X-660-71-429
PREPRINT

NASA TM X- 65729

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OCTOBER 1971

GSFC

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ABSTRACT

The effect of the ionized gas on synchrotron emission in the interstellar medium is investigated. A detailed calculation of the synchrotron emissivity of cosmic electrons, assumed to have an isotropic pitch-angle distribution in a uniform magnetic field, is made as a function of frequency and observation angle with respect to the field. The results are presented both as a local emissivity and as an intensity, the latter obtained by neglecting free-free absorption in the interstellar medium and by assuming that the emissivity is constant along the line of sight. The comparison of these results with previous studies on the nature of the low-frequency turnover of the galactic nonthermal radio background reveals that, except if the component perpendicular to the line of sight of the interstellar magnetic field is small ($\lesssim 1\ \mu G$), the suppression of synchrotron emission by the ambient electrons has in general a lesser effect than free-free absorption by these electrons, and that in some cases ($B_\perp \sim 5\ \mu G$, $n_e < 0.03$) this suppression effect is almost entirely negligible.

Introduction

Synchrotron radiation produced by relativistic electrons in a magnetoactive plasma is affected by the ambient ionized medium in that the emission at low frequencies is strongly suppressed (e.g., Razin 1960, Ramaty 1969). In a recent paper, Lerche (1971) has suggested that because of this effect, the galactic nonthermal radio background below ~1MHz observed by Alexander et al. (1969, 1970) on board the RAE satellite could not be synchrotron radiation by cosmic electrons, since the interstellar parameters, which by free-free absorption reproduce the observed radio spectrum at low frequencies, (Goldstein, Ramaty and Fisk 1970) will lead to the complete suppression of the emission by the ionized medium.

It is the purpose of the present paper to demonstrate that if the theory of synchrotron emission in an ambient plasma is properly taken into account, for acceptable interstellar densities and magnetic fields, the suppression effect of the ionized medium in general causes only a moderate reduction in the synchrotron emissivity of the cosmic electrons, a reduction which does not invalidate the synchrotron origin of the nonthermal radio background. In the discussion below we first summarize the pertinent cosmic-ray and interstellar parameters. We then treat the theory of synchrotron radiation in a plasma with application to the interstellar medium and compare numerical results with the galactic nonthermal radio background observed in the direction of the anticenter. We find that even though the suppression of synchrotron emission by the ambient plasma does not necessitate an alternative mechanism for the production of the nonthermal radio background at low frequencies as suggested by Lerche (1971), it nonetheless allows for a smaller amount of free-free absorption than if the effect of the ambient medium is neglected.

Synchrotron Emission in the Interstellar Medium

The synchrotron emissivity of the interstellar medium depends on the density and spectrum of cosmic electrons, on the magnitude, structure and orientation of interstellar magnetic field, and on the density of ambient free electrons in interstellar space. In the 10 to 100 MHz region, where free-free absorption and plasma suppression are presumably negligible, the observed nonthermal radio background depends on frequency approximately as $\nu^{-0.4}$ (e.g. Webber 1968). The energy spectrum of the cosmic electrons which produce this radio emission therefore, should be of the form $E^{-\Gamma}$, where E is electron energy and Γ is the spectral index equal to about 1.8. It has been shown by Goldstein, Ramaty, and Fisk (1970) that if solar modulation is taken into account, a cosmic electron density given by

$$N(\gamma) \simeq 2 \times 10^{-9} \gamma^{-1.8} \text{ electrons cm}^{-3}(mc^2)^{-1}, \qquad (1)$$

where $\gamma = E/mc^2$, is consistent with observations of cosmic electrons near earth at energies less than $\sim$ 3 GeV, and that if the component of the interstellar magnetic field perpendicular to the line of sight is about 5μG, this density can account for the nonthermal radio background below $\sim$ 100 MHz from the direction of the anticenter, corresponding to a collection distance L = 4 kpc. The electron observations at higher energies (e.g. Bleeker et al. 1968) indicate that the spectral index Γ increases to about 2.6 at energies greater than about 3 GeV. Since radio emission in the frequency range of interest for the present paper (< 100 MHz) is produced almost exclusively by electrons below 3 GeV, we shall ignore this spectral break, and we shall use the relativistic electron spectrum given by equation (1) in all our calculations below.

