ON THE EXISTENCE OF AN IONIZED LAYER ABOUT THE GALACTIC PLANE

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Summary

The radio frequency spectrum observed in directions towards the galactic pole shows a maximum near 5 Mc/s. It seems unlikely that the synchrotron process responsible for the emission can give such a maximum and it is suggested that the observed fall in the flux density at lower frequencies is caused by absorption in an ionized layer parallel to the galactic plane.

To avoid an excessive value of the calculated electron density the kinetic temperature is taken as low as is consistent with the maintenance of ionization, about 10^4 °K. At this temperature the gas cannot fill the galactic halo but must form a layer along the galactic plane, the layer having a half-width of the order of 10^{21} cm.

The electron density is found to be about $0 \cdot 1$ cm^{-3} so that along a line of sight to the galactic pole there are of the order of 10^{20} electrons. The mass of the layer is $\sim 5 \times 10^8 M_{\odot}$ and its rate of radiation in the Balmer continuum is $10^7 L_{\odot}$. The radiation rate per unit volume is $\sim 10^{-26}$ erg cm^{-3} s^{-1} in the Balmer continuum and the total radiation rate is $\sim 5 \times 10^{-26}$ erg cm^{-3} s^{-1}, a value close to the average emission of ionizing radiation by O and B stars.

I. DATA

Figure 1 shows recently published spectra of the galactic radiation (Ellis, Waterworth, and Bessell 1962). The lower spectrum is typical of directions towards the galactic pole and has a maximum near 5 Mc/s. On the low frequency side of the maximum the curve steepens rapidly to a slope of $+2$ for frequencies in the range $1 \cdot 5$–2 Mc/s, implying that at these frequencies the flux density S is proportional to $\sim f^2$. The curve falls more slowly in the high frequency side of the maximum, eventually reaching a slope of about —$0 \cdot 75$, i.e. $S \sim f^{-0 \cdot 75}$.

The upper of the two spectra of Figure 1 is typical of those found in directions towards the galactic centre at latitudes near 20°. An important difference between these two spectra is the shift in the spectral maximum to higher frequencies. For galactic latitude $b = 20°$ the maximum of S occurs at $f \sim 7$ Mc/s.

II. THE ELECTRON-SECONDARY SPECTRUM AND THE SYNCHROTRON FREQUENCY SPECTRUM

For protons not too near the base of the cosmic ray spectrum, the differential energy spectrum is $\mathrm{d}E/E^{5/2}$. Electron secondaries produced in nuclear collisions have closely the same spectrum, $\mathrm{d}\gamma/\gamma^{5/2}$, where electron energies are written as $\gamma\, mc^2$.

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This is because the multiplicity in the production of mesons is approximately independent of E up to the highest energies of interest. Hence, if the electron energies are not appreciably degraded, the energy spectrum is $\mathrm{d}\gamma/\gamma^{5/2}$ and the resulting synchrotron spectrum is $\mathrm{d}f/f^{3/4}$, in agreement with the curve of Figure 1 at higher values of f.

However, energy losses become important at low values of γ because of ionization and collision effects. Such effects are important for $\gamma < \sim 10^3$. For a magnetic intensity $\sim 2\times 10^{-6}$ gauss this causes a modification of the frequency spectrum for $f < \sim 10$ Mc/s, which is just the region in which the curve of Figure 1 changes its behaviour. But it does not seem as if a maximum can be produced by this effect. Thus the electron energy spectrum is modified to $\mathrm{d}\gamma/\gamma^{3/2}$ and the resulting frequency spectrum is $\mathrm{d}f/f^{1/4}$ (Hoyle 1960), so that $S \propto f^{-1/4}$, which continues to increase as f decreases.

