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RADIO FREQUENCY NOISE EMISSION FROM ORBITING PROTONS

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ABSTRACT

The accepted explanation for low radio frequency noise of galactic origin lies in the synchrotron radiation emitted by cosmic ray protons. The detailed calculations of this effect seem to require a higher galactic magnetic field than is inferred to be present from observations of Zeeman splitting of the 21 cm hydrogen line. Moreover, the explanation of the frequency dependence of the noise below 10 mc seems to require unrealistic conditions to exist in the galactic corona. This paper investigates the possibility of explaining the observed galactic noise as radiation arising from protons in orbit around charged intergalactic dust particles. The result indicates the effect is two to six orders of magnitude too weak to explain the observed noise intensity.

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INTRODUCTION

The low radio frequency noise from a few megacycles to a few hundred megacycles discovered by Jansky (ref. 1) in the 1930's were early recognized to be of galactic origin. Before precise measurements of the frequency spectrum had been made, Reber (ref. 2) proposed that the noise was caused by the thermal free-free radiation of the ionized hydrogen gas in interstellar space. Then, beginning in the 1950's as more precise measurements of the spectral intensity of the noise became available, Kiepenheuer (ref. 3), and later Ginsburg and Shklovsky in the Soviet Union proposed that the noise was generated from the synchrotron radiation produced when charged particles travelling at relativistic velocities spiral around lines of magnetic field. If these charged particles--cosmic rays--have a number distribution which varies with their energy as $E^{-\beta}$ then the synchrotron radiation should have a frequency spectrum which varies as $\omega^{-1/2(\beta-1)}$. From the experimentally determined cosmic ray proton energy distribution of $E^{-5/2}$, the synchrotron radiation should have a power spectrum varying as $\omega^{-3/4}$. This frequency dependence is in general agreement with the radio noise measurements above 10 mc. Below 10 mc it is in considerable disagreement and Hoyle and Ellis (ref 4) have attempted to explain the discrepancy by invoking the low frequency attenuation of radio waves due to the ionized interstellar medium. However, such an explanation seems to require an excessively high hydrogen concentration $(10^{-1}/cm^3)$ in the galactic corona.

Perhaps the most serious shortcoming of the synchrotron radiation explanation of galactic noise is the rather high value of galactic magnetic field required to give the observed noise intensity. Woltjer (ref. 5) finds a general field of 3×10^{-5} gauss is necessary in order to fit the radio data. On the other hand, measurements of the Zeemann effect on the 21 cm hydrogen line by Davies (ref. 6) imply that the actual galactic field is 5 to 7×10^{-6} gauss. Since the intensity of the synchrotron noise radiation is proportional to $H^{1/2(\beta + 1)}$, this value of field would reduce the amount of synchrotron radiation almost two orders of magnitude below the observed noise value.

Thus, at this point, there seem to be two difficulties in accepting synchrotron radiation as the source of low frequency galactic noise. One is the disagreement between the expected and observed noise spectrum below 10 mc and the other is the requirement for what seem to be excessively high galactic magnetic fields. It is, therefore, desirable to investigate other mechanisms for the production of galactic noise. One such mechanism investigated here is the bremsstrahlung radiation from protons which are in capture orbits around a charged interstellar dust particle. Although more careful calculations of the effect could be done, the rather crude estimates made here would seem to rule out this mechanism as giving rise to the intensity of the galactic noise which is actually observed.

THE NATURE OF THE GALACTIC NOISE

The dominant component of radio noise below 1 kmc or so is non-thermal in origin in that its spectral brightness variation is not independent of frequency. Figure 1 shows a rough plot of the experimental observations (ref. 7). From 18 to 400 mc, the observations indicate a brightness spectral index of $\alpha = 0.65 \pm 0.15$ where the brightness varies as $\omega^{-\alpha}$. Around 7 mc, there is a brightness peak and for low frequencies the brightness appears to vary as ω^2. This non-thermal radiation comes both from strongly emitting regions in the galactic disc and more weakly from the galactic corona.