The magnitude of the interstellar magnetic field is highly uncertain. Arguments regarding the confinement of cosmic rays and the stability of the galactic gas disk indicate fields of about 3 to 5 μG (Parker 1969). A review of the extant observational data (Verschuur 1970) suggests an average magnetic field of 2 ± 1 μG, whereas pulsar observations (Manchester 1971) are consistent with a local field of about 3.5 μG, even though some regions of interstellar space may possess much lower magnetic fields. The density of free electrons, in both clouds and the intercloud medium, is of the order 0.03 cm^{-3} (Hjellming, Gordon, and Gordon 1969). However, a result of uncertainties of the interpretation of the observational data and possible spatial fluctuations in the interstellar medium, significant departures from this value cannot be ruled out. Therefore, in order to present a treatment of synchrotron emission in the interstellar magnetoplasma which is as general as possible, we shall calculate the synchrotron emissivity as a function of parameters which are normalized to the plasma and gyro frequencies, a procedure which reduces the dependence of the emissivity on the ambient electron density and magnetic field to simple multiplicative factors. For a given, energy-independent, spectral index of the cosmic electrons, the absolute normalization of the cosmic electron density is also a multiplicative factor, so that the only remaining nonlinear parameter is the angle of observation with respect to the interstellar magnetic field. We proceed now to consider the appropriate formulas of synchrotron emission in the interstellar medium and the suitable transformations which lead to this nondimensional representation.

The frequency and angular distribution of the synchrotron emissivity of ultrarelativistic electrons, which have an isotropic pitch-angle distribution and radiate in a static and uniform magnetic field $\vec{B}$ immersed in a plasma of index of refraction $n = (1 - \nu_p^2/\nu^2)^{1/2}$, is given by

$$j(\nu,\theta) = \int \eta(\nu,\theta,\gamma)\, N(\gamma) d\gamma \quad \text{ergs (cm}^3\text{sec sr Hz)}^{-1}, \tag{2}$$

where (Ginzburg and Syrovatskii 1965)

$$\eta(\nu,\theta,\gamma) = \frac{\sqrt{3}}{4\pi}\,\frac{e^3 B}{mc^2}\,\sin\theta\,[1 + \nu_p\gamma/\nu]^{-1/2}\, F(\nu/\nu_c{}^1) \tag{3}$$

In these equations, θ is the observation angle with respect to $\vec{B}$, $F(x) = x \int_x^\infty K_{5/3}(y)\, dy$, and

$$\nu_c{}^1 = 3/2\, \nu_B \gamma^2 \sin\theta\, [1 + (\nu_p\gamma/\nu)^2]^{-3/2} \tag{4}$$

where $\nu_B = eB/(2\pi mc)$, $\nu_p = e(n_e/(\pi m))^{1/2}$, and n_e is the density of the ambient electrons.

By introducing the variables

$$\bar{\nu} = \nu\nu_B/\nu_p^2 \quad \text{and} \quad \bar{\gamma} = \gamma\nu_B/\nu_p \ , \tag{5}$$

the synchrotron emissivity produced by electrons in the interval $\gamma_1 \leq \gamma \leq \gamma_2$ can be written as

$$j(\nu,\theta) = \frac{\sqrt{3}}{4\pi}\frac{e^3 B}{mc^2}\sin\theta\left(\frac{\nu_B}{\nu_p}\right)^{\Gamma-1} k \int_{(\nu_B/\nu_p)\gamma_1}^{(\nu_B/\nu_p)\gamma_2} \bar{\gamma}^{-\Gamma} d\bar{\gamma}\left[1 + \frac{\bar{\gamma}^2}{\bar{\nu}^2}\right]^{-1/2} F\left[\frac{2}{3}\frac{\bar{\nu}}{\sin\theta\bar{\gamma}^2}\left(1+\frac{\bar{\gamma}^2}{\bar{\nu}^2}\right)^{3/2}\right] \tag{6}$$