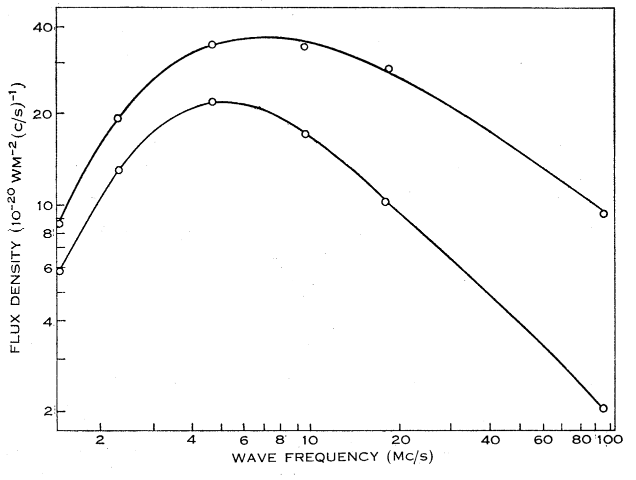

Fig. 1.—Spectra of the galactic radiation. The upper curve is typical of galactic latitudes near 20° in the direction of the centre. The lower curve is typical of high galactic latitudes.

To obtain a maximum it seems necessary for absorption to occur in the interstellar gas. The attenuation effect of an ionized gas of electron density N_e and kinetic temperature T_e is determined by the factor $\exp -\int \mathrm{d}\tau$, where the integral is taken between the point of origin of the radiation and the point of reception according to Fermat's principle, with

$$\mathrm{d}\tau/\mathrm{d}s = 2\zeta N_e^2/T_e^{3/2}f^2, \tag{1}$$

where s is distance measured along the track of the radiation, and ζ is a logarithmic factor (Pawsey and Bracewell 1955) that is close to $0\cdot 2$ for the values of T_e, N_e of interest in the present problem, so that

$$\mathrm{d}\tau/\mathrm{d}s \simeq 0\cdot 4N_e^2/T_e^{3/2}f^2. \tag{2}$$

It will turn out that the necessary electron densities are surprisingly high, and for this reason the available parameters will be chosen to lead to the smallest result for N_e. In particular, we note that the attenuation increases with decreasing T_e, and hence we choose the least value of T_e consistent with the hydrogen of the interstellar medium being appreciably ionized, namely, $T_e \simeq 10^4$ °K. Gas at this temperature will certainly not fill the halo of the Galaxy, but will be confined to a layer a few hundreds of parsecs thick. This leads immediately to the following model.

III. The Model

We take the observer at the centre of a sphere of radius R, and we take the observer to lie on the central plane of a layer of width 2L, as shown in Figure 2.

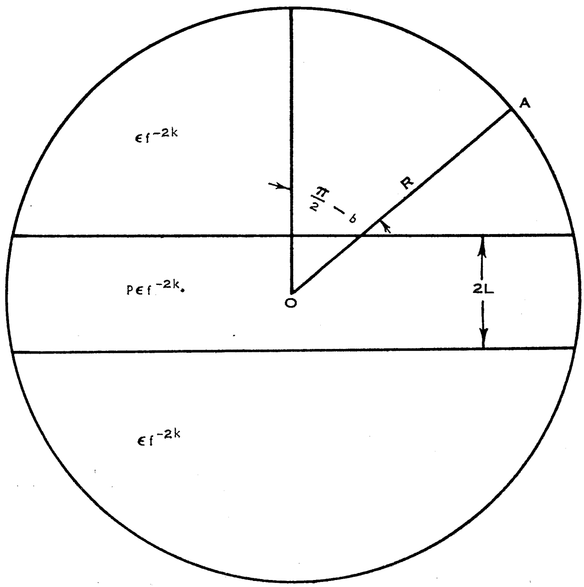

Fig. 2.—Model of galactic halo and ionized layer in the plane of the Galaxy.

The electron density and kinetic temperature in the layer are N_e, T_e. Absorption outside the layer is neglected. Emission of radio waves by the synchrotron process is taken to follow the spectrum $\mathrm{d}f/f^{2k}$ both inside and outside the layer. For $f < \sim 10$ Mc/s, we expect k to be about $\frac{1}{8}$, in accordance with the above remarks concerning ionization losses. For the region outside the layer, but inside the sphere, we take the emissivity per unit volume $(\mathrm{c/s})^{-1}$ to be $4\pi\epsilon f^{-2k}$, while in the layer we take $4\pi p\epsilon f^{-2k}$, p and ϵ being constants and the emission being assumed isotropic.

