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III-3-7. The Galactic Radio Spectrum and the Energy Spectrum of Cosmic Ray Electrons

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On the assumption that the radio emission from the Galaxy at metre wavelengths is due to the synchrotron radiation from cosmic ray electrons moving in the interstellar magnetic fields, it is possible to derive information from the radio measurements concerning the energy spectrum of the electrons and the spatial distribution of the electrons and magnetic field in the Galaxy. The radiation from a relativistic electron moving in a magnetic field is characterized by a spectrum $F(\nu/\nu_c)$ (see Oort and Walraven[1]) where the frequency $\nu_c=6.3\times10^{18}H_{\perp}E^2$ ($H_{\perp}$ in gauss, E in ergs). The power radiated is constant within a factor of 2 from very low frequencies ($\nu\simeq0.01\,\nu_c$) up to frequencies of approximately ν_c and falls off steeply at higher frequencies. For electrons of 1 Bev moving in a field of 10^{-5} gauss, the value of $\nu_c=160$ Mc/s and thus it is with electrons of energy about 1 Bev with which we are concerned in the part of the galactic radio spectrum which has been observed so far.

It has been shown by Ginzburg[2] that, for a distribution of electrons having a differential energy spectrum of the form

$$n(E)=KE^{-\gamma}\,,$$

then the radio flux, $S\propto\nu^{(1-\gamma)/2}$.

If the electron energy spectrum can be described by a single value of γ only over a limited range of E, then it is still approximately true that the radio spectrum is or the form $\nu^{(1-\gamma)/2}$ over a correspondingly limited range of frequencies.

Observations of the galactic radiation have led, in the past, to a variety of values for the radio spectrum lying in the range $S\propto\nu^{-0.4}$ to $S\propto\nu^{-0.8}$. Recent measurements by Costain[3] at Cambridge gave a value of $S\propto\nu^{-0.37\pm0.04}$ over the frequency range 38–178 Mc/s. This very low value for the spectral index made it desirable to check it by a further series of measurements. These have been made by Turtle, Pugh, Paulini-Toth and Kenderdine at frequencies of 26, 38, 178 and 404 Mc/s. (to be published in Mon. Not. Roy. Ast. Soc.) The experiments follow up and extend Costain's work. The two important precautions taken by Costain were also made in this work:

(1) The galactic noise power was calibrated against the noise power generated in an accurately matched resistive load at several different temperatures.

(2) At the three lower frequencies, antenna systems were used which were geometrically similar and scaled in size proportionally to the wavelength. This procedure has the advantage that, even if the antenna pattern is not accurately known, the same region of sky is studied in all the observations.

The beam widths of the antennas were $15°\times40°$. With this comparatively low resolving power it is only possible to distinguish unambiguously for measurement the radiation from the disc in the region of the anticentre and the radiation from the halo of the Galaxy.

The results show a curved spectrum when plotted on a log S-log ν scale having $S\propto\nu^{-0.35}$ at the lower frequencies near 30 Mc/s steepening to $S\propto\nu^{-0.8}$ at frequencies near 300 Mc/s. The spectra for the galactic disc and for the halo are identical within the limits of error. The slopes of the straight lines joining the measured points at the extreme frequencies of 26 and 404 Mc/s are -0.53 ± 0.04 for the disc and -0.55 ± 0.04 for the halo.

These results present two very interesting features:

(1) There is no observed difference in spectrum between the disc and halo of the Galaxy. The calculated life times of electrons of energies in the relevant range are at least 10^7 years in the Galaxy and it might be expected that good mixing would occur between the disc and the halo. From the emission per unit volume in the disc and halo, derived from intensity measurements, the

ratio of the magnetic field in the disc to that in the halo must be about 5. The radio spectra should therefore be similar in shape in the disc and the halo but would be shifted to 5 times higher frequencies in the disc than in the halo since $\nu_c \propto H$. Observing at any particular frequency the halo radiation should then have a steeper spectrum than the radiation from the disc. This difficulty might be overcome either by finding unsuspected systematic errors in some of the observations, resulting in a much smaller value for the curvature of the spectrum or by assuming that the magnetic field in the halo is equal to that in the disc but occupies a much smaller fraction of the available volume. Neither alternative seems particularly attractive at present.

(2) The slope of the spectrum at low frequencies is -0.35 and even the mean slope over the whole frequency range is -0.54. These values correspond to differential energy spectra of the electrons of $E^{-1.7}$ and $E^{-2.08}$. Burbidge discussed the production of electrons as secondaries arising from collisions between the primary cosmic ray nuclei and the interstellar gas, and showed that they were reasonably sufficient in number to provide the observed radio emission. But the energy spectrum of the secondary electrons would be at least as steep as that of the primary protons for the energies with which we are concerned (electrons of $\sim$1 Bev produced mainly from protons having energies up to say 25 Bev). Taking γ for the protons to be 2.5, the radio spectrum of the secondary electrons would be steeper than $\nu^{-0.75}$ which is well outside the limits of error. The only loss mechanism which would tend to flatter the spectrum, *i.e.* one which acts preferentially on the low energy electrons, would be ionization, but the energies of the electrons are too high for this to be important. It therefore seems unlikely that the cosmic ray electrons in the Galaxy are simply secondaries arising from the primary proton flux.

If the curvature of the radio spectrum is confirmed, the derived energy spectrum exhibits an important phenomenon. The value of γ changes from 1.7 to 2.6 over a range of frequencies of about 16 to 1 and thus an energy range in the electrons of only 4 to 1. We may hope that such a striking curvature in the electron energy spectrum may reflect some identifiable physical process.

References

1) J. H. Oort and Th. Walraven: Bull. Astron. Ned. **12** (1956) 285.
2) V. L. Ginzburg: Nuovo Cimento Supp. **3** (1956) 38.
3) C. H. Costain: Mon. Not. Roy. Ast. Soc. **120** (1960) 248.

Discussion

Hayakawa, S.: I would like to know your feeling if the spectrum shown in OR III-3-10 Fig. 1, 2 agrees with your observations. This is based on the synchrotron radiation of the secondary electrons and the flattering of the spectrum towards low energy is due to chiefly to the energy spectrum of pions produced by nuclear interactions.

Baldwin, J.E.: The agreement with the shape of the radio spectrum looks quite good. It seems to depend on the assumption of fields as strong as 10^{-4} gauss in the Galaxy. It is important to discuss the problem of the stability of a region where the field is as high as this.