where we have assumed that in the γ-interval in question, $N(\gamma) = k\gamma^{-\Gamma}$. The integrand in equation (6) is independent of both ν_p and ν_B and hence also of the assumed ambient electron density and magnetic field. The functions plotted in Figure 1 represent this integrand multiplied by $\bar{\gamma}^{\Gamma}$, and are proportional to the synchrotron emissivity of isotopic and mono-energetic electrons in a plasma. Below their maxima these emissivities decrease rapidly with decreasing $\bar{\gamma}$, so that for sufficiently small values of γ_1, the integral in equation (6) is independent of the lower limit of integration. As can be seen from Figure 1, for all values of $\bar{\nu}$ at which there still is appreciable emission, a γ_1 which satisfies $(\nu_B/\nu_p)\gamma_1 < 0.2$ can be considered as sufficiently small. Since in the interstellar medium ν_p/ν_B is probably greater than about 10^2, the effect of the lower limit on the integral in equation (6) is negligible if $\gamma_1 < 0.2\ \nu_p/\nu_B \simeq 20$. Since as discussed above, for the frequencies of interest $N(\gamma)$ can be considered to be a power law with constant spectral index up to arbitrary large values of γ, the integral in equation (6) is independent of the upper limit of integration as well. As stated above, therefore, the emissivity given in equation (6) depends on B and n_e, as well as on the normalization constant k, through simple multiplication factors only.

We have evaluated equation (6) with $(\nu_B/\nu_p)\gamma_1 < 0.2$ and $\gamma_2 \rightarrow \infty$. The results are shown in Figure 2 for $k = 2\times10^{-9}\sin^{-1.4}\theta$. We have renormalized the cosmic electron density by $(\sin\theta)^{(\Gamma+1)/2}$ in order to take into account the angular dependence of synchrotron radiation at frequencies where the effect of the medium is negligible. As can be seen, at high frequencies the spectrum varies as $\nu^{-0.4}$, consistent with the $\nu^{-(\Gamma-1)/2}$ dependence of synchrotron radiation in vacuum. The effect of the medium becomes important approximately at $\nu \approx \nu_R$, where $\nu_R\nu_B/\nu_p^2 \simeq 1/\sin\theta$. This defines a cutoff frequency

$$\nu_R \simeq 30\frac{ne}{B\sin\theta} \quad , \qquad (7)$$

but as can be seen from Figure 2, any definition of ν_R is somewhat arbitrary since the transition from pure power-law to complete cutoff takes place over at least 2 decades of frequency. The effect of θ on the cutoff should in particular be noticed, since at the low frequencies where the emission is suppressed by the ambient plasma there is a large variation of the emission with observation angle, even after the $(\sin\theta)^{(\Gamma+1)/2}$ dependence at high frequencies is taken into account. Because of this effect, the radio emissivity at low frequencies of a region in interstellar space which is viewed at a small angle with respect to the field in that region can be quite low, while at the same time the region would have a much larger emissivity at higher frequencies. This is simply the manifestation of the angular dependence of the cutoff frequency ν_R given in equation (7).

Discussion

We proceed now to compare the results of our calculations with observational data. We use the observed radio spectrum in the direction of the galactic anticenter, since the radiation from the direction of the poles may contain a large contribution from the halo or metagalactic space. The observational data, as compiled by Goldstein, Ramaty and Fisk (1970) is shown in Figure 3 together with the calculated intensities

$$I = jL \qquad (8)$$

where j is the emissivity given in Figure 2, and L is the length of the line of sight along which radiation is collected. Equation (8) is obtained by neglecting free-free absorption and by assuming that the emissivity is constant along the line of sight. The cosmic electron densities used in Figure 3 are renormalized by $(B\sin\theta)^{(\Gamma+1)/2}$, so that all the radio intensities shown in the Figure are equal at the high frequencies, and for $B\sin\theta=5\mu G$, $N(\gamma)$ is equal to the density given by equation (1).

By neglecting the effect of the medium on the emissivity, Goldstein, Ramaty and Fisk (1970) have shown that free-free absorption in the intercloud medium at a temperature of 4000K can account for the observed radio spectrum with $n_e = 0.03$ cm^{-3} and $B\sin\theta=5\mu G$. As can be seen from Figure 3, for the same parameters, the suppression of synchrotron emission by the ambient electrons is negligible and by no means does it invalidate the synchrotron origin of the nonthermal radio background at low frequencies. In fact, for $B\sin\theta=5\mu G$ and $n_e = 0.03$, the ambient medium lowers the emissivity at 0.5 MHz, for example, only by a factor of about 0.6, a decrease which can be compensated for, without changing the electron density, by increasing the temperature by a factor of ~ 1.4. Such an increase is certainly permissible, since estimates of the temperature of the intercloud medium are uncertain by at least an order of magnitude, varying from about 10^3K (Hjellming, Gordon and Gordon 1969) to 10^4K (Field, Goldsmith and Habing 1969).