It is not hard to see that the flux S per steradian $(\mathrm{c/s})^{-1}$ for an aerial pointing in the direction OA is given by

$$S = \frac{\epsilon}{f^{2k}}\left[p\int_0^{L\operatorname{cosec} b} \mathrm{e}^{-\tau(x)}\mathrm{d}x + (R - L\operatorname{cosec} b)\mathrm{e}^{-\tau(L\operatorname{cosec} b)}\right], \tag{3}$$

where

$$\tau(x) = 2\zeta N_e^2/T_e^{3/2}f^2.\, x \simeq 0\cdot 4N_e^2/T_e^{3/2}f^2.\, x. \tag{4}$$

Defining

$$y = 2\zeta N_{\mathrm{e}}^2/T_{\mathrm{e}}^{3/2}f^2.\ L\operatorname{cosec} b = \tau(L\operatorname{cosec} b), \tag{5}$$

and carrying out the simple integration in (3), we obtain

$$S = \frac{\epsilon}{f^{2k}}\left[\frac{pL\operatorname{cosec} b}{y}(1-\mathrm{e}^{-y})+(R-L\operatorname{cosec} b)\mathrm{e}^{-y}\right]. \tag{6}$$

The first term in the brackets gives the contribution of the disk, the second gives that of the spherical halo.

In the following we are only concerned with the frequency dependence of (6), and this is contained in the variation of y with f. To study this dependence it is convenient to write (6) as a product of a non–frequency-dependent factor with a frequency-dependent factor, that is,

$$S = \left[\epsilon(R-L\operatorname{cosec} b)\left(\frac{T_{\mathrm{e}}^{3/2}}{2\zeta N_{\mathrm{e}}^2 L\operatorname{cosec} b}\right)^k\right][qy^{k-1}(1-\mathrm{e}^{-y})+y^k\mathrm{e}^{-y}], \tag{7}$$

where

$$q = pL\operatorname{cosec} b/(R-L\operatorname{cosec} b). \tag{8}$$

Evidently we have simply to consider

$$qy^{k-1}(1-\mathrm{e}^{-y})+y^k\mathrm{e}^{-y}. \tag{9}$$

The relative importance of the disk and the halo is contained in the factor q. Although in our model q is independent of galactic longitude, differences with respect to galactic longitude could readily be allowed for through variations of q. It would similarly be possible to allow for a non-isotropic halo through variations of q. Indeed, if we can show that the frequency spectrum (9) is insensitive to q, our model can be considered to cover much more complicated situations in which the halo emissivity varies both with galactic latitude and longitude. This will now be shown to be the case.

In Figure 3 we give separate plots for the functions $y^{k-1}(1-\mathrm{e}^{-y})$, $y^k\mathrm{e}^{-y}$, taking $k = \frac{1}{8}$. The ordinate scale is adjusted to give $0\cdot5000$ at the maximum in both cases. The abscissa scale $-\frac{1}{2}\log y+0\cdot2$ is a frequency scale, since $-\log y = 2\log f+\text{constant}$. The normalization of this scale depends of course on N_{e}, T_{e}, and this will be considered at a later stage. The maximum for the disk contribution occurs at $y = 0\cdot262$, that for the halo contribution at $y = k = 0\cdot125$.

The two curves of Figure 3 are of nearly the same shape, both giving a satisfactory correspondence with the observed curve of Figure 1. That for the halo gives slightly better agreement, particularly in the steepness of the fall at low frequencies. In fact, it is easy to show that the logarithmic slope of $y^k\mathrm{e}^{-y}$ plotted against $-\frac{1}{2}\log y$ becomes $+2$ at $y = k+1$, which exceeds the value $y = k$ by $(k+1)/k$. Since $y \propto f^{-2}$, it follows that the slope becomes $+2$ at a frequency less than that at maximum $(y = k)$ by $\sqrt{\{k/(k+1)\}}$. For $k = \frac{1}{8}$ this factor equals $\frac{1}{3}$, in good agreement with the observed situation.