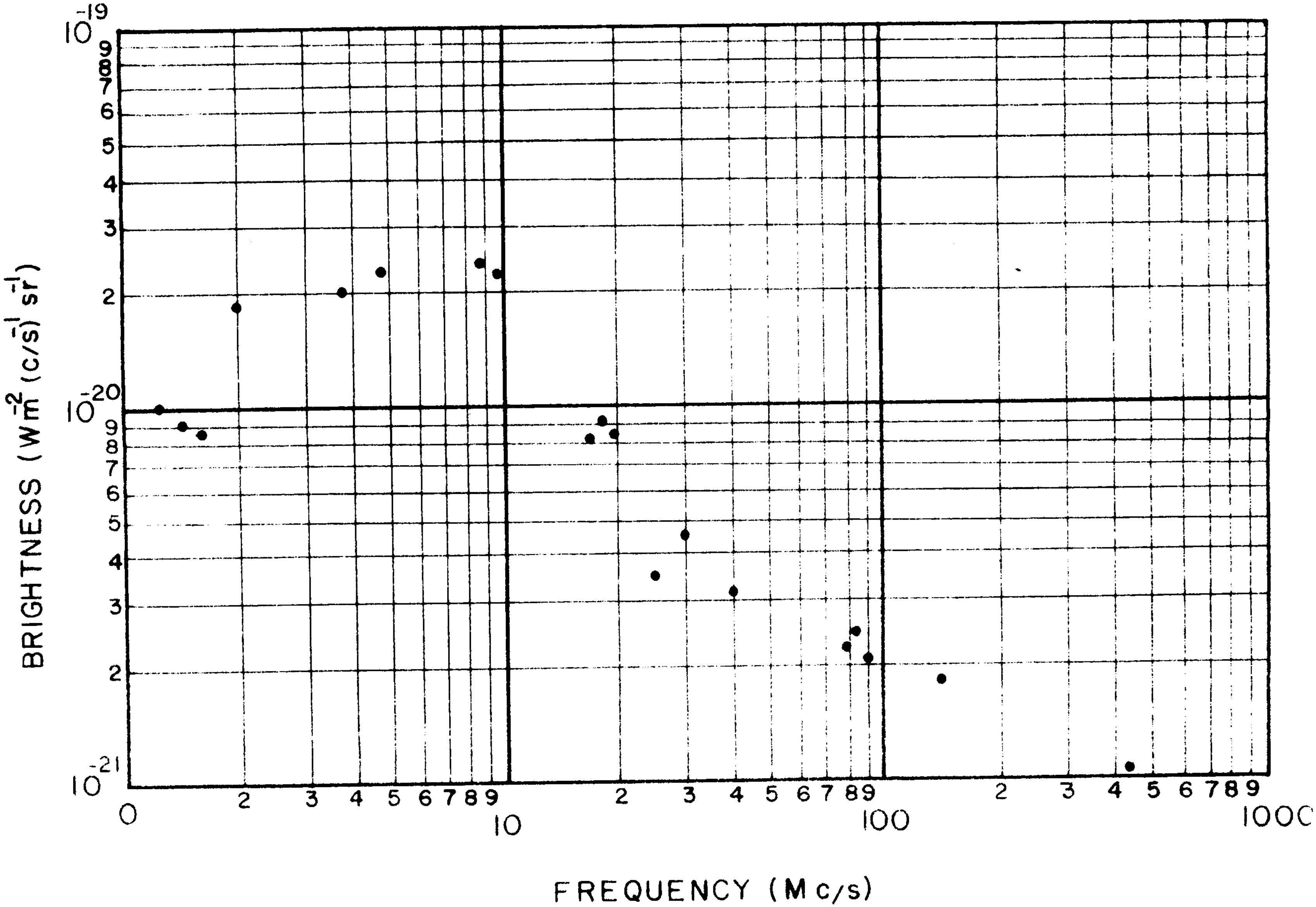

Figure 1 Spectral Variation of Radiofrequency Galactic Noise

In addition to the non-thermal radiation, there is a thermal component from the galactic disc due to ionized hydrogen (ref. 8). This emission clearly reveals the spiral arms of our galaxy.

SOME CHARACTERISTICS OF THE GALAXY

Our galactic disc is some 25 kpc (1 kpc = 3.09×10^{19} m) in diameter and 4 kpc in thickness. It is surrounded by a galactic corona of perhaps 300 kpc in radius. The interstellar medium in the galactic disc is primarily hydrogen. The majority of the hydrogen is neutral (H_I regions) but near stars and within the spiral arms, the hydrogen is ionized (H_{II} regions). Table 1 gives the estimated mass of hydrogen in the galactic disc (ref. 9).

TABLE 1

Mass of Hydrogen in the Galactic Disc

Type	Mass in Solar Masses
H_I-neutral	1.4×10^9
H_{II}-ionized	6×10^7

These values correspond to a density of hydrogen of about 1 atom per cm^3. The temperature of the ionized hydrogen is thought to be about 10^4 °K.

