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# Thermalization of synchrotron radiation from field-aligned currents†

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Three-dimensional plasma simulations of interacting galactic-dimensioned current filaments show bursts of synchroton radiation of energy density $1{\cdot}2 \times 10^{-13}$ erg/cm$^3$ which can be compared with the measured cosmic microwave background energy density of $1{\cdot}5 \times 10^{-13}$ erg/cm$^3$. However, the synchrotron emission observed in the simulations is not blackbody. In this paper, we analyze the absorption of the synchrotron emission by the current filaments themselves (i.e., self-absorption) in order to investigate the thermalization of the emitted radiation. It is found that a large number of current filaments ($>10^{31}$) are needed to make the radiation spectrum blackbody up to the observed measured f.equency of 100 GHz. The radiation spectrum and the required number of current filaments is a strong function of the axial magnetic field in the filaments.

## 1. Introduction

Some aspects of galaxy formation, including morphology, isophotic data, rotational curves, etc., are described by an interacting, field-aligned current model proposed by Peratt and Green (1983). When two such field-aligned current filaments interact, a burst of synchrotron radiation is emitted due to the abrupt change in longitudinal electric field of the filaments. Three-dimensional particle-in-cell simulations using the code SPLASH (Buneman *et al.*, 1980), show bursts of energy with an energy density equivalent to $1{\cdot}2 \times 10^{-13}$ erg/cm$^3$. If the spectrum were blackbody, this would correspond to a temperature of 2·0 K. However, the radiation spectrum in general is not blackbody. In this paper, we study the thermalization of the field-aligned current model to both galactic and cosmological questions. This study is also related to geophysical phenomenon and to the physics of electromagnetic pulse phenomena in the atmosphere.

In laboratory applications, interacting field-aligned currents (often called Birkeland currents, Fälthammar 1986; Peratt 1986a, 1986b) have found practical application as high energy sources of microwaves and x-rays. The shorter wavelength x-rays (and gamma rays) define the discrete sources themselves. The microwaves produced are absorbed and thermalized by a substance called *eccosorb*, a filamentary highly-conducting material placed around very high power microwave generators. In cosmic plasma, highly conducting Birkeland filaments whose dimensions are tens of kiloparsecs in width may play the role of *eccosorb*, thermalizing the microwave radiation produced in filament interactions and producing the highly isotropic background 'glow' (figure 1).

The possibility that small (0·1–1 mm) grains distributed as intergalactic dust may serve to absorb and re-emit the radiation emitted from galaxies has been extensively

† Paper dedicated to Professor Hannes Alfvén on the occasion of his 80th birthday, 30 May 1988.

