X-611-68-208
PREPRINT

DETERMINATION OF THE CORONAL MAGNETIC FIELD AND THE RADIO-EMITTING ELECTRON ENERGY FROM A TYPE IV SOLAR RADIO BURST

Reuven Ramaty*

NASA-Goddard Space Flight Center
Greenbelt, Maryland

Richard E. Lingenfelter**

Institute of Geophysics and Planetary Physics
University of California, Los Angeles, California

May 1968

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

*NAS-NASA Post-Doctoral Resident Research Associate

**Research supported by the National Research Foundation under grant GP-849

DETERMINATION OF THE CORONAL MAGNETIC FIELD AND THE RADIO-EMITTING ELECTRON ENERGY FROM A TYPE IV SOLAR RADIO BURST

Reuven Ramaty

NASA-Goddard Space Flight Center
Greenbelt, Maryland

Richard E. Lingenfelter

Institute of Geophysics and Planetary Physics
University of California, Los Angeles, California

ABSTRACT

The intensity and frequency spectrum of gyro-synchrotron emission from energetic solar electrons radiating in coronal magnetic fields are calculated. These calculations, based on a recent study of the generation of gyro-synchrotron emission in a magnetoactive plasma, are applied to a Type IV radio burst originating at a high altitude in the solar corona. It is shown that the observed frequency spectrum of the burst, which exhibits very sharp low and high frequency cutoffs, can be best understood in terms of gyro-synchrotron emission in an ionized medium and that from the observed frequency spectrum and the ambient coronal density it is possible to deduce both the magnetic field at the site of the emission and the range of electron energies responsible for the burst.

DETERMINATION OF THE CORONAL MAGNETIC FIELD AND THE RADIO-EMITTING ELECTRON ENERGY FROM A TYPE IV SOLAR RADIO BURST

INTRODUCTION

Type IV solar radio bursts are generally assumed to be gyro-synchrotron radiation from energetic electrons interacting with chromospheric and coronal magnetic fields. Since the ambient matter in the chromosphere and corona is partially or totally ionized, this interpretation of Type IV bursts requires the detailed understanding of the generation and propagation of radio waves in a plasma.

In a previous paper, (Ramaty and Lingenfelter, 1967) we showed that the observed low-frequency cutoffs exhibited by Type IV bursts (Takakura and Kai, 1961) could be best understood in terms of the suppression of synchrotron emission at low frequencies due to the influence of the ionized medium and that for radiation produced in the solar corona this suppression effect is more important than absorption near the ambient gyro or plasma frequencies. This possibility was recently substantiated by Boischot and Clavelier (1967), who pointed out that the very sharp low frequency cutoff of a Type IV solar burst, which they observed to originate at a large distance from the solar surface, must indeed be a suppression effect rather than absorption, since at the frequency of the observed cutoff, the ambient coronal plasma could not significantly affect the propagation of radio waves.

The suppression of synchrotron emission at low frequencies owing to the influence of the ionized medium was investigated by Tsytovich (1951), Ginzburg (1953), Razin (1957, 1960) and Ginzburg and Syrovatskii (1964, 1965). These studies, however, were limited to radiation from ultrarelativistic electrons and were therefore not generally applicable to Type IV solar radio emission which most probably results principally from electrons of only mildly relativistic energies.

The influence of the ionized medium on gyro-synchrotron emission of intermediate energy electrons was investigated recently by Ramaty (1968). In this study explicit expressions were given for synchrotron emission spectra from single electrons, and it was shown that if in the ambient medium, the ratio of the plasma to the gyro-frequency is of the order of or larger than the Lorentz factor of the radiating electron, these emission spectra will exhibit sharp low frequency cutoffs even if the electrons are only mildly relativistic. Moreover, for plasma-to-gyro frequency ratios much larger than the Lorentz factor of the emitting electron, the total emission will also be strongly suppressed.

In the present paper we shall use these results to evaluate the gyro-synchrotron emission spectrum and intensity from a distribution of energetic electrons in a magnetoactive plasma. We shall then apply these calculations to a Type IV radio burst which was observed on September 14, 1966 by Boischot and Clavelier (1967). According to these observers (Boischot and Clavelier, 1967; Boischot, private communication), the burst started at 1100 UT and originated at an altitude of about 1 solar radius, its emission spectrum peaked at a frequency of 230 MHz and exhibited very sharp low and high-frequency cutoffs.

We shall show that the observed intensity and frequency spectrum of such an event can indeed be understood in terms of gyro-synchrotron emission of energetic electrons in a magnetoactive plasma. The low frequency cutoff is the result of the suppression of the emission due to the influence of the ionized medium, while the high-frequency cutoff must reflect a similar high-energy cutoff in the spectrum of the radiating electrons. As a result, the observed radio power is generated only by electrons within a fairly narrow range of energies centered about a mean value which may be defined as a characteristic electron emission energy. From the observed frequency spectrum of the burst it is possible to deduce unique relationships between the ambient electron density at the site of the emission and both the local magnetic field and the characteristic electron emission energy. Since the electron distribution in the corona is fairly well known, the results of this study can be used for the simultaneous determination of both the magnetic field and electron energy responsible for a given Type IV burst. The values of these parameters can then be compared with other determinations of coronal magnetic fields as well as with direct observations of relativistic solar electrons at the earth.

GYRO-SYNCHROTRON EMISSION IN A MAGNETOACTIVE PLASMA

The frequency spectrum of gyro-synchrotron emission from an electron of arbitrary energy, moving in a circular orbit in an isotropic electron plasma permeated by a static uniform magnetic field, is given by (Ramaty, 1968)

$$P(\nu,\gamma) = \sum_{s=1}^{\infty} \frac{2e^4 B^2}{m^2 c^3} \frac{1-\beta^2}{\beta} \frac{1}{n^2} \delta\left(\nu - \frac{s\nu_B}{\gamma}\right) \cdot \left[s\beta^2 n^2 J'_{2s}(2s\beta n) - s^2(1-\beta^2 n^2) \int_0^{\beta n} J_{2s}(2sx)\, dx \right] \tag{1}$$

In this expression β and γ are the velocity and Lorentz factor, respectively, of the energetic electron, ν_B is the cyclotron frequency of the ambient electrons, B is the static magnetic field, and J_s is a Bessel function of order s. The index of refraction n is in general different for the ordinary and extraordinary modes and is given by an anisotropic expression depending on the angle between the magnetic field and the direction of propagation. If, however, the plasma frequency ν_P is much larger than ν_B, for frequencies greater than ν_P the index of refraction can be approximated by the isotropic expression

$$n = \sqrt{1 - \nu_P^2/\nu^2} \tag{2}$$

In the present problem, for all cases of interest we indeed have $\nu >> \nu_P >> \nu_B$.

Equation (1), with n given by Equation (2) was evaluated numerically (Ramaty, 1968) for various values of γ, ν_P and ν_B, and it was shown that if

$(\nu_B/\nu_P)\,\gamma \lesssim 1$, the emission is significantly suppressed at low frequencies. By comparing Equation (1) with a similar expression for emission in vacuum, (Takakura, 1960) it can be seen that this suppression effect is essentially the result of the transformation of γ into a frequency-dependent "effective" Lorentz factor, γ_1, given by

$$\gamma_1 = \frac{1}{\sqrt{1 - \beta^2 n^2}} = \frac{\gamma}{\sqrt{1 + \frac{9}{4}\,\frac{1 - 1/\gamma^2}{\alpha^2\,\gamma^2\,(\nu/\nu_c)^2}}} \tag{3}$$

where $\nu_c = (3/2)\,\nu_B\gamma^2$ is the characteristic frequency of synchrotron emission and the parameter α is defined as

$$\alpha = (3/2)\ \nu_B/\nu_P \tag{4}$$

From these calculations, it was found that for a fixed value of γ, as α decreases, the low-frequency cutoff and the frequency of maximum emission are shifted toward higher values. At the same time, a decreasing α causes the radiation to be emitted into a narrower band of frequencies and the total power emitted by the electron to decrease.