If the interstellar magnetic field, however, is smaller than 5μG and/or if this field is observed on the average at an angle less than 90°, the effect of the ionized medium on the synchrotron emission may become much more pronounced. Such a situation would require significantly less free-free absorption than estimated by Goldstein, Ramaty and Fisk (1970), and, in particular, it allows an intercloud temperature much larger than the 4000 K estimated by these authors. Moreover, in certain extreme cases ($B\sin\theta \lesssim 1\mu$G, for example) the emission may be completely cutoff below ~ 0.5 MHz. It should be pointed out, however, that if the average perpendicular component of the interstellar magnetic field is less than 5μG, the corresponding average cosmic-electron intensity along the line of sight has to be larger than the electron intensity seen near earth, even after the effects of solar modulation are taken into account. This point has already been made by Setti and Woltjer (1971), and it may mean either that as a result of a galactic inhomogeneity the cosmic electron density just outside the solar cavity is lower than the average density along the line of sight to the anticenter, or that the solar modulation of cosmic electrons is larger than previously estimated.

In summary, therefore, the effect of the ionized medium on synchrotron emission in the interstellar medium is significantly smaller than that of free-free absorption. A complete cutoff at frequencies greater than ~ 0.5 MHz is quite unlikely, since it requires that $B\sin\theta$ be less on the average than ~ $0.5\mu G$ and $n_e \gtrsim 0.03\ cm^{-3}$. Nonetheless, when the effects of the plasma on synchrotron emission are taken into account, a smaller amount of free-free absorption is required to account for the observed low-frequency turnover than if the emission is computed in vacuum. The synchrotron emissivity of the interstellar medium may fluctuate as a result of fluctuations in either or both the perpendicular component of magnetic field and the cosmic electron density. As pointed out in this paper, as a result of the directionally dependent low frequency cutoff of synchrotron radiation in a plasma, an additional source of fluctuation at low frequencies is the orientation of the magnetic field with respect to the line of sight. When this effect is taken into account, future high resolution measurements of the radio background at low frequencies may provide information on the structure and degree of randomness of the interstellar magnetic field.

Acknowledgment

I wish to thank Dr. S. A. Kellman for a critical reading of the manuscript.

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Figure Captions

1. Synchrotron emissivity, in units of ($\sqrt{3}/4\pi$)(e^3B/mc^2)sinθ, of monoenergetic ultrarelativistic electrons with isotopic pitch-angle distribution in a homogeneous, cold and isotopic electron plasma permeated by a static and uniform magnetic field. The solid and dashed lines correspond to emission at $\theta = 90°$ and $\theta = 30°$, respectively, where θ is the angle between the line of sight and the magnetic field. $F(x) = x \int_x^\infty K_{5/3}(y)dy$, $\bar{\upsilon} = \upsilon\upsilon_B/\upsilon_p^2$ and $\bar{\gamma} = \gamma\upsilon_B/\upsilon_p$.

2. Synchrotron emissivity in the interstellar medium. The given form of the cosmic electron density $N(\gamma)$ is assumed to hold for $\gamma \gtrsim 0.2\ \upsilon_p/\upsilon_B$, where υ_p and υ_B are the plasma and gyro frequencies in the emitting region. The angle θ defines the orientation of the interstellar magnetic field in the emitting region with respect to the line of sight. For $\theta = 90°$, the value of $N(\gamma)$ at $\gamma \simeq 6000$ (3 GeV) is approximately equal to the observed cosmic electron density near earth.

3. Intensity of the nonthermal radio background in the direction of the anticenter. Open circles represent the observational data. The various curves, for the indicated average magnetic fields and observation angles along the line of sight, are the calculated intensities obtained by neglecting free-free absorption in interstellar space. The cosmic electron density is given by $N(\gamma)$, the ambient electron density by n_e, and the length of the line of sight by L.