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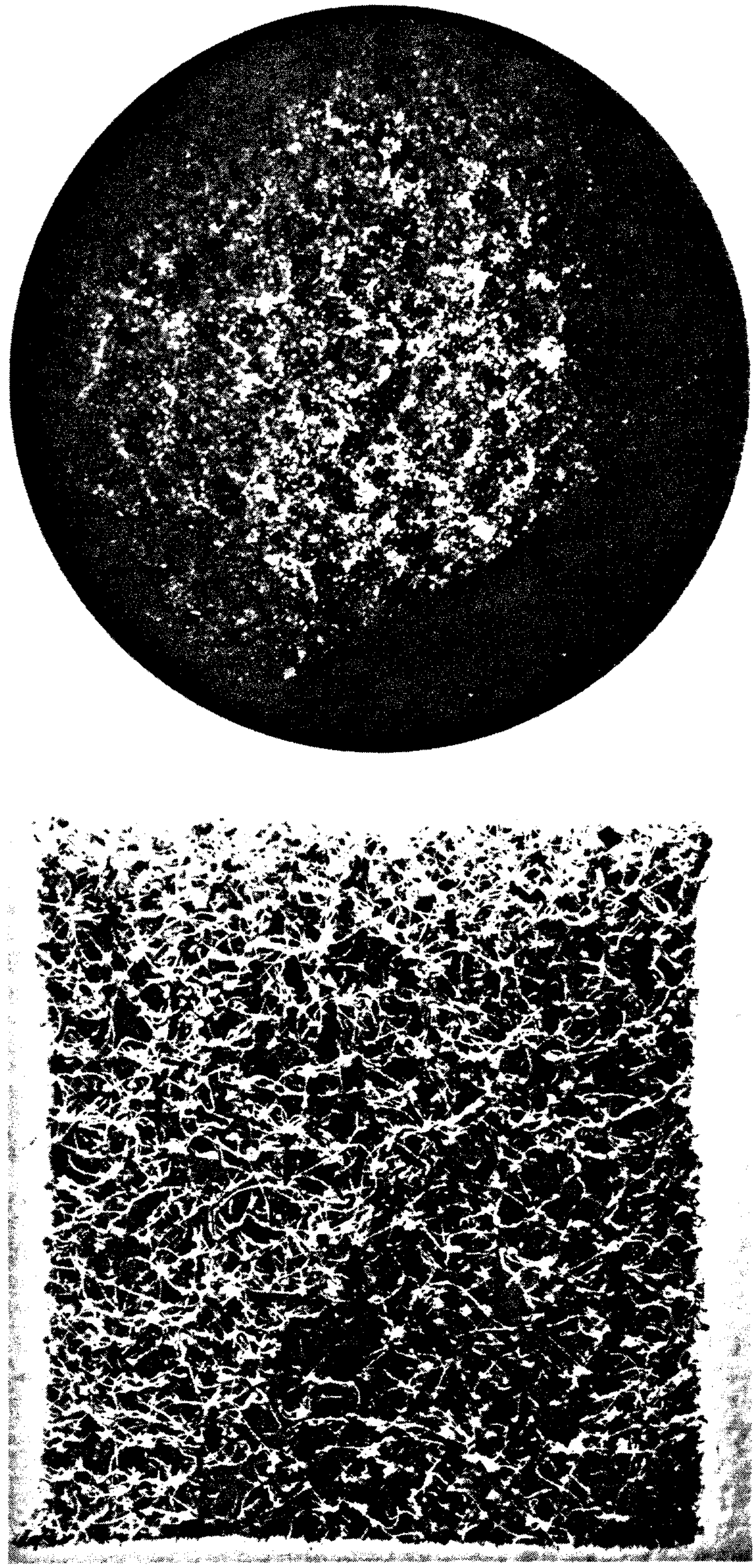

FIGURE 1. (a) Visible (optical) universe consisting of galaxies brighter than 19th magnitude; (b) a photograph of *eccosorb,* a material used to thermalize high-power microwaves in the laboratory.

investigated (Hoyle *et al.* 1984, Wickramasinghe *et al.* 1975, Alfvén & Mendis 1977, etc.). Many of these dust particle theories face difficulties with respect to explaining the blackbody spectrum, the isotropy of the radiation, and the untenably large optical depths at visual wavelengths. In this study, we take a different approach, in that the current filaments which are the sources of the synchrotron radiation themselves take the place of the conducting graphite needles (Wickramasinghe *et al.* 1975), so that the sources of the synchroton radiation may thermalize the radiation through self-absorption.

## 2. Calculations

We first consider the model used in the simulations. A long plasma filament scaled to galactic dimensions (35 kpc, or $10^{23}$ cm, a typical galactic width) consists of electrons and ions with their densities equal, $n_i = n_e$ (figure 2). The electron density is $n_e = 1{\cdot}8 \times 10^{-3}\,\mathrm{cm}^{-3}$, the current $I \simeq 10^{19} - 10^{20}$ amps, and the axial electron temperature is around 30 keV. In these filaments also, we assume a longitudinal electric field. These electric fields arise from electrostatic double layers (Peratt & Green 1983) that form periodically along the current filaments, a result of charge separations initiated by the Buneman two-stream instability. The direction of the Birkeland filament defines the axial magnetic field $B_z$. Concomittant with the axial current flow $I_z$ is an azimuthal field $B_\theta$. Typical values for the fields in the simulations are $E_z = 60\,\mathrm{mV/m}$, $B_\theta = 2{\cdot}5 \times 10^{-4}$ G, and $B_z = 2 \times 10^{-4}$ G. A plot from the numerical simulation of the synchrotron energy versus time is given in figure 3.

