 1966; Bridle, 1967). They used scaled antennas to adjust the antenna patterns and calibrated the observed flux with standard noise sources. They have separated the galactic component from the extragalactic one by the method utilizing the difference in spectral index between them. In order to convert these relative spectra into absolute volume emissivities (figure 3) we made the two sets (Purton, and Yates/Wielebinski) coincide at 85 Mc/s and adopted 15 °K/kpc and 1.2 °K/kpc for the absolute volume emissivities of the disk and the halo at 404 Mc/s

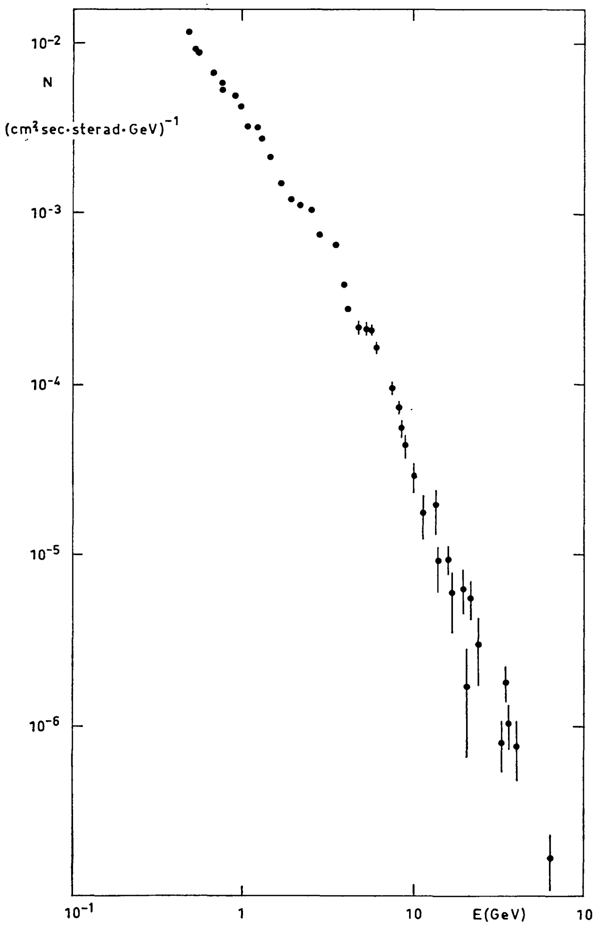

Figure 2. The energy spectrum of the cosmic-ray electrons, obtained from balloon observations at Kiruna, Sweden (geomagnetic cut-off rigidity 0.5 GeV) by the Cosmic Ray Working Group at Leiden (Bleeker *et al.*, 1967).

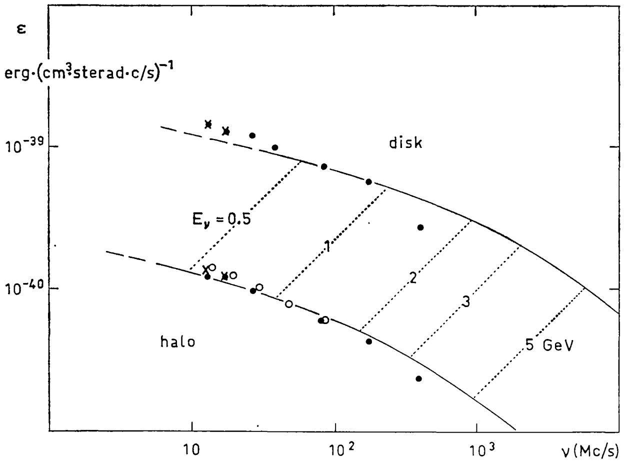

Figure 3. Calculated and observed volume emissivities in the galactic radio spectrum. Solid circles represent the observations by PURTON (1966), open circles those by YATES and WIELEBINSKI (1966), and crosses those by BRIDLE (1967).

(OKUDA and TANAKA, 1967). It is seen from figure 3 that the radio spectra calculated from the observed electron spectrum explain the observed spectra of both the disk and the halo rather well, if reasonable values of the galactic magnetic field are adopted (1.5×10^{-5} G for the disk and 2.5×10^{-6} G for the halo). The remaining difference may be a solar modulation effect. The calculated spectra are slightly flatter than the observed ones. This means that the electrons responsible for the galactic radio emission, i.e., between 0.3 and 3 GeV, have a steeper energy spectrum than the cosmic-ray electrons observed near the Earth. The solar modulation seems to be small, in any case, for otherwise the radio spectrum would become too steep.