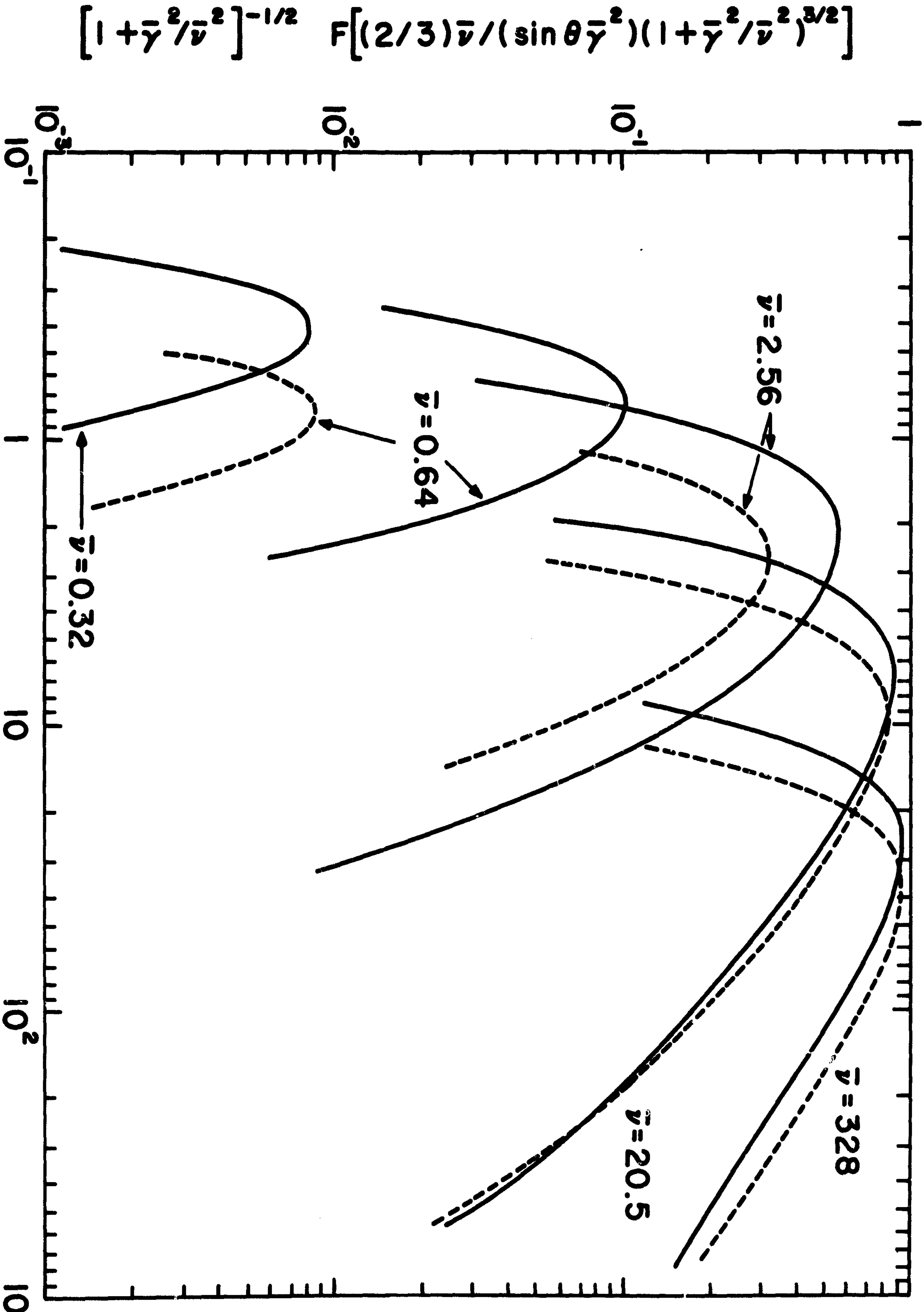

$[1+\bar{\gamma}^2/\bar{\nu}^2]^{-1/2}\ F[(2/3)\bar{\nu}/(\sin\theta\,\bar{\gamma}^2)(1+\bar{\gamma}^2/\bar{\nu}^2)^{3/2}]$
$\bar{\gamma}$
$\bar{\nu}=0.32$
$\bar{\nu}=0.64$
$\bar{\nu}=2.56$
$\bar{\nu}=20.5$
$\bar{\nu}=328$

