# RADIO ELECTRONS AND MAGNETIC FIELDS IN THE GALACTIC HALO*

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## ABSTRACT

The density of radiating electrons in the galactic halo is re-examined in the light of recent cosmic-ray data. A flux $\phi_h(E) \approx 0\,8 \times 10^{-2}\, E^{-2\,4}$ (cm$^2$ sec ster GeV)$^{-1}$ in 0 6–3.5 GeV is proposed; this is 1–2 per cent of the quiescent primary proton flux and is higher than estimates used previously in deriving the halo magnetic field from radio brightness measurements and models of the halo. The halo field implied by such a flux is $\approx$ (2–3.5) $\times 10^{-6}$ gauss; the lower figure corresponds to the uniform radio emissivity originally given for the halo by Baldwin, the higher to Mills's value for the central regions. Higher field estimates obtained analogously by other authors are discussed.

In the course of estimating the inverse Compton radiation from the halo of our Galaxy (Felten and Morrison 1963; Felten 1965) we have had occasion to redo and update the familiar comparison (Biermann and Davis 1960; Woltjer 1961) between data on primary cosmic-ray electrons and on the radio brightness of the Galaxy at high latitudes. Since this comparison is of substantial independent interest, we have thought it suitable for presentation in this separate paper.

It would be an exaggeration to describe the halo as a well-known radio source. Early models of cosmic-ray acceleration and diffusion (Fermi 1949, 1954; Morrison, Olbert, and Rossi 1954) and radio emission (Westerhout and Oort 1951) in the Galaxy were based on spiral-arm and disk structures and took no account of a halo. Shklovsky (1952) was the first to propose a halo model, and the idea gained currency in the West through the work of Baldwin (1955), who succeeded in fitting galactic radio isophotes with simple homogeneous spherical and spheroidal models of the halo having radii $\approx$10–16 kpc. He observed also a similar halo around the Andromeda galaxy (M31) having radius $R_h \approx 100'$ or 16 kpc and a volume emissivity some six times smaller than that of our halo. This Andromeda halo was subsequently observed by a multitude of experimenters (Seeger, Westerhout, and Conway 1957; Hanbury Brown and Hazard 1959; Baldwin and Costain 1960; Leibacher 1964), with its reported sizes ranging as high as $R_h \approx 5°$ or 50 kpc, though the higher-frequency, higher-resolution studies (Large, Mathewson, and Haslam 1959; Kraus 1964; De Jong 1965) generally gave considerably smaller dimensions. It now appears that most other external galaxies do not show halo emission (De Jong 1965). Recently there has been a retreat from the halo concept among observers, and Baldwin himself (1963) has recanted and attributed the radio "halo" of our Galaxy to sidelobe errors. Nevertheless even the skeptical paper of Kraus (1964) on Andromeda gives substantial evidence of an emitting region much larger than his resolution, and in any case there are theoretical arguments (Parker 1965) for postulating a halo around our Galaxy, whether or not it is easily detectable. For a recent discussion of the observational data see Mills (1964).

In this situation an elaborate model of the halo would clearly be presumptuous. We take Baldwin's simplest homogeneous spherical model, having $R_h \approx 16$ kpc $\approx 5 \times 10^4$ lt-yr $\approx 5 \times 10^{22}$ cm.

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A relativistic electron gyrating in a magnetic field (Schwinger 1949; Oort and Walraven 1956) generates synchrotron radiation at a rate $\approx 9.9 \times 10^{-16}\ \gamma^2 B_\perp^2$ eV/sec, where $B_\perp$ (in microgauss) is the perpendicular component and $\gamma \equiv E/m_0c^2$ is the Lorentz factor. The spectral distribution has characteristic frequency

$$\nu_s\ (\text{Mc}) \approx 4.2 \times 10^{-6}\ \gamma^2\ B_\perp\ , \qquad (1)$$

with $B_\perp$ again in $\mu$G. If the energy spectrum of electrons in a region of cosmic space is of the power-law form

$$n(\gamma)d\gamma \approx n_0\gamma^{-m}d\gamma\ \text{cm}^{-3}\ , \qquad (2)$$

and the region also contains a chaotic $B$-field, then the expected synchrotron brightness temperature of this region on the celestial sphere is

$$T_b(\nu) \approx 1.6 \times 10^8\ (4.9 \times 10^2)^{3-m}\ n_0[R(\text{lt-yr})][B(\mu\text{G})]^{(1+m)/2}[\nu(\text{Mc})]^{-(m+3)/2}\ , \qquad (3)$$

where $R$ is the dimension of the radiating region along the line of sight. We will discuss elsewhere (Felten and Morrison 1966) the derivation and limitations of this formula; the approximations involved, mainly assumptions of isotropy for the particle velocity and $B$-field distributions and a delta-function treatment of the single-particle emission spectrum, are familiar (Hoyle 1960; Ginzburg and Syrovatskii 1965).