The strong steepening in Purton's radio data between 178 Mc/s and 404 Mc/s is very hard to understand from the energy spectrum of the cosmic-ray electrons. Since the function $F(\alpha^{-2})$ has a broad distribution extending into the high-energy region, such a rapid change in radio spectral index could be explained only by a sharp cut-off in the electron spectrum around 1 or 2 GeV. There is no such indication in the observed electron spectrum. A recent observation at 610 Mc/s by Howell (private communication) suggests that the point at 404 Mc/s given by Purton may be too low.

We may conclude that the observed spectrum of the cosmic-ray electrons represents the galactic electron spectrum rather well. There is only a faint indication of some solar modulation, thus providing a good basis for the method of deriving the galactic magnetic field employed in the paper by OKUDA and TANAKA (1967).

Acknowledgements

The author would like to express his sincere thanks to the staff of the Leiden Observatory, especially to Professor J. H. Oort, for their kind hospitality during his stay at the observatory when this work was done. He is also grateful to Professor H. C. van de Hulst for his valuable discussions and kind advice on the manuscript. He is indebted to the members of the Cosmic Ray Working Group in the Kamerlingh Onnes Laboratory, Leiden, for making the electronic computer available to him.

References

B. AGRINIER, Y. KOECHLIN, B. PARLIER, G. BOELLA, G. DEGLI-ANTONI, C. DILWORTH, L. SCARSI and G. SIRONI, 1964, *Phys. Rev. Letters* **13** 337

J. A. M. BLEEKER, J. J. BURGER, A. SCHEEPMAKER, B. N. SWANENBURG and Y. TANAKA, 1965, *Proc. Ninth Int. Conf. Cosmic Rays* (The Institute of Physics and The Physical Society, London) **1** 327

J. A. M. BLEEKER, J. J. BURGER, A. J. M. DEERENBERG, A. SCHEEPMAKER, B. N. SWANENBURG and Y. TANAKA, 1967, *Proc. Tenth Int. Conf. Cosmic Rays*, to be published

A. H. BRIDLE, 1967, *Mon. Not. Roy. Astr. Soc.* **136** 219

R. R. DANIEL and S. A. STEPHENS, 1966, *Phys. Rev. Letters* **17** 935

J. A. EARL, 1961, *Phys. Rev. Letters* **6** 125

J. L'HEUREUX and P. MEYER, 1967, *Proc. Tenth Int. Conf. Cosmic Rays*, to be published

J. L'HEUREUX, P. MEYER, S. DEV VERMA and R. VOGT, 1967, *Proc. Tenth Int. Conf. Cosmic Rays*, to be published

P. MEYER and R. VOGT, 1962, *Phys. Rev. Letters* **8** 387

H. OKUDA and Y. TANAKA, 1967, *Proc. Tenth Int. Conf. Cosmic Rays*, to be published

J. H. OORT and T. WALRAVEN, 1956, *Bull. Astr. Inst. Netherlands* **12** 462

C. R. PURTON, 1966, *Mon. Not. Roy. Astr. Soc.* **133** 463

I. S. SHKLOVSKY, 1960, *Cosmic Radio Waves* (Harvard Univ. Press)

A. J. TURTLE, J. F. PUGH, S. KENDERDINE, I. I. K. PAULINY-TOTH, 1962, *Mon. Not. Roy. Astr. Soc.* **124** 297

W. R. WEBBER and C. CHOTKOWSKI, 1967, *J. Geophys. Res.* **72** 2783

G. WESTERHOUT, CH. L. SEEGER, W. N. BROUW and J. TINBERGEN, 1962, *Bull. Astr. Inst. Netherlands* **16** 187

R. WIELEBINSKI, J. R. SHAKESHAFT and I. I. K. PAULINY-TOTH, 1962, *Observatory* **82** 158

K. W. YATES and R. WIELEBINSKI, 1966, *Australian J. Phys.* **19** 389