Although the relative importance of the disk and the halo cannot be decided from a consideration of the galactic frequency spectrum alone, a comparison with the spectra of extragalactic sources should allow such a decision to be made. For sources with spectra intrinsically the same as that of the Galaxy the flux maximum will be at the same frequency as that of galactic radiation (from the same latitude) if the galactic radiation is derived mainly from the halo, but there will be a difference if the galactic radiation is derived mainly from the disk. The sense of the difference in the latter case is that the frequency at maximum will be higher for the source than for the Galaxy, the difference being determined by the square root of the values of y at which $y^{k-1}(1-e^{-y})$ and $y^k e^{-y}$ take their maximum values. For $k = \frac{1}{8}$ the difference is given by the factor $(0\cdot262/0\cdot125)^{1/2} = 1\cdot45$. For directions towards the galactic pole the frequency at maximum is about 5 Mc/s for galactic radiation. Hence for sources in high galactic latitudes the frequency at maximum should also be near

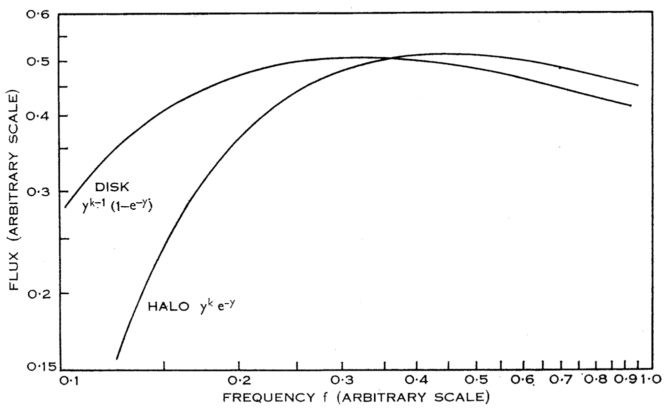

Fig. 3.—Logarithmic plots of the functions $y^{k-1}(1-e^{-y})$ and $y^k e^{-y}$ with $k = \frac{1}{8}$.

5 Mc/s if the galactic radiation is derived mainly from the halo, but should be near 7 Mc/s if the galactic radiation is derived mainly from the disk. While it is perhaps premature to base a decision on two examples, the indication from the sources in Fornax ($b = 56°$) and in Centaurus ($b = 20°$), is that no such displacement to higher frequency occurs for Fornax, and that the displacement for Centaurus (Fig. 4) (Ellis 1962) simply corresponds to that expected from the low latitude value. The implication therefore is that the main source of the galactic radiation lies in the halo. Since this case leads to the smaller value of N_e, and since the appropriate curve of Figure 3 is also in better agreement with observation, we shall now suppose that the contribution of the disk can be neglected.

IV. The Electron Density

The electron density is easily obtained from (5), using the observed frequency of the maximum in directions towards the galactic poles $f \simeq 5$ Mc/s. Thus, putting $y = k = 0\cdot125$ for the value of y at the maximum, putting $f = 5\times10^6$ c/s, cosec $b = 1$, $\zeta \simeq 0\cdot2$, we obtain $N_e = 2\cdot8\times10^6 L^{-1/2} T_e^{3/4}$. Taking $T_e = 10^4$ °K as a minimum value for ionized hydrogen, a half-width $L = 300$ parsec for the layer is a reasonable estimate. The resulting density is close to 10^{-1} cm^{-3}, a surprisingly high value. The mass of ionized hydrogen is also surprisingly high if the layer is taken to cover the whole of the galactic plane. The area of the face of the Galaxy is about 3×10^{45} cm^2, the mass per unit area is $2\times10^{20}m_{\mathrm{H}}$ g cm^{-2}, where m_{H} is the mass of the hydrogen atom in grams, and the total mass is therefore $\sim6\times10^{65}m_{\mathrm{H}}\simeq10^{42}$ g $\simeq5\times10^{8}M_{\odot}$.

The radiation in the Balmer continuum is about 10^{-26} erg cm^{-3} s^{-1}, giving a total emission from the whole layer of $\sim5\times10^{40}$ erg s$^{-1}\simeq10^{7}L_{\odot}$. The emission in the Lyman continuum is about five times larger than this.

Since the energy content of the gas, including ionization energy, is about $1\cdot5$ eV cm^{-3} the time required for radiative cooling is only of order 10^{14} s. Either the internal energy must be maintained from an external source or the gas will cool very rapidly. The average rate of production of ionizing radiation by O and B stars has been estimated as 10^{-25} erg cm^{-3} s^{-1}, a value very close to our radiation rate.