We may derive $m$ for the halo electrons from observations of the temperature spectral index, $-(m+3)/2$. Even for the best observed frequency range, 10–400 Mc, however, there is disagreement whether the non-thermal spectrum of the Galaxy is adequately represented by a power law with constant $m$. Near the galactic plane Komesaroff (1961) found $m$ constant and $\approx 2.2$. In later studies Turtle, Pugh, Kenderdine, and Pauliny-Toth (1962) claimed that $m$ increases from lower to higher frequencies, both near the plane and in the direction of the north galactic pole. This result has not been confirmed in the most recent survey by the Sydney group (Wielebinski and Yates 1965), who again find the data consistent with a constant $m \approx 2.3$. Evidently there is still some latitude here for theoretical models; for purposes of calculation we assume provisionally a constant $m \approx 2.4$, roughly the same as the spectrum of primary cosmic rays above 2–3 GeV (Singer 1958, pp. 269 ff.; Morrison 1961, pp. 6 ff.).

For the halo, $R$ in equation (3) is the distance from Earth to the halo "boundary"; in the polar directions we have $R^2 \approx R_h^2 - R_e^2$, where $R_e \approx 10$ kpc is the Earth's distance from the galactic center (Fernie 1962); this gives $R \approx 12$ kpc $\approx 4 \times 10^4$ lt-yr. At $\nu = 178$ Mc we find (Turtle and Baldwin 1962) that the total brightness temperature near the north galactic pole is $\approx 140°$ K, of which $\approx 30°$ and possibly more appears to be extragalactic in origin (Turtle *et al.* 1962). These results are consistent with earlier surveys at other frequencies (Shklovsky 1960, pp. 47 ff.). Setting the halo contribution $\approx 110°$ K at 178 Mc and making these substitutions in equation (3), we find that

$$n_0[B(\mu\text{G})]^{1.7} \approx 4.9 \times 10^{-7}\ . \qquad (4)$$

An assumed value for $B$ in the halo will now determine the halo electron spectrum; therefore we may obtain some information about $B$ by comparing the resulting spectrum with observations of primary cosmic-ray electrons. In Figure 1 we summarize recent data on the differential energy spectrum of electrons in the range 100 MeV–100 GeV important for radio astronomy. For some of the experiments the representation on such a graph is strongly dependent on the assumed form of the electron spectrum; in each such case we have normalized provisionally by assuming $m \approx 2.4$. These are all balloon observations, and corrections for secondaries become troublesome for points below a few hundred MeV, so that these points should be regarded as upper limits. There is clear evidence for a flattening of the spectrum in this region.

The four lines in the figure are halo electron spectra derived from equations (2) and