The emission spectrum from a distribution of electrons $N(\gamma)$ is given by

$$P(\nu) = \int_1^\infty d\gamma\, P(\nu,\gamma)\, N(\gamma) \tag{5}$$

where $N(\gamma)\,d\gamma$ is the total number of radiating electrons having Lorentz factors in $d\gamma$ around γ. Substituting Equation (1) into Equation (5) and using the relationship

$$\delta\left(\nu - \frac{s\nu_B}{\gamma}\right) = \frac{s\nu_B}{\nu^2}\,\delta\left(\gamma - \frac{s\nu_B}{\nu}\right)$$

we obtain that

$$P(\nu) = \frac{\sqrt{3}\,e^3 B}{mc^2}\,Q_\alpha(\nu/\nu_B) \tag{6}$$

where

$$Q_\alpha\left(\frac{\nu}{\nu_B}\right) = \frac{4\pi}{\sqrt{3}} \sum_{s=1}^{\infty} \frac{1}{bn^2}\left[b^2n^2 J'_{2s}(2sbn) - s(1-b^2n^2)\int_0^{bn} J_{2s}(2sx)\,dx\right] N\left(\frac{s\nu_B}{\nu}\right) \tag{7}$$

and

$$b = \frac{\sqrt{s^2\,\nu_B^2/\nu^2 - 1}}{s\nu_B/\nu} \tag{8}$$

$$n = \sqrt{1 - \frac{9}{4\alpha^2}\left(\frac{\nu_B}{\nu}\right)^2} \tag{9}$$

As can be seen from Equations (7), (8), and (9), for a given $N(\gamma)$, $Q_\alpha(\nu/\nu_B)$ depends only on α and ν/ν_B. Therefore, when the emission spectrum is expressed as a function of ν/ν_B, the influence of the medium is determined solely by the magnitude of the parameter α.

There is no direct information on the number and energy spectrum of accelerated electrons at the sun but relativistic electrons associated with solar flares were observed near the earth on various occasions (Cline and McDonald, 1968 a, b; Simnett, 1968; Sullivan, 1968). The measured spectra of these particles in the energy range of about 2 to 10 Mev could be characterized by power laws, $N(\gamma) \sim \gamma^{-\Gamma}$, where the spectral index Γ varies from flare to flare and is somewhat time dependent for a given flare, but is in general limited to the range $2 < \Gamma < 5$. Because of the very sharp high-frequency cutoff in the spectrum of the 14 September 1966 burst, mentioned above, however, the energy spectrum of the radiating electrons must be much steeper at high energies than the observed spectra of these particles at the earth. We have assumed therefore, that the spectrum of the radiating electrons is truncated at some high energy and is thus given by

$$N(\gamma) = \begin{cases} k\gamma^{-\Gamma}, & \gamma \leq \gamma_u \\ 0, & \gamma > \gamma_u \end{cases} \tag{10}$$

where Γ is allowed to vary in the range $2 < \Gamma < 5$ and γ_u is treated as a free parameter. Using Equation (10), with $k = 1$ and Γ equal to either 2 or 5, we have numerically evaluated Equation (7) for several values of γ_u and α. By comparing these calculations with the observations, we find that for a given value of γ_u, within the experimental errors, the spectrum of the burst at 1100 UT on 14 September, 1966 (Boischot and Clavelier, 1967) can be fitted within a limited range of values of the parameter α. The calculated spectra for four arbitrary values of γ_u and the corresponding limiting and best fitting values of α are shown in Figures (1) and (2), for $\Gamma = 2$ and $\Gamma = 5$ respectively. Also shown are the data points which represent the observed spectrum, (Boishot and Clavelier, 1967), normalized in both frequency and intensity to the theoretical curves corresponding to the best fitting values of α.

As can be seen from these figures, the limiting ranges and the best fitting values of α are the same for both $\Gamma = 2$ and $\Gamma = 5$. This results from the fact that the emission is produced by a fairly narrow range of electron energies and is thus essentially independent of the spectral shape of the electron distribution. We can define therefore a characteristic electron emission energy, $\bar{\gamma}$, such that for an electron spectrum $N(\gamma)$ given by Equation (10) and normalized to 1 electron per unit γ at $\bar{\gamma}$, the flux densities at the frequency of maximum emission, ν_m, are the same for both $\Gamma = 2$ and $\Gamma = 5$. We can also define an equivalent range $\overline{\Delta\gamma}$ around $\bar{\gamma}$ such that these flux densities also equal the flux density at ν_m from monoenergetic electrons normalized to 1 electron per unit γ at $\bar{\gamma}$. According to these definitions, $\bar{\gamma}$ and $\overline{\Delta\gamma}$ can be obtained from

$$\int p(\nu_m, \gamma)\,(\gamma/\bar{\gamma})^{-2}\,d\gamma = \int p(\nu_m, \gamma)\,(\gamma/\bar{\gamma})^{-5}\,d\gamma = p(\nu_m, \bar{\gamma})/\overline{\Delta\gamma} \qquad (11)$$

where $p(\nu, \gamma)$ is given by Equation (1).

Using the numerical evaluations of Equation (1), mentioned above, (Ramaty, 1968) and the emission spectra given in Figures (1) and (2), which best fit the observed spectrum of the burst, we have determined $\bar{\gamma}$ and $\overline{\Delta\gamma}$. These are shown in Table 1. As can be seen, the values of $\overline{\Delta\gamma}$ are generally quite small compared to $\bar{\gamma}$, indicating that the observed emission is indeed produced by a very limited range of electron energies around $\bar{\gamma}$. This "monoenergetic" nature of the emission is a consequence of the suppression of the emission of the lower energy electrons due to the influence of the ionized medium and of the assumed cutoff at high energies required by the observed burst spectrum.

MAGNETIC FIELDS, PLASMA DENSITIES AND ENERGETIC ELECTRONS

The magnetic field at the site of the emission can now be deduced by comparing the calculated emission spectra, which are shown in Figures (1) and (2) as functions of ν/ν_B, to the measured frequency spectrum for the September 14, 1966 burst.

The resultant cyclotron frequencies for each combination of α, $\bar{\gamma}$ and Γ are given in Table 2. As can be seen the product $\alpha\bar{\gamma}$ is essentially a constant of about .42 for the best fitting values of α and $\bar{\gamma}$, even though the observed spectrum of the burst can be fitted by a variety of values of these parameters. This relationship is the result of the "monoenergetic" nature of the emission and Equation (3), according to which for ultrarelativistic energies the influence of the medium is only a function of the product $\alpha\gamma$. This simple relationship tends to break down for non-relativistic energies, as can be seen from Table 2 for $\bar{\gamma}$ = 2.11. As can be further seen, for a fixed $\bar{\gamma}$ the cyclotron frequency decreases with decreasing α, since, as discussed above, the frequency of maximum emission is shifted toward higher values and therefore a lower magnetic field is required to account for an observed burst at a given frequency. It can also be seen that the cyclotron frequencies deduced for an electron spectrum with $\Gamma = 5$ are slightly higher than those for $\Gamma = 2$. The reason for this is that for a steeper electron spectrum the interval $\overline{\Delta\gamma}$ contains relatively less high energy electrons and therefore a higher magnetic field is required to produce the emission at a given frequency.

From Equation (4) and the cyclotron frequencies deduced above, we can determine the plasma frequencies associated with each set of values of α and ν_B. These are also shown in Table 2 for $\Gamma = 2$ and $\Gamma = 5$. As can be seen, for each value of $\overline{\gamma}$ and the corresponding best value of ν_P, the product $3/2\ \nu_P\overline{\gamma}$ is essentially a constant independent of ν_B and approximately equal to 230 MHz, which is the observed frequency of maximum emission of the 14 September 1966 burst. Thus, when the observed spectra are sufficiently narrow, reflecting the strong influence of the medium and the "monoenergetic" nature of the resultant gyro-synchrotron radiation, the frequency of maximum emission is independent of the local magnetic field and is given approximately by the simple relationship

$$\nu_m \approx 1.5\,\nu_P\overline{\gamma} \tag{12}$$

On the other hand, the spectral shape of the burst determines $\alpha\overline{\gamma}$, from which the local field may be obtained as a function of the ambient electron density.