In addition to hydrogen there is a variety of other atoms (neutral and ionized) present with a density considerably less, perhaps 10^{-3} per cm^3. The net positive charge is of course balanced by the presence of electrons, also assumed to be at a temperature of 10^4 °K.

Interspersed with these constituents of the interstellar medium are small dust particles. From optical absorption data, the density of the dust is of the order of 10^{-25} gm/cm^3. The dust grains are of small radius ($\sim 10^{-5}$ cm) and a calculated number distribution (ref. 10) shows

$$N(a) = N(o)\ e^{-0.69(a/a_o)^{2.6}} \tag{1}$$

where N(a) is the number of dust grains with radius near a, and a_o = 2.5×10^{-5} cm. This distribution varies slowly until a approaches a_o and then declines rapidly for larger radii. The composition of the dust particles is not well known but is presumably a variety of the heavier elements. If one assumes that all the dust particles are sphere of radius 10^{-5} cm having a density equivalent to that of Fe (7.8 gm/cm^3), then the number density of dust particles is 2×10^{-11} cm^{-3}.

Spitzer (ref. 11) has made calculations of the charge which these dust grains would accumulate. He considers the effects of cosmic rays, photoionization, and the capture of electrons and protons. He finds these latter two effects the most important and because of greater velocity of the electrons for a given temperature, shows that the grains will acquire a net negative charge of some 150 e corresponding to a potential of -2.2 volts. This value is relatively insensitive to whether the dust grain is in an H_I or H_{II} region. The number of protons captured per second on a negatively charged dust particle is

$$p = 4\ na^2\ (\pi\ kT/3m)^{1/2}\ (1 + 3V/2V_d) \tag{2}$$

where

n = the particle density of protons

T = the temperature of the protons

m = the proton mass (gm/cm^3)

a = the dust particle radius

V = the dust particle potential in electron volts

V_d = the proton mean thermal energy in electron volts

For a dust particle of 10^{-5} cm, with a potential of -2.2 ev and a proton temperature of 10^4 °K, and density of 1/cm^3, $p \cong 10^{-3}$/sec. Thus, on the average, a proton strikes the dust particle once every 20 minutes.

Radiation of an Orbiting Proton

A negatively charged dust particle is likely to have one or more protons in Keplerian orbits around it. Each such proton will radiate electromagnetic energy and, if otherwise undisturbed, will approach closer and closer to the particle until it is finally captured. We can obtain a crude estimate of the frequency range of the radiation and the power radiated by considering a proton to be in a circular orbit a distance r away from a dust particle carrying Z electrons. Under these conditions, the frequency of the proton motion and of its radiation is

$$\omega = (Z e^2/4\pi \epsilon \, m r^3)^{1/2} \qquad (3)$$

For a dust particle having 150 charges, a proton orbiting at a distance of 18 microns will radiate at a frequency of 10 mc. The orbiting proton is equivalent to a dipole of strength er and thus radiates a power

$$P = \frac{1}{3} \frac{\omega^4 e^2 r^2}{4 \pi \epsilon c^3} \qquad (4)$$

In terms of frequency alone, the radiated power is

$$P = 1.02 \times 10^{-37} Z^{2/3} f^{8/3} \text{ watts} \qquad (5)$$

At 10 mc, with Z = 150, the power radiated is 1.4×10^{-33} watts.

The power radiated comes at the expense of the energy of the particle,

$$E = -\left(\frac{Ze^2}{8\pi\epsilon r}\right)$$

$$= -\frac{1}{2}\left(\frac{Ze^2\omega}{4\pi\epsilon}\right)^{2/3} m^{1/3} \qquad (6)$$

Noting that the rate of energy loss is slow compared to an orbit period, we have

$$\frac{d\omega}{dt} = \frac{\omega^3 e^2}{4\pi\epsilon c^3 m} \qquad (7)$$

By integrating this equation, one finds that a proton starting at an orbit of 18 microns and radiating initially at a frequency of 10 mc will slowly spiral in and be captured by the dust particle in some 10^3 years. Since the dust particle is struck by a proton and by an electron once every twenty minutes, the orbiting proton will be perturbed from its orbit by these incoming charges long before this time of "radiative capture".

Let us assume the average lifetime of each orbiting proton is τ. Then the radiated power spectrum of each proton is the product of the previous expression for the power it radiates at frequency ω and the fraction of its lifetime it spends in the vicinity of ω.

$$P_1(\omega) = P\,\frac{dt}{\tau} = P\,\frac{(dt/d\omega)\,d\omega}{\tau}$$

$$= \left(\frac{1}{3}\tau\right)\left(\frac{Ze^2}{4}\ \epsilon\right)^{2/3} m^{1/3}\left(\frac{d\omega}{\omega^{1/3}}\right) \qquad (8)$$

Total Radiation from the Galaxy

Note that the radiation spectrum of an individual proton is inversely proportional to a power of the frequency due to the much smaller fraction of time the proton spends in an orbit of frequency ω as the frequency increases.