Figure 1

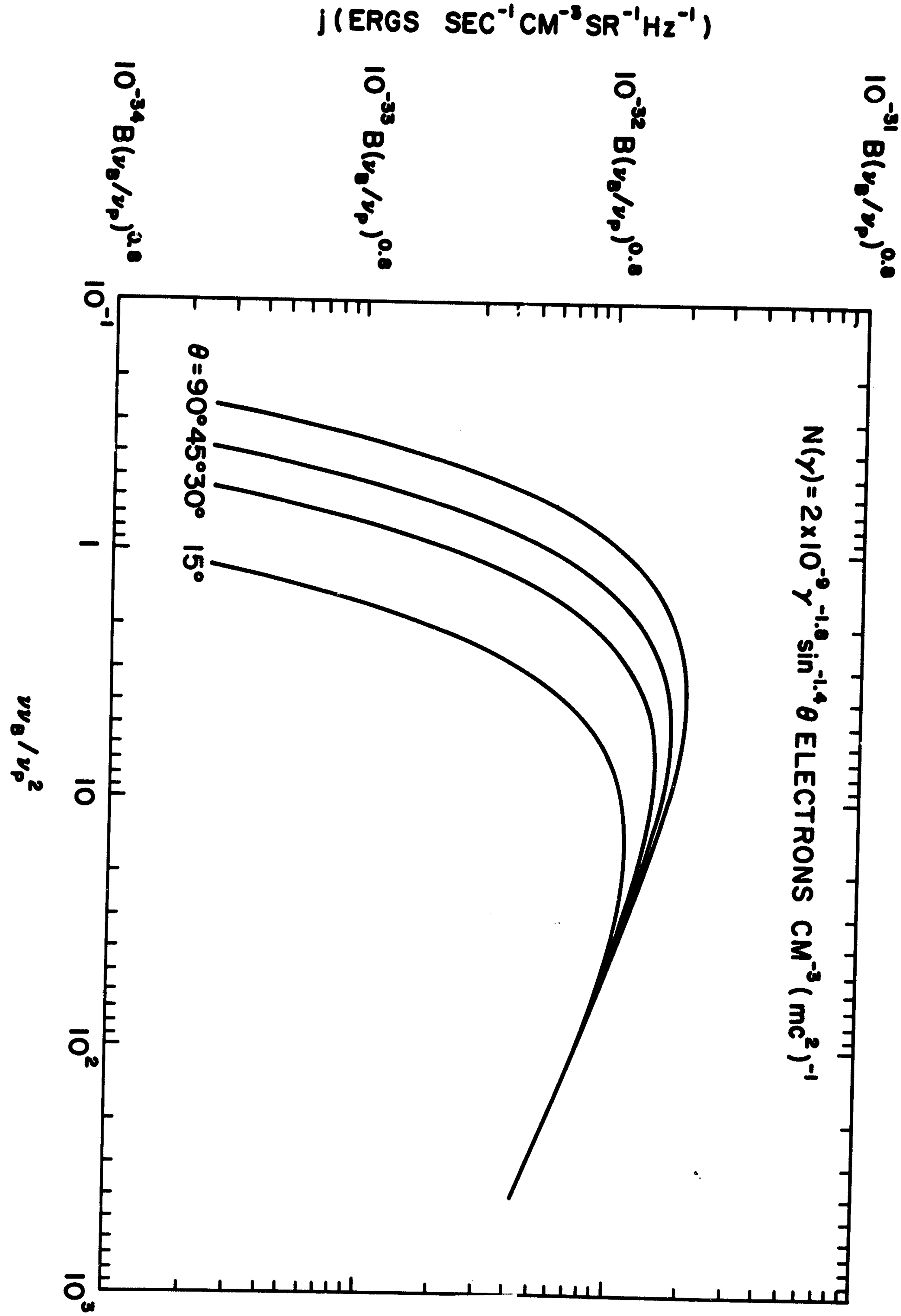
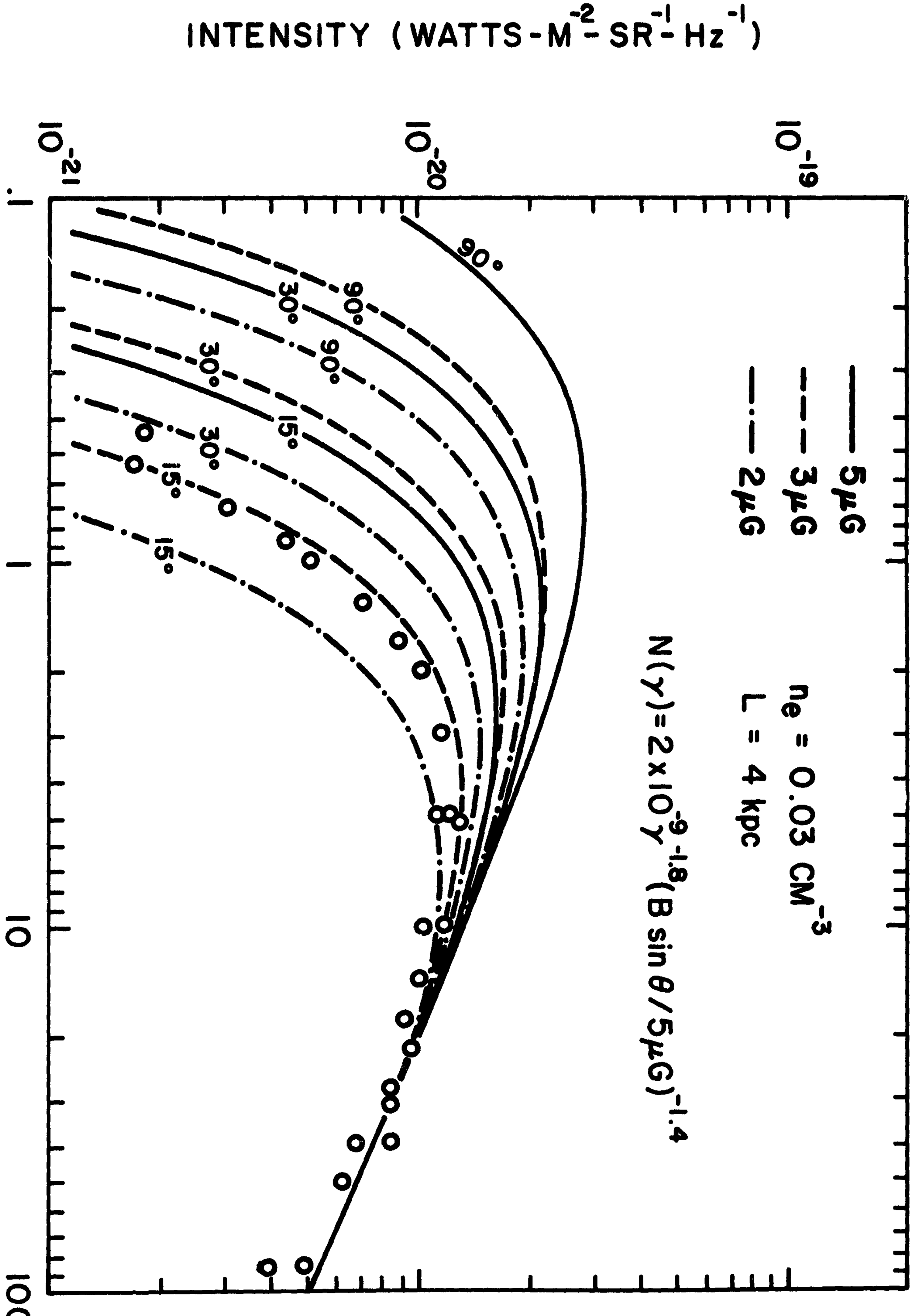

j(ERGS SEC^{-1}CM^{-3}SR^{-1}Hz^{-1})
10^{-31} B(ν_B/ν_p)$^{0.8}$
10^{-32} B(ν_B/ν_p)$^{0.8}$
10^{-33} B(ν_B/ν_p)$^{0.8}$
10^{-34} B(ν_B/ν_p)$^{0.8}$
N(γ)=2x10^{-9} $\gamma^{-1.8}$ sin$^{-1.4}$ θ ELECTRONS CM^{-3} (mc^2)$^{-1}$
θ=90° 45° 30° 15°
10^{-1}
1
10
10^2
10^3
$\nu\nu_B/\nu_p^2$

Figure 2



INTENSITY (WATTS-M^{-2}-SR^{-1}-Hz^{-1})
10^{-19}
10^{-20}
10^{-21}
5μG
3μG
2μG
n_e = 0.03 CM^{-3}
L = 4 kpc
$N(\gamma)=2\times10^{-9}\gamma^{-1.8}(B\sin\theta/5\mu G)^{-1.4}$
90°
30°
15°
.1
1
10
100
ν (MHz)

Figure 3