The magnetic field B and the characteristic electron energy $\bar{\gamma}$, required to produce the observed burst, are shown in Figure (3) as functions of the ambient plasma density, n_e. In this figure, the 4 "data" points correspond to the 4 choices of γ_u used in the calculations described above. The errors in the field and density values correspond to both the ranges of the parameter α and the variations introduced by the different spectral indexes Γ, and the errors in $\bar{\gamma}$ represent the values of $\overline{\Delta\gamma}$ given in Table 1. As can be seen, the same emission spectra can be generated by lower energy electrons in regions of high densities and high fields or by higher energy electrons in regions of low densities and low fields. These qualitative relationships are of course consistent with the constancy of $\nu_p\bar{\gamma}$ and $\alpha\bar{\gamma}$ mentioned above.

Using the spectra shown in Figures (1) and (2) and the magnetic fields given in Table 2, we have evaluated the flux densities at the earth for all the combinations of α and ν_B considered above. The resultant spectra, normalized at the sun to 1 electron per unit γ at $\bar{\gamma}$ are shown in Figures (4), (5), (6) and (7) for $\bar{\gamma}$ = 2.11, 4.25, 8.3 and 16.6 respectively. As can be seen, the frequency of maximum emission is indeed independent of ν_B and in all cases is approximately equal to 230 MHz, as required by the observational data. The allowed ranges of the values of ν_B, then, are determined solely from the observed spectral shape of the burst.

The ranges of the ambient densities, magnetic fields and energies of the radiating electrons corresponding to the observed spectrum of the 1100 UT, 14 September 1966 burst, can be compared with other estimates of coronal densities and fields as well as with direct measurements at the earth of relativistic solar electrons.

The available data on the electron density distribution in the corona were summarized by Malitson and Erickson (1966) and Newkirk (1967). At an altitude of about 1 solar radius estimates of the coronal density in a streamer range from about 3×10^7 cm^{-3}, based on studies of Type II and Type III radio bursts, to about 1×10^7 cm^{-3} based on optical measurements (Hepburn, 1955; Newkirk, 1961). The densities in coronal streamers at 1 solar radius are about an order of magnitude larger than the densities in undisturbed regions of the corona calculated from van de Hulst's (1950) model which at this altitude range from about 3×10^6 cm^{-3} at the equator to 2×10^5 cm^{-3} at the poles.

Estimates of the distribution of coronal magnetic fields, determined from radio observations, were summarized by Takakura (1966) and a general review on the subject was given by Newkirk (1967). According to Takakura (1966), at an altitude of 1 solar radius the magnetic field obtained from Type II bursts is of the order of a few gauss but higher values, of the order of 10 gauss, are obtained from Type I and Type III bursts. These discrepancies may be attributed to spatial variations and local effects, but as pointed out by Newkirk (1967), the estimates of coronal magnetic fields based on Type I, Type II and Type III bursts are extremely uncertain, mainly because of the various interpretations attributed to the basic observational data.

Estimates of the coronal field derived from observations of Type IV bursts without taking into account the influence of the medium (Takakura and Kai, 1961) gave field values of about 10 gauss at an altitude of 1 solar radius. It was shown by Ramaty and Lingenfelter (1967), however, that by taking into account the influence of the ionized coronal plasma on the generation of Type IV bursts, the same observations could be accounted for by fields of only 1 to 2 gauss. Using a rather crude approximation of this effect for the interpretation of the 14 September 1966 burst, Boischot and Clavelier (1967) found that the magnetic field at 1 solar radius is of the order of 0.5 gauss. Coronal fields of only a few tenths of a gauss, probably corresponding to undisturbed regions, can be deduced from the observed damping of the oscillatory motion of filaments (Hyder, 1966; Newkirk, 1967).

If we assume that at the site of the emission of the 1100 UT, 14 September 1966 burst the electron density ranges from 10^7 to 3×10^7 cm^{-3}, as determined from optical and Type II and Type III radio burst observations discussed above, then from Figure (3) we find that the magnetic field at 1 solar radius varies from about 0.5 to 1.5 gauss. This range of field values is consistent with our previous estimates (Ramaty and Lingenfelter, 1967) as well as with the magnetic field deduced from Type II bursts (Takakura, 1966).

From the present study, however, we can also find the characteristic electron emission energies corresponding to these density and field values. As can be seen from Figure (3), for densities ranging from about 10^7 to 3×10^7 cm^{-3}, the characteristic emission electron energy varies from about 1.5 to 2.5 Mev. Relativistic electrons with energies up to about 8 Mev were observed at the earth on September 14, 1966 (Cline and McDonald, 1968b). These particles started to arrive at about 1040 UT, their intensity peaked at about 1300 UT, and the best estimate of the injection time at the sun is at about 1008 UT, comparable with the observed starting time at 1014 UT of a 2B flare. The spectrum of these electrons could be represented by a power law with a constant spectral index of 3.5 to 4 up to the highest observed energy of about 8 Mev. If these observed electrons and the electrons required to produce the Type IV burst at 1100 UT were of the same origin, the high energy cutoff at about 3 Mev in the spectrum of the radiating electrons could be caused either by energy losses through synchrotron radiation of the electrons remaining in solar magnetic fields or by an energy dependent escape mechanism which would let the higher energy electrons escape and be detected at the earth, whereas at the same time the lower energy particles would remain at the sun and move slowly up into the corona, to emit the observed radio burst. If the high-energy cutoff is caused by synchrotron losses only, a time averaged field of about 200 gauss is required to produce such a cutoff at 3 Mev. Such a field is quite reasonable if the electrons spend a major fraction of their trapping time in the lower chromosphere where the flare originates. If an energy dependent escape mechanism was responsible for the release of the electrons from the sun, the time averaged field would be smaller.

On the other hand however, the electrons which were observed at the earth and those which produced the Type IV burst in the corona could have different origins. This possibility was considered by Boischot et al (1967) who suggested that the electrons which produced the burst were locally accelerated in the corona by a turbulent plasma energized by shock waves propagating upward in the solar atmosphere. At the present time it is impossible to decide which of the two processes, acceleration in the chromosphere and subsequent trapping at the sun or local acceleration in the corona, is the more adequate to explain the observed phenomena. Hopefully observations of additional radio bursts, in particular time dependent spectral measurements may help to distinguish between these possible electron sources.

In addition, we should consider the possibility that the Type IV burst was produced in a coronal region having a lower electron density, say of the order of 2×10^6 cm^{-3}, corresponding to non-streamer equatorial densities. In such a region, as can be seen from Figure (3), we find that the field at the site of the emission is of the order of 0.1 gauss and the characteristic electron emission energy is about 5 to 6 Mev. These field values are consistent with estimates of coronal magnetic fields at 1 solar radius over non-active regions. Since in this case the electron energy required to account for the Type IV burst is comparable with the upper energies of the electrons observed at the earth, the radiating electrons would have had to have been trapped at the sun in lower field regions so as to minimize the energy losses suffered by synchrotron radiation. Local acceleration in the corona in this case is quite unlikely, because of the low ambient densities and magnetic fields and because of the high electron energies required to produce the observed burst.

Finally, the total number of electrons at the sun can be determined from the measured peak flux density of 10^{-20} W/m^2 Hz at 200 MHz at 1104 UT, 14 September 1966 (Nederhorst Observatory, 1966). Using this measured flux density, and the best fitting curves shown in Figures (4), (5), (6) and (7) we have determined the total number of electrons at the sun per unit γ at the values of $\bar{\gamma}$ given in Table 1. Then by using the values of $\overline{\Delta\gamma}$ which are also given in Table 1, we obtained the total number of radiating electrons required to produce the observed burst. These values are given in Table 3 for $\Gamma = 2$ and $\Gamma = 5$. As can be seen, the differential number of electrons at the sun is almost independent of the assumed spectral index and moreover since the values of $\overline{\Delta\gamma}$ become smaller for larger $\bar{\gamma}$, the total number of electrons at the sun is almost the same for each value of $\bar{\gamma}$ considered. As can be seen from Table 3, the total number of electrons, N_0, required to produce the observed radio flux density is between 5×10^{33} and 8×10^{33} electrons with energies of about 2.5 Mev, if the emissions originate in coronal streamers, and about 9×10^{33} electrons of about 6 Mev if the emission region is in the undisturbed corona.