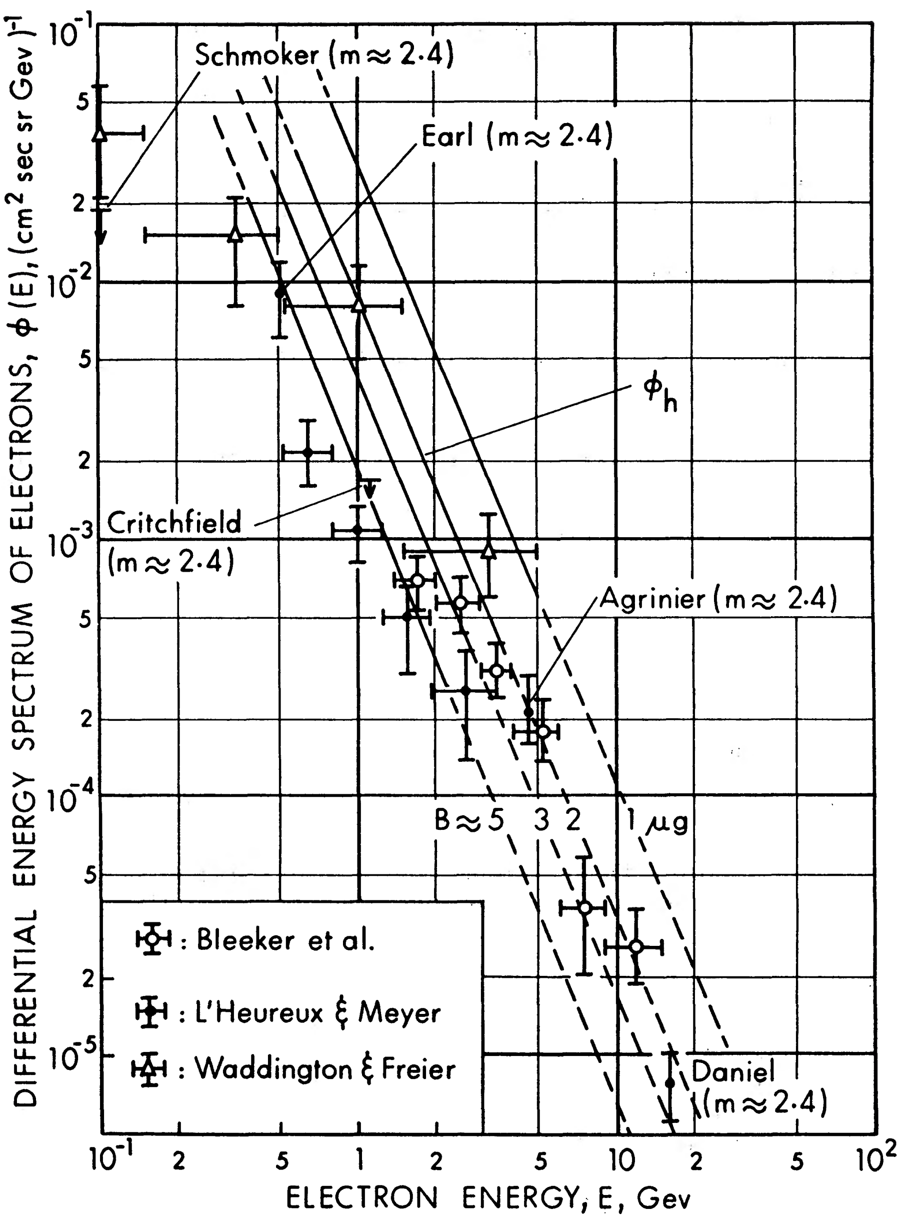


FIG. 1.—Observations of primary cosmic-ray electrons (Critchfield, Ney, and Oleksa 1952; Earl 1961; Agrinier *et al.* 1964; Schmoker and Earl 1965; L'Heureux and Meyer 1965; Daniel and Stephens 1965; Bleeker, Burger, Scheepmaker, Swanenburg, and Tanaka 1965; Waddington and Freier 1965). Where an assumption regarding spectral shape is necessary to plot the data differentially, we have normalized provisionally by assuming a power-law spectrum with $m \approx 2.4$. Also shown are differential spectra (*solid lines*) derived from the polar radio brightness of the halo, taken as a homogeneous sphere of radius 16 kpc. The four lines correspond to four assumed values (shown) for the mean magnetic field in the halo.

(4), for $m \approx 2.4$ and four assumed values of $B$ (1, 2, 3, and 5 $\mu$G). They are shown as *solid* lines in the energy ranges which correspond in equation (1) to characteristic frequencies between 10 and 400 Mc; it is in these ranges that comparisons between the radio and cosmic-ray data are most cogent. Clearly the curve for $B \approx 2$ $\mu$G gives the best fit to the most recent data of Waddington and Freier (1965), and also to the five higher-energy points; even a smaller $B$ is not excluded, especially when we consider that the spectrum may well steepen above 5 GeV (Gould and Burbidge 1966). The results of Earl (1961) and of L'Heureux and Meyer (1965), on the other hand, lie close to the line $B \approx 5$ $\mu$G. Meyer (1965), in making a comparison analogous to our Figure 1, was impressed by this, and concluded that large values of $B$ and/or $R$ are required to make the cosmic-ray and radio-brightness results compatible.[1] We wish to emphasize that the Waddington-Freier and L'Heureux-Meyer spectra, covering the same energy range but obtained on different dates, are only marginally compatible, and that in such cases it is reasonable to regard the discrepancies as manifestations of solar modulation, and to take an upper envelope of all the data as most truly representative of the *galactic* electron spectrum in this range. The lower points, and perhaps also the flatter spectrum obtained by L'Heureux and Meyer, are then to be interpreted as heliocentric effects.[2] In the case of Earl's point it is a known fact that the proton flux during the flight was also abnormally low. We suggest therefore that the curve $B \approx 2$ $\mu$G gives adequate agreement with the cosmic-ray observations, and, adopting

$$B_{\text{halo}} \approx 2\ \mu\text{G}\,, \tag{5}$$

we label this curve as $\phi_h$, the halo electron flux:

$$\phi_h(E) \approx 0.8 \times 10^{-2} E^{-2.4}\ (\text{cm}^2\ \text{sec ster GeV})^{-1}\ (0.6 \lesssim E \lesssim 3.5)\,. \tag{6}$$

Of course the flux outside 0.6–3.5 GeV is not determined by these arguments.