This spectrum is sketched in Figure 2. The frequency ω_1 is the initial frequency of radiation set by the initial orbit distance of the proton. The final frequency, ω_2, is the proton orbit frequency a time τ later. In actuality there will be some probability distribution for the initial capture radius and hence the initial frequency ω_1 as well as one for the lifetime τ and hence for ω_2. A detailed study of the statistical dynamics of proton capture must be made in order to determine whether the resulting spectrum would indeed agree with the experimentally determined values shown in Figure 1. Before that labor is undertaken, however, it is well to make an order-of-magnitude calculation to discover whether this mechanism of radiation could conceivably give the values of brightness measured.

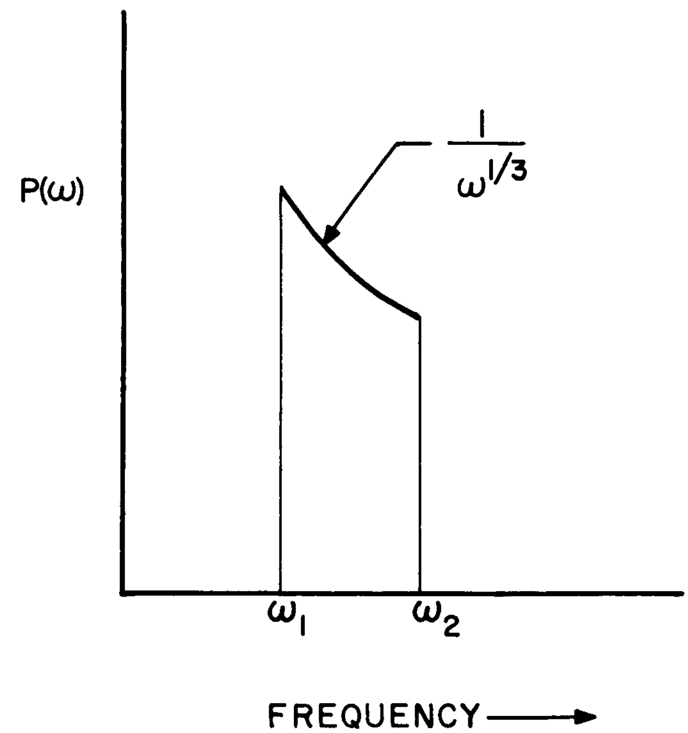

Figure 2 Spectral Distribution of Power Radiated by an Orbiting Proton

Let us make the following crude assumptions. We assume that each dust particle in a region of ionized hydrogen has n protons in orbit and we take n = 10. We assume that 10% of the hydrogen is ionized. We further assume that each orbiting proton starts at the same radius equivalent to a radiating frequency of 10 mc. and that its orbiting lifetime τ is short compared to the capture lifetime of 10^3 years. Thus, the change of frequency will be relatively small. The total power radiated per unit area per steradian will then be

$$P_T = \frac{NDn}{4\pi} P \qquad (9)$$

where N = average number density of dust particles which are surrounded by ionized hydrogen

D = distance to edge of galaxy

n = average number of protons orbiting a dust particle

P = power radiated by each proton

Taking N as 10% of the total dust particle density ($N = 10^{-6}/m^3$), $D = 5 \times 10^{20}$ m, the distance in the direction of the galactic center, and n = 10

$$P_T = \frac{4 \times 10^{14} \text{ P watts}}{m^2 \text{ sr}} \qquad (10)$$

Using the previously calculated value of P for 10 mc radiation of 1.4×10^{-33} watts, we get

$$P_T = \frac{5.6 \times 10^{-19} \omega}{m^2 \text{ sr}} \qquad (11)$$

CONCLUSION

From Figure 1, we can calculate the observed total power from 1 mc to 1000 mc to be of the order of 8×10^{-13} watts/ (m^2 sr). While it is conceivable that by assuming a higher average frequency and a larger number of orbiting protons, one could increase the estimate of P_T up to perhaps as much as 10^{-15} ω/(m^2 sr), no realistic assumptions will allow an estimate as large as the figure actually observed. We must, therefore, conclude that this mechanism cannot be responsible for galactic radiofrequency noise.

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