According to Cline and McDonald (1968b and private communication), the number of electrons greater than 3 Mev released from the sun on September 14, 1966 was about 5×10^{30} based on an isotropic diffusion fit of the observed time dependence of the electron flux at the earth. The 14 September 1966 burst occurred on the west limb of the sun and therefore this estimate may be somewhat low, but even under the extreme assumption of isotropic release and rectilinear particle propagation, the number of electrons in interplanetary space above 3 Mev does not exceed 3×10^{31}. The two to three orders of magnitude discrepancy, therefore, between this number and that required to produce the observed Type IV burst seems to indicate that only a small fraction of the flare electrons escaped from the sun. By comparing the measured electron fluxes in interplanetary space on July 7, 1966 with those required to produce the observed high energy X-ray burst at the sun, Cline and McDonald (1968b) came to a similar conclusion, namely that for the 7 July 1966 flare as well, a large fraction of the accelerated electrons may have remained trapped at the sun and did not escape into interplanetary space.

SUMMARY

We have demonstrated that from the observed frequency spectrum of a Type IV burst it is possible to determine both the coronal magnetic field and the energies of the radiating electrons as functions of the ambient electron density at the site of the emission in the corona. Since the spectrum of a Type IV burst may be measured quite accurately, the main uncertainty in these determinations results from uncertainties in the ambient coronal density. More radio measurements are required, therefore, and these coupled with particle observations at the earth should provide a more complete understanding of the structure of the corona and of the sequence of events following a solar flare.

REFERENCES

Boishot, A. and B. Clavelier: 1967, Astrophys. Letters, 1, 7.

Boishot, A., Clavelier, B., Mangeney, A. and C. Lacombe: 1967, Comp. Rend., 265, 1151.

Cline, T. L. and F. B. McDonald: 1968a, Proc. Tenth Internat. Conf. on Cosmic Rays, to be published.

Cline, T. L. and F. B. McDonald: 1968b, Solar Physics, to be published.

Ginzburg, V. L.: 1953, Usp. Fiz. Nauk 51, 343.

Ginzburg, V. L. and S. I. Syrovatskii: 1964, The Origin of Cosmic Rays, Macmillan and Company, New York.

Ginzburg, V. L. and S. I. Syrovatskii: 1965, Ann. Rev. Astron. and Astrophys., 3, 297.

Hepburn, N.: 1955, Astrophys. J., 122, 445.

Hulst, H. C. van de: 1950, B.A.N. 11, 135.

Hyder, C. L.: 1966, Z. Astrophys. 63, 78.

Malitson, H. H. and W. C. Erickson: 1966, Astrophys. J., 144, 337.

Nederhorst Observatory: 1966, Reports of Nederhorst Observ. Netherlands for September 1966.

Newkirk, G.: 1961, Astrophys. J., 133, 983.

Newkirk, G.: 1967, Ann. Rev. Astron. and Astrophys., 5, 213.

Ramaty, R.: 1968, J. Geophys. Res., 73, 3573.

Ramaty, R. and R. E. Lingenfelter: 1967, J. Geophys. Res. 72, 879.

Razin, V. A.: 1957, Dissertation, Gorkii State University, Unpublished.

Razin, V. A.: 1960, News of Higher Educational Institutions, Ministry of Higher Education, Radio Physics Series, 3, 73.

Simnett, G. M.: 1968, Paper read at Midwest Cosmic Ray Conference, Iowa City, Iowa.

Sullivan, James D.: 1968, Paper read at Midwest Cosmic Ray Conference, Iowa City, Iowa.

Takakura, T.: 1960, Publ. Astron. Soc. Japan, 12, 325.

Takakura, T.: 1966, Space Sci. Rev. 5, 80.

Takakura, T. and K. Kai: 1961, Publ. Astron. Soc. Japan, 13, 94.

Tsytovich, V. N.: 1951, Vestnik Moscow. Univ. 6, No. 11, Ser. Fiz. — Mat. i Estestven. Nauk, No. 7, 27.

Table 1

γ_u	α	$\bar{\gamma}$	$\overline{\Delta\gamma}$
2.5	0.25	2.11	1.4
5	0.1	4.25	0.52
10	0.05	8.3	0.28
20	0.025	16.6	0.14

Table 2

$\bar{\gamma}$	α	ν_B (MHz)		ν_P (MHz)	
		$\Gamma = 2$	$\Gamma = 5$	$\Gamma = 2$	$\Gamma = 5$
2.11	0.20	9.2	9.6	69	72
	0.25	11.6	12.1	70	72.5
	0.30	14.3	14.8	71.5	74
4.25	0.08	1.91	1.92	35.8	36.0
	0.10	2.40	2.50	36.0	37.5
	0.12	2.91	3.10	36.4	38.2
8.3	0.04	0.46	0.51	17.2	19.1
	0.05	0.58	0.66	17.4	19.7
	0.06	0.70	0.81	17.5	20.2
16.6	0.02	0.115	0.127	8.65	9.5
	0.025	0.146	0.164	8.75	9.85
	0.03	0.177	0.200	8.85	10.0

Table 3

	$N(\bar{\gamma})$ (Electrons/unit γ)		N_0 (Electrons)	
$\bar{\gamma}$	$\Gamma = 2$	$\Gamma = 5$	$\Gamma = 2$	$\Gamma = 5$
2.11	3.6×10^{33}	3.1×10^{33}	4.8×10^{33}	4.2×10^{33}
4.25	1.47×10^{34}	1.43×10^{34}	7.6×10^{33}	7.4×10^{33}
8.3	3.1×10^{34}	2.67×10^{34}	8.5×10^{33}	7.7×10^{33}
16.6	6.67×10^{34}	5.9×10^{34}	9.3×10^{33}	8.3×10^{33}

FIGURE CAPTIONS

1. Gyro-synchrotron emission spectra in an ionized medium for various values of the parameter α defined in Equation (4) and for electron distributions which are power laws in γ with spectral index -2 and high energy cutoffs at the indicated values of the parameter γ_u.

2. Gyro-synchrotron emission spectra in an ionized medium for various values of the parameter α defined in Equation (4) and for electron distributions which are power laws in γ with spectral index -5 and high energy cutoffs at the indicated values of the parameter γ_u.