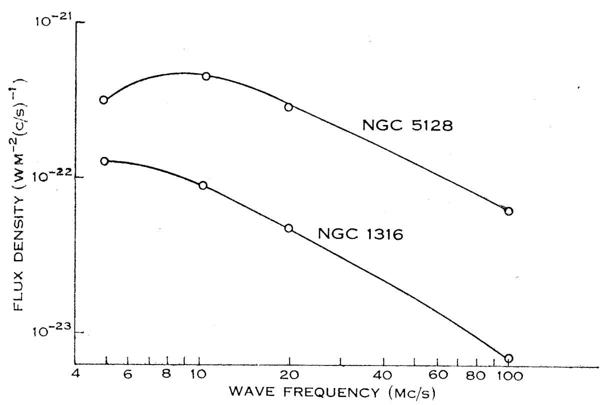

Fig. 4.—Spectra of the external galaxies NGC 5128 and NGC 1316 derived from the results of Ellis (1962).

V. The Faraday Rotation Effect

If the magnetic field maintains an approximately constant direction in the neighbourhood of the observer there will be a Faraday rotation for any polarized source of radiation. For a source external to the layer the path length is L cosec b, remembering that the Sun lies quite close to the galactic plane, and the total number of electrons along the line of sight is $N_{\mathrm{e}}L$ cosec b. The Faraday rotation is determined by the product of this quantity with the line of sight component H_{ls} of the field, i.e. by $N_{\mathrm{e}}L\ H_{\mathrm{ls}}$ cosec b. In accordance with the low values of the magnetic intensity suggested by recent work on star formation (Fowler and Hoyle 1962, for example), we take $H_{\mathrm{ls}}\simeq10^{-6}$ gauss. With $N_{\mathrm{e}}=0\cdot1$ cm^{-3}, $N_{\mathrm{e}}LH_{\mathrm{ls}}$ cosec $b=10^{14}$ cosec b. In a recent report Cooper and Price (1962) give $N_{\mathrm{e}}LH_{\mathrm{ls}}$ cosec $b\simeq2\cdot5\times10^{14}$ for the source NGC 5128 at $b=20°$. The agreement between our estimate and the requirement of Cooper and Price would appear to provide strong support for the ideas of the present paper, and for a local explanation of the observed Faraday effect.

VI. The Dependence on Galactic Latitude and Longitude

Finally we consider the frequency spectrum for different values of b. Since the flux maximum always occurs at $y = k$ we see that the frequency at maximum varies with b according to $\text{cosec}^{1/2}\, b$. With the maximum at 5 Mc/s for $b = 90°$ we see that the frequency at maximum shifts to $\simeq 8 \cdot 5$ Mc/s for $b \simeq 20°$. This is in general agreement with observation. Although more extensive observations are most desirable on this point it is to be noted that an exact dependence on $\text{cosec}^{1/2}\, b$ is not to be expected for small values of b, since the value of k is not likely to be maintained for $f > \sim 10$ Mc/s. At the higher frequencies the relevant electron energies become so high ($\gamma \sim 10^3$) that ionization losses are of much less importance. Thus as the frequency increases above about 10 Mc/s we expect the "effective" value of k to change gradually from about $\frac{1}{8}$ to about $\frac{3}{8}$. This change should prevent the frequency at the flux maximum from increasing much above 10 Mc/s, even though $b \to 0$.

Some information on the general extent of the ionized layer considered here is provided by observations in different longitudes. Shain (1954) in an analysis of a similar model has shown that the ratio of the flux densities S_1, S_2 at two frequencies is given by

$$\ln(S_1/S_2)\ \text{cosec}\ b.$$

Using results at $18 \cdot 3$ and 100 Mc/s he found that this relationship is obtained for longitudes near 320°, i.e. towards the galactic centre, but that near longitudes 200° the value of $\ln(S_1/S_2)$ is almost constant for all latitudes. More recent observations below 10 Mc/s (Ellis, personal communication) have shown similarly that the spectrum is independent of latitude in these latter directions and that it is typically represented by the lower curve in Figure 1. These results may be explained if the density in the disk falls rapidly with radius from the galactic centre at distances greater than that of the Sun but is almost constant at lesser distances. More detailed observations are expected to throw light on the density distribution.

VII. References

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