In 2–10 GeV Singer (1958) estimates the average "quiescent" primary proton flux as $\Phi(E) \approx 0.4\ E^{-2.15}$ (cm$^2$ sec ster GeV)$^{-1}$. Our $\phi_h$ from equation (6) is $\approx$1–2 per cent of $\Phi$; the observed electron/proton ratio at 4.5 GeV is (1.5 $\pm$ 0.4) per cent (Agrinier, Koechlin, Parlier, Boella, Degli Antoni, Dilworth, Scarsi, and Sironi 1964). In the strongly modulated range $\approx$1 GeV (Earl 1961) the observed ratio is (3 $\pm$ 1) per cent, suggesting that solar modulation does not affect the ratio drastically. Our equation (6) seems to be in tolerable agreement with all relevant observations.

Why is our field estimate, $B \approx 2$ $\mu$G, smaller than those of previous authors? There are two reasons: (1) We have adopted a larger electron flux, reflecting more recent data; (2) We have adopted a halo model with a smaller radio emissivity. Our equation (4) corresponds to a uniform emissivity $dP/(d\tau d\nu) \approx 6 \times 10^{-40}$ erg (cm$^3$ sec [c/s])$^{-1}$ $\approx 1.4 \times 10^8$ W(pc$^3$ ster [c/s])$^{-1}$ at 81 Mc, close to the value derived by Baldwin (1955). Mills (1958), in a more elaborate analysis involving an inhomogeneous spheroidal model with central concentration, derived a central emissivity which (after correction for a revision in the galactic distance scale) is about 2.5 times ours. (To obtain the same result in a

[1] Meyer's argument is somewhat overstated because he used for the radio brightness a hemisphere average, with no subtraction for the disk component or for extragalactic radiation; but this is a minor point.

[2] *Note added in proof.*—Balloon results from 1965 (graciously made available prior to publication by J. L'Heureux and by W. R. Webber and C. Chotkowski) have determined more precisely the electron spectrum from 20 MeV to 5 GeV at solar minimum. This spectrum falls below the points of Waddington and Freier on Fig. 1 (which were troubled by poor statistics and secondary contamination), and at energies below a few GeV it confirms the flatter slope indicated earlier by the results of L'Heureux and Meyer. Since this flattening at low energies is not reflected in the galactic radio data, it is best understood as a local effect of solar modulation. R. Ramaty (private communication) finds that with reasonable parameters the solar wind can produce substantial modulation even at solar minimum. At higher energies ($E \gtrsim 3$ GeV) the modulation is presumably small, and we see a better sample of the galactic electron spectrum.

homogeneous model we would have to take the characteristic path length in the polar directions as $\approx 5$ kpc rather than 12.) In view of the large amount of radio fine structure now known to exist at high latitudes, we suspect that Mills's emissivity for the halo is too high, and that at least part of the emission is assignable to the disk; the lower value may be more nearly correct. Suppose, however, that we use the higher value; this corresponds to multiplying the right side of equation (4) by 2.5. The characteristic $B$-fields for the lines in Figure 1 must then be increased by a factor $(2.5)^{1/1\ 7} \approx 1.7$. With the low electron flux indicated by the early observations of Critchfield, Ney, and Oleksa (1952), a high $B$ is then implied; even multiplying that flux by a factor $\approx 3$ to account for possible solar modulations, we would still find $B \gtrsim 5\ \mu$G. This conclusion was correctly reached by Biermann and Davis (1960) and by Woltjer (1961).[3] But at present it should be emphasized that if the halo contains an electron flux like $\phi_h$, as large as or larger than that measured by Waddington and Freier in their 1964 flights, then $B$ for the halo cannot be taken $>3$–$4\ \mu$G even for generous estimates of the radio emissivity.

Sironi (1965), in a recent paper similar in spirit to the present work and using some of the post-1960 electron data, still obtains the figure $B \approx 5\ \mu$G; thus his result contradicts that offered here. Part of the discrepancy results from the fact that Sironi aimed for an upper limit on $B$ by eschewing any correction for an extragalactic component of $T_b$. But a larger factor appears to stem from his unspecified renormalization of all the radio data, a renormalization assertedly based on a single absolute measurement at 404 Mc (Pauliny-Toth and Shakeshaft 1962). Absolute measurements at such high frequencies are complicated by large corrections, and different surveys fail to agree in cold regions of the sky (at 400 Mc, cf. Seeger, Stumpers, and van Hurck 1960). Our normalization at 178 Mc is therefore likely to be more reliable. Sironi has also lumped polar brightness measurements together with others made near the plane, and with hemisphere averages; his assumed effective path length $R \approx 10$ kpc is too short for use with such data.

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[3] It should be noted that Ginzburg and Syrovatskii (e.g , 1964) have repeatedly considered smaller fields, $\approx 3\ \mu$G, though they seem to have equivocated somewhat regarding the resultant discrepancy between radio and cosmic-ray data.

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