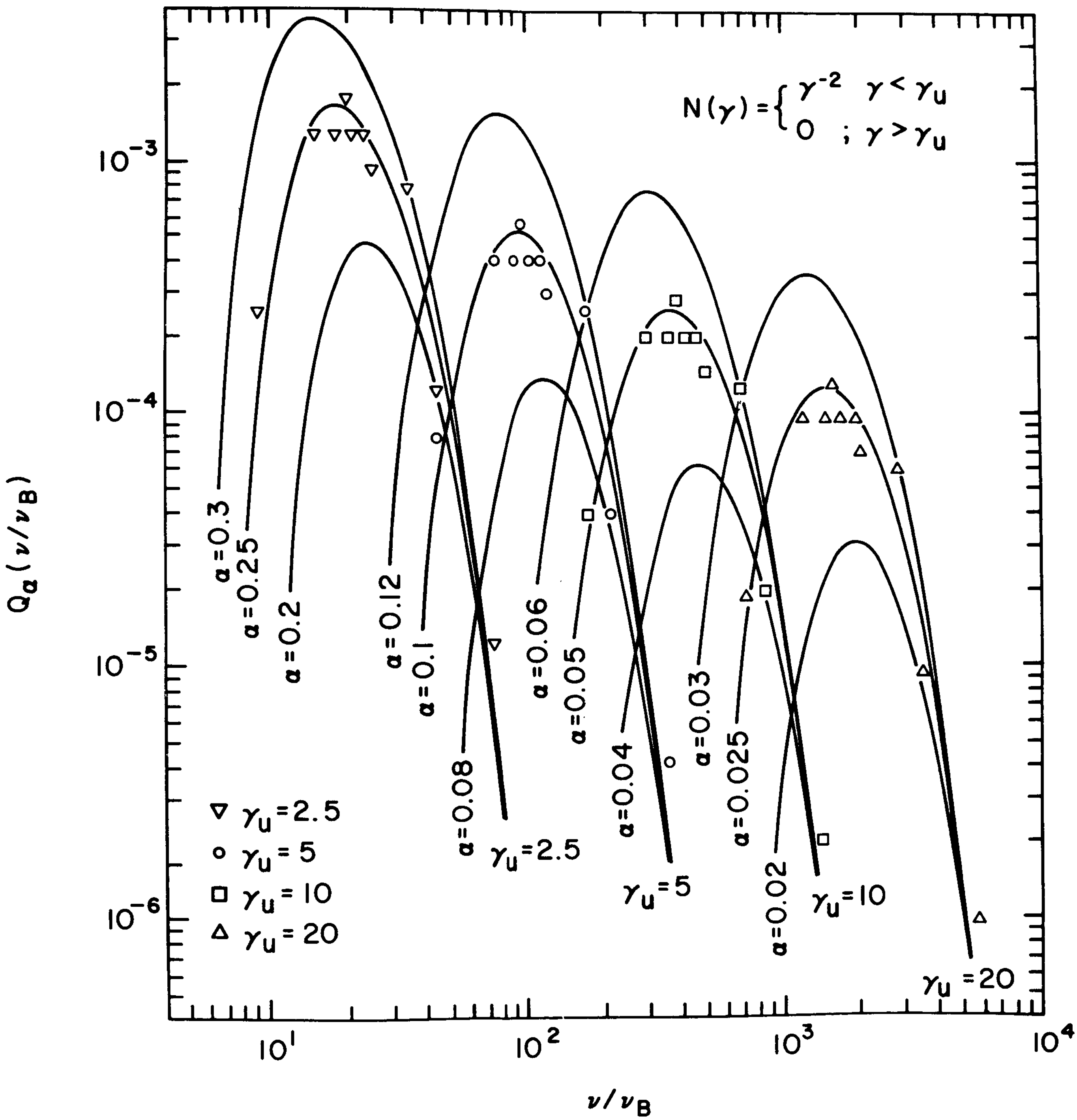
3. The magnetic field B and the mean electron emission Lorentz factor $\overline{\gamma}$ as functions of the electron density n_e at the site of the emission of the 14 September 1966 burst. These functions were determined by fitting the theoretical distributions shown in Figures 1 and 2 to the observed frequency spectrum of the 1100UT Type IV radio burst.

4. Flux densities at the earth for a range of gyro and plasma frequencies which best fit the observed shape and frequency of maximum emission of the observed Type IV burst on September 14, 1966. These spectra were calculated for electron distributions which are power laws in γ with spectral indexes -2 and -5 and normalized at the sun to 1 electron per unit γ at $\overline{\gamma}$ = 2.11. The data points represent the observed spectrum of the burst and are normalized to the best fitting theoretical distributions.

5. Flux densities at the earth for a range of gyro and plasma frequencies which best fit the observed shape and frequency of maximum emission of the observed Type IV burst on September 14, 1966. These spectra were calculated for electron distributions which are power laws in γ with spectral indexes -2 and -5 and normalized at the sun to 1 electron per unit γ at $\overline{\gamma}$ = 4.25. The data points represent the observed spectrum of the burst and are normalized to the best fitting theoretical distributions.

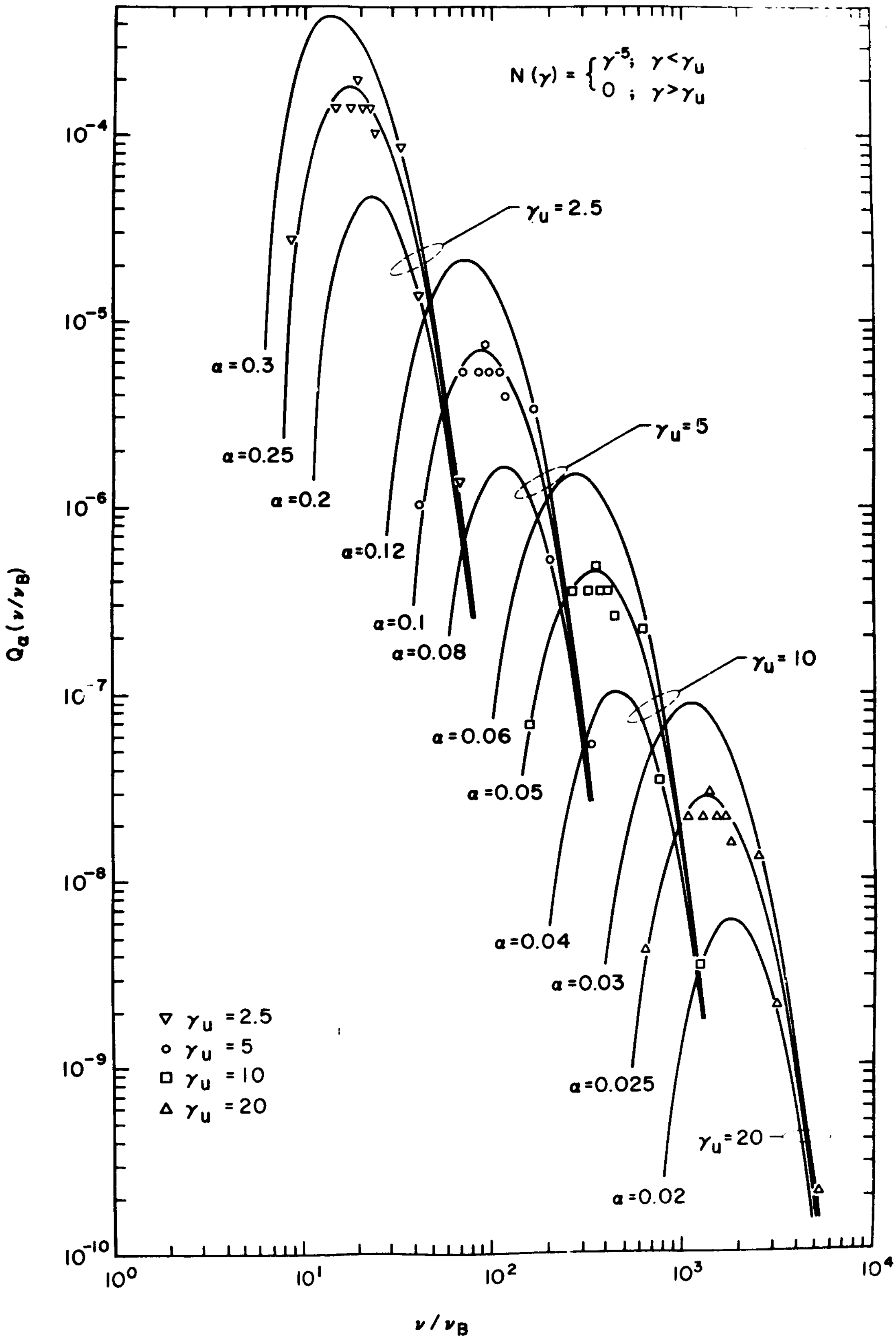
6. Flux densities at the earth for a range of gyro and plasma frequencies which best fit the observed shape and frequency of maximum emission of the observed Type IV burst on September 14, 1966. These spectra were calculated for electron distributions which are power laws in γ with spectral indexes -2 and -5 and normalized at the sun to 1 electron per unit γ at $\overline{\gamma}$ = 8.3. The data points represent the observed spectrum of the burst and are normalized to the best fitting theoretical distributions.

7. Flux densities at the earth for a range of gyro and plasma frequencies which best fit the observed shape and frequency of maximum emission of the observed Type IV burst on September 14, 1966. These spectra were calculated for electron distributions which are power laws in γ with spectral indexes -2 and -5 and normalized at the sun to 1 electron per unit γ at $\overline{\gamma}$ = 16.6. The data points represent the observed spectrum of the burst and are normalized to the best fitting theoretical distributions.



$N(\gamma) = \begin{cases} \gamma^{-2} & \gamma < \gamma_u \\ 0 \; ; & \gamma > \gamma_u \end{cases}$
$Q_\alpha(\nu/\nu_B)$
ν/ν_B
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^1
10^2
10^3
10^4
$\alpha=0.3$
$\alpha=0.25$
$\alpha=0.2$
$\alpha=0.12$
$\alpha=0.1$
$\alpha=0.08$
$\alpha=0.06$
$\alpha=0.05$
$\alpha=0.04$
$\alpha=0.03$
$\alpha=0.025$
$\alpha=0.02$
$\gamma_u=2.5$
$\gamma_u=5$
$\gamma_u=10$
$\gamma_u=20$
▽ $\gamma_u=2.5$
○ $\gamma_u=5$
□ $\gamma_u=10$
△ $\gamma_u=20$

Fig. 1



$N(\gamma) = \begin{cases} \gamma^{-5}; & \gamma < \gamma_u \\ 0; & \gamma > \gamma_u \end{cases}$
$\gamma_u = 2.5$
$\gamma_u = 5$
$\gamma_u = 10$
$\gamma_u = 20$
$a = 0.3$
$a = 0.25$
$a = 0.2$
$a = 0.12$
$a = 0.1$
$a = 0.08$
$a = 0.06$
$a = 0.05$
$a = 0.04$
$a = 0.03$
$a = 0.025$
$a = 0.02$
▽ $\gamma_u = 2.5$
○ $\gamma_u = 5$
□ $\gamma_u = 10$
△ $\gamma_u = 20$
$Q_a(\nu/\nu_B)$
ν/ν_B
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^0
10^1
10^2
10^3
10^4

Fig. 2

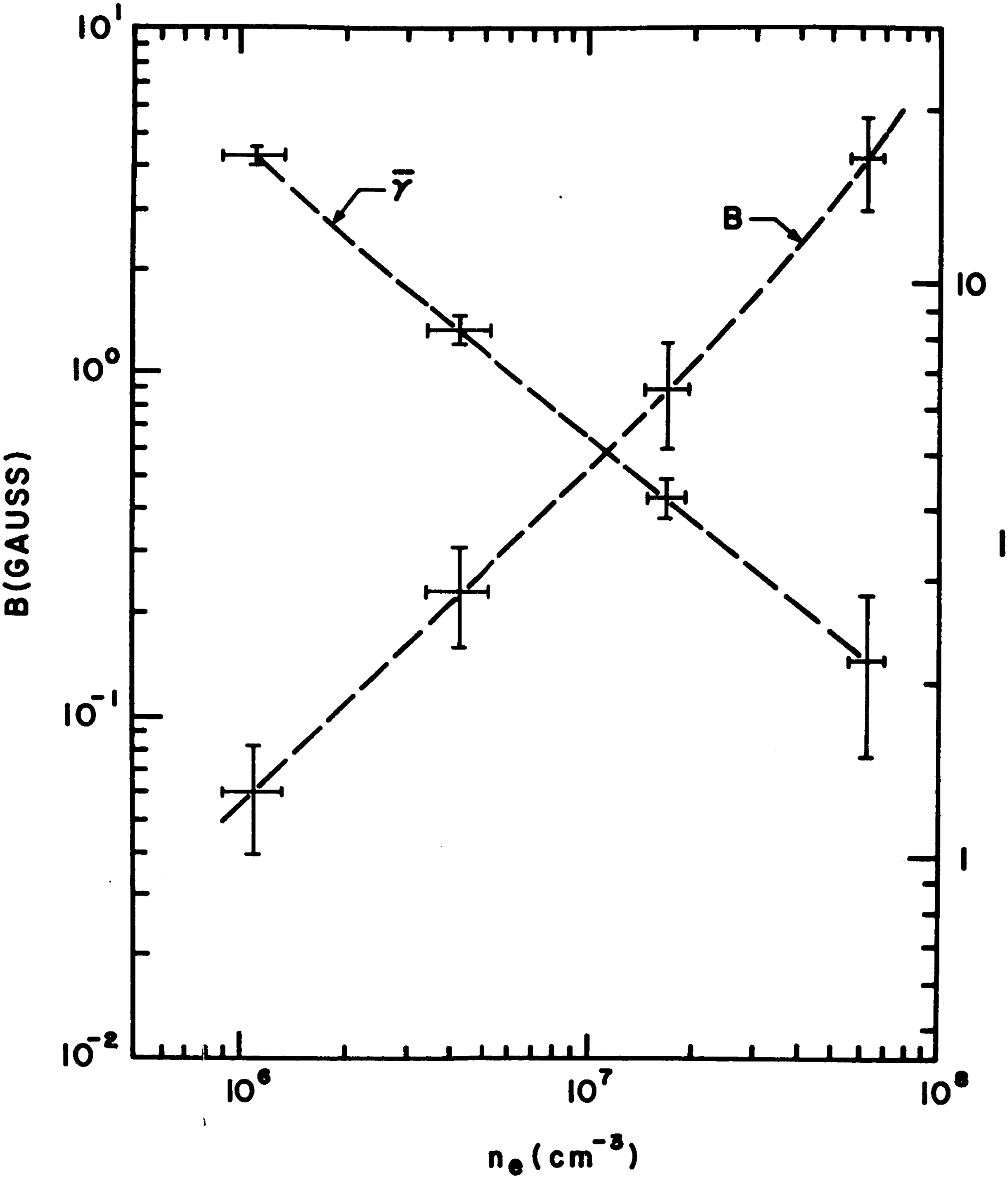


Fig. 3

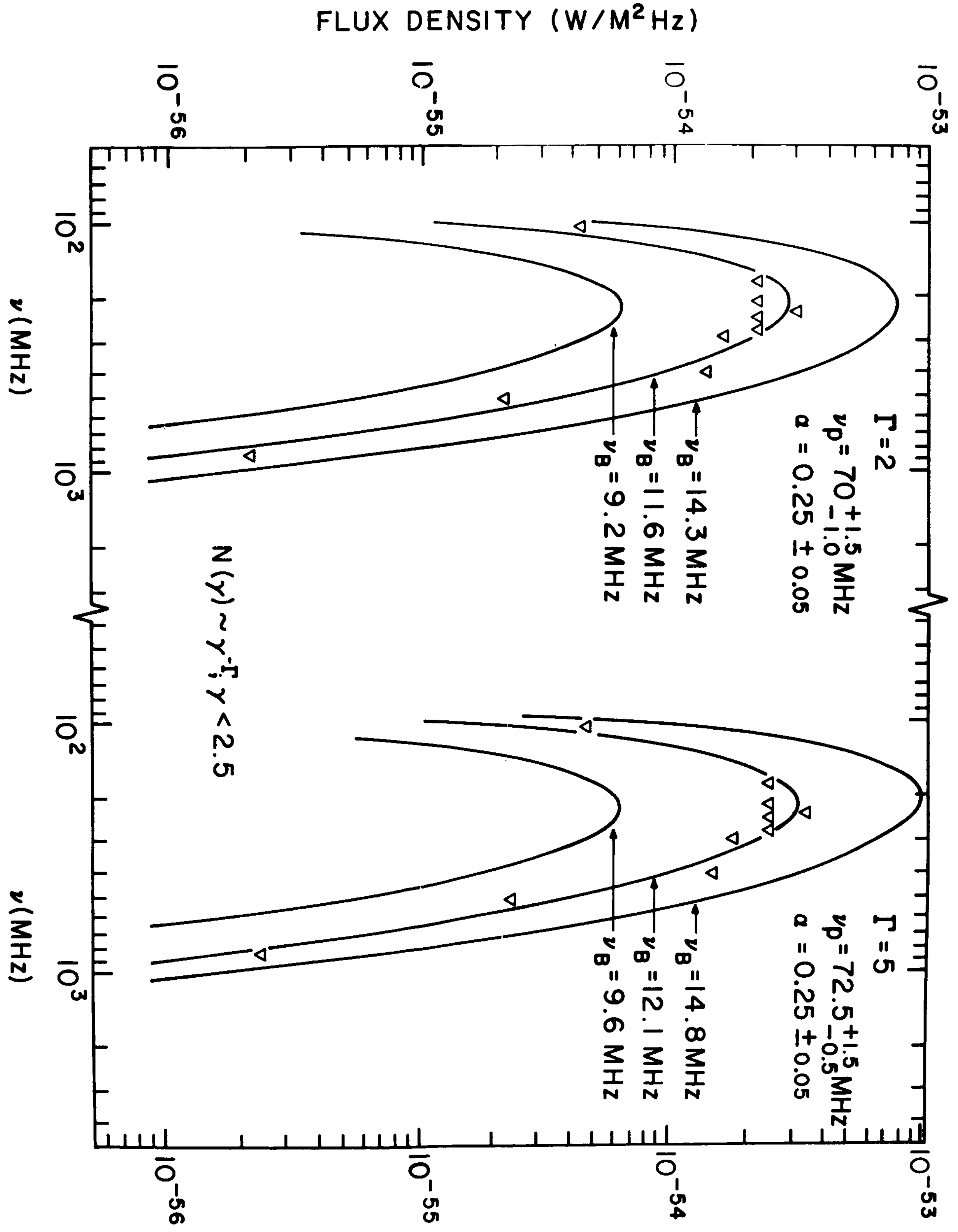
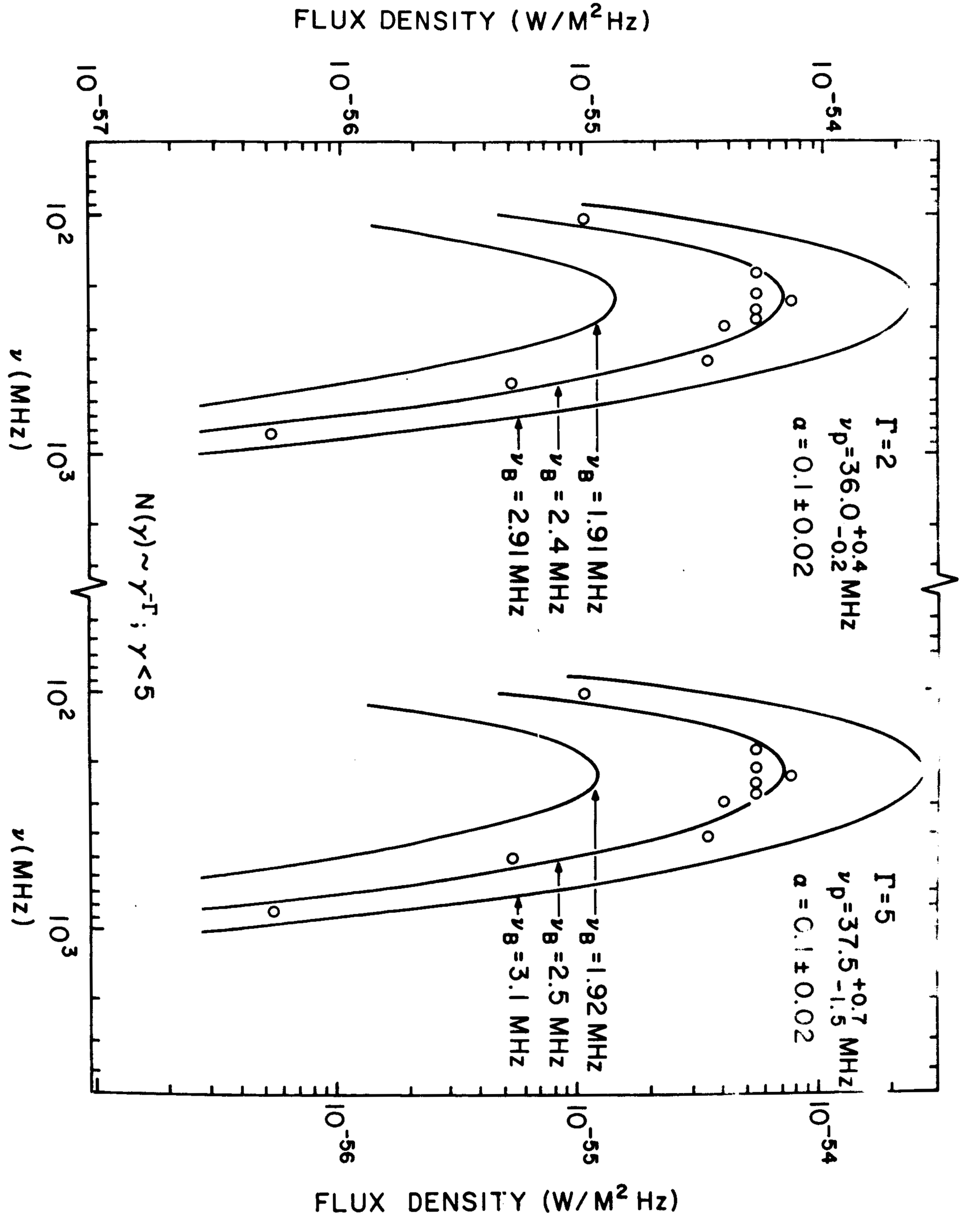
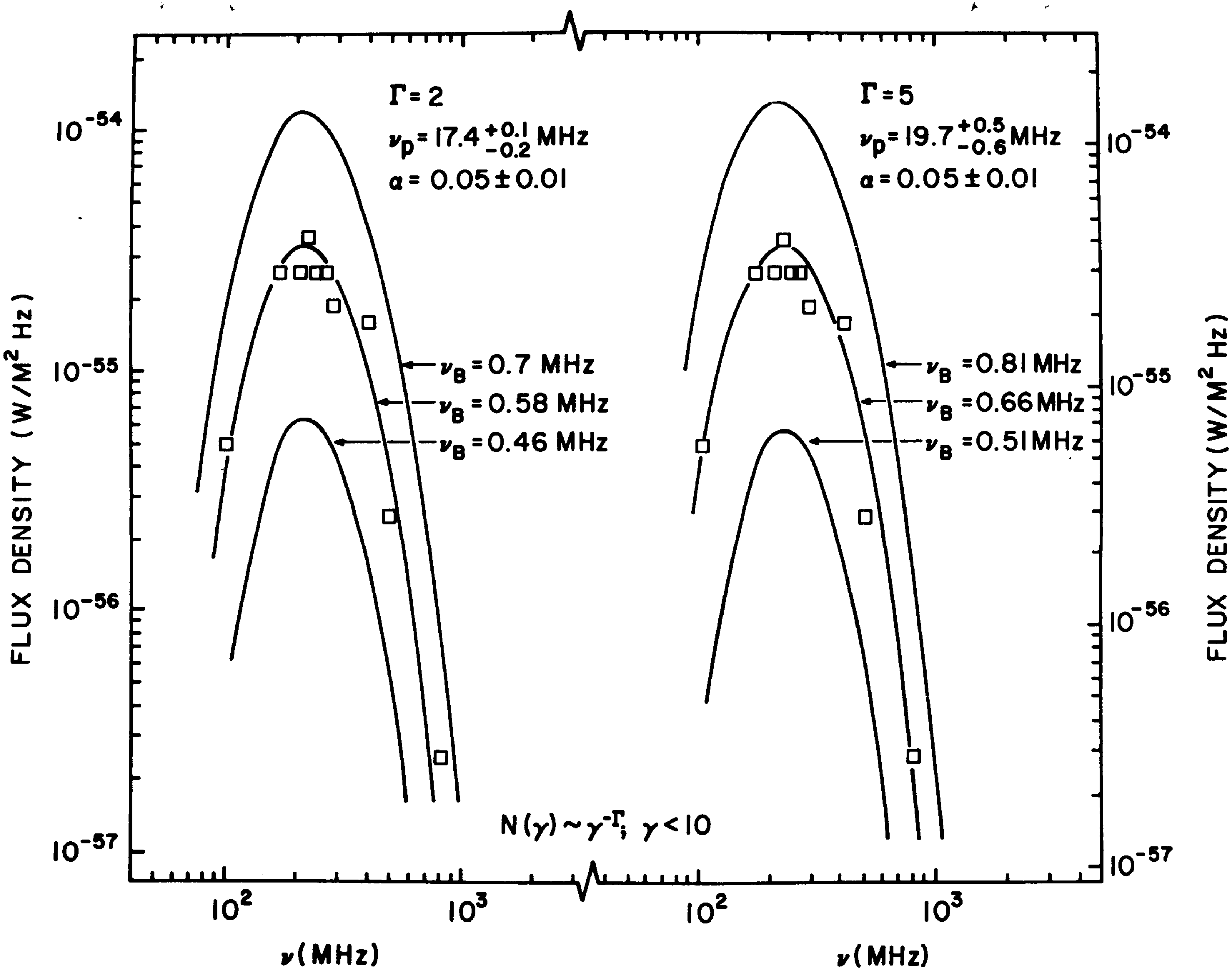

FLUX DENSITY (W/M²Hz)
10⁻⁵³
10⁻⁵⁴
10⁻⁵⁵
10⁻⁵⁶
10²
10³
ν(MHz)
Γ=2
νp=70+1.5−1.0 MHz
α = 0.25 ± 0.05
νB=14.3MHz
νB=11.6MHz
νB=9.2MHz
N(γ)~γ^−Γ; γ<2.5
Γ=5
νp=72.5+1.5−0.5 MHz
α = 0.25 ± 0.05
νB=14.8MHz
νB=12.1 MHz
νB=9.6 MHz

Fig. 4



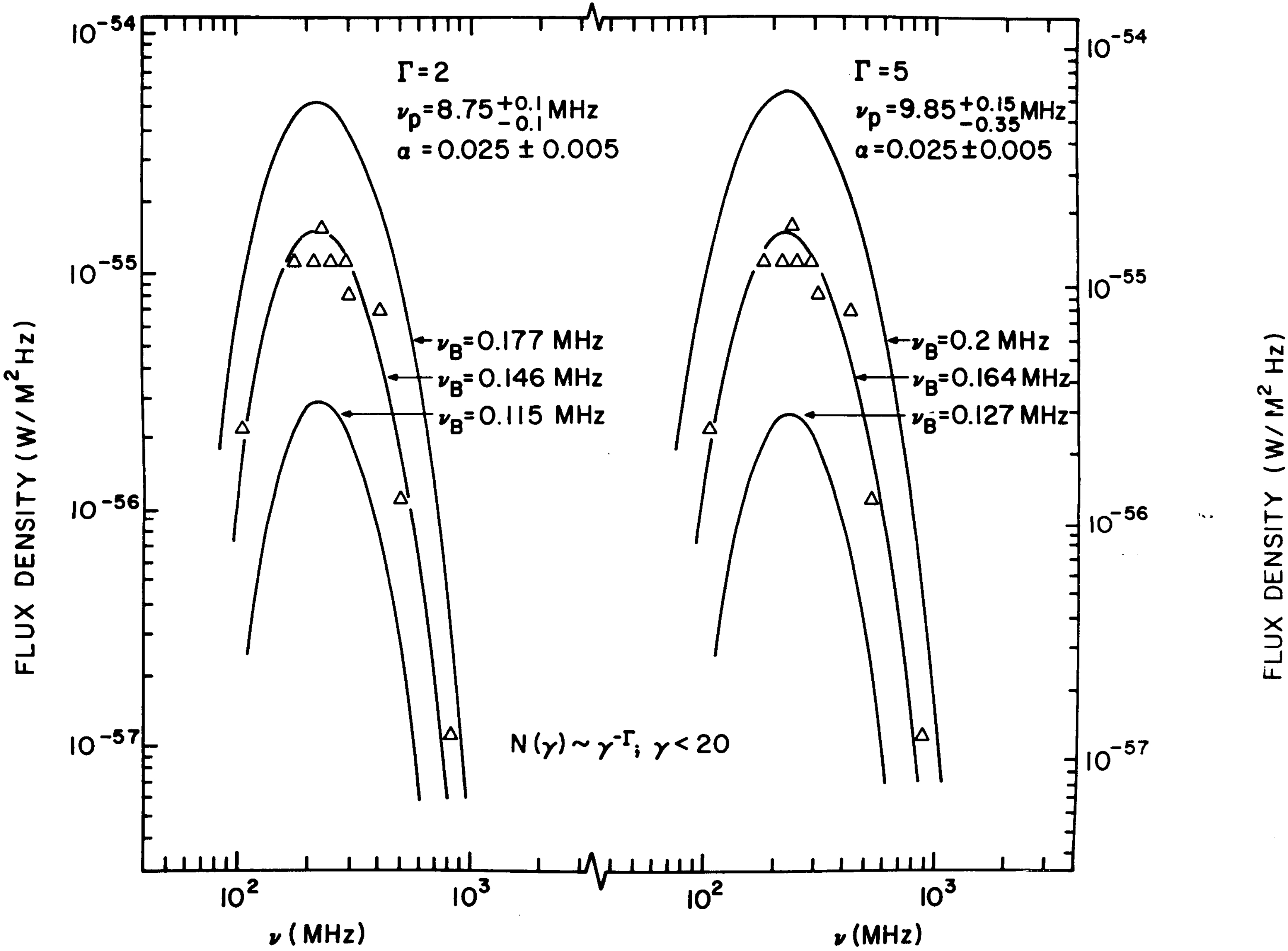
FLUX DENSITY (W/M^{2}Hz)
Γ=2
ν_p=36.0$^{+0.4}_{-0.2}$ MHz
α = 0.1 ± 0.02
ν_B = 1.91 MHz
ν_B = 2.4 MHz
ν_B = 2.91 MHz
N(γ) ~ γ$^{-Γ}$; γ<5
Γ=5
ν_p=37.5$^{+0.7}_{-1.5}$ MHz
α = 0.1 ± 0.02
ν_B = 1.92 MHz
ν_B = 2.5 MHz
ν_B = 3.1 MHz
ν (MHz)

Fig. 5



Γ = 2
νp = 17.4 +0.1 -0.2 MHz
α = 0.05 ± 0.01
Γ = 5
νp = 19.7 +0.5 -0.6 MHz
α = 0.05 ± 0.01
νB = 0.7 MHz
νB = 0.58 MHz
νB = 0.46 MHz
νB = 0.81 MHz
νB = 0.66 MHz
νB = 0.51 MHz
N(γ) ~ γ^-Γ; γ < 10
FLUX DENSITY (W/M² Hz)
10^-54
10^-55
10^-56
10^-57
10^2
10^3
ν (MHz)

Fig. 6



$\Gamma = 2$
$\nu_p = 8.75^{+0.1}_{-0.1}$ MHz
$a = 0.025 \pm 0.005$
$\nu_B = 0.177$ MHz
$\nu_B = 0.146$ MHz
$\nu_B = 0.115$ MHz
$\Gamma = 5$
$\nu_p = 9.85^{+0.15}_{-0.35}$ MHz
$a = 0.025 \pm 0.005$
$\nu_B = 0.2$ MHz
$\nu_B = 0.164$ MHz
$\nu_B = 0.127$ MHz
$N(\gamma) \sim \gamma^{-\Gamma}; \gamma < 20$
FLUX DENSITY (W/M^2 Hz)
10^{-54}
10^{-55}
10^{-56}
10^{-57}
10^2
10^3
ν (MHz)

Fig. 7