To determine the self-absorption of a plasma, one usually calculates the absorption coefficient for the radiation originating from the motion of the free electrons in the plasma, assuming that the entire system is in thermal equilibirum. This is equivalent to requiring that the electron distribution function of the plasma be Maxwellian. In the current model presented here, we assume that the synchrotron emission is produced by these electrons, and that any background plasma (which is assumed cold and weakly refracting) does not interact with the radiation. A single electron therefore emits as it does in vacuum, and more complicated considerations (such as the Razin–Tsytovich effect) are not applicable.

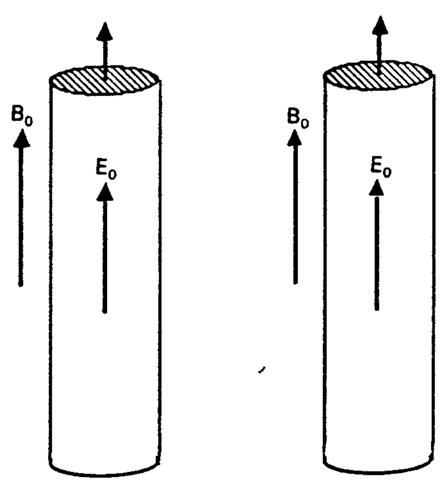


FIGURE 2. Basic geometry under consideration. Interacting parallel Birkeland currents of width ~35 kpc.

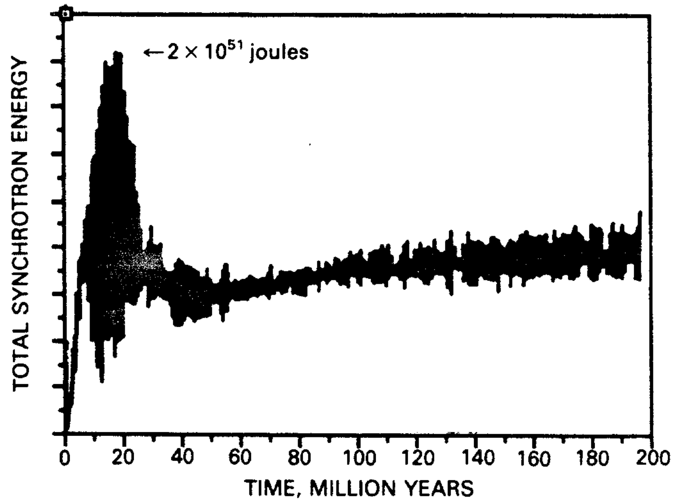


FIGURE 3. Total radiated synchrotron energy as a function of time from a numerical simulation of interacting Birkeland filaments scaled to galactic dimensions. Radiated energy density is calculated to be $1{\cdot}2 \times 10^{-13}$ erg/cm$^3$ which would correspond to a 2°K blackbody temperature if the spectrum were blackbody.

The particle distribution function for a directed electron current in a plasma filament is not necessarily Maxwellian, though for an initial calculation it will be a convenient assumption. The self-absorption problem including a non-Maxwellian distribution function is an involved calculation, and will be presented in a later publication. The results do not, however, appear to be considerably different from those presented here. The absorption coefficient for radiation in a weakly refracting plasma of stationary ions and of electrons with an anisotropic distribution function $f(p_\parallel, p_\perp)$ is given by (Hirshfield & Bekefi 1963; Bekefi 1966)

$$\begin{aligned}\alpha_\omega(\theta) = -\frac{16\pi^4 c}{\omega^2} N \int_0^\infty dp_\perp \int_{-\infty}^\infty dp_\parallel \eta_\omega(p_\parallel, p_\perp, \theta)\\ \left\{\frac{\epsilon}{c}\frac{\partial f}{\partial p_\perp} - \left[p_\parallel \frac{\partial f}{\partial p_\perp} - p_\perp \frac{\partial f}{\partial p_\parallel}\right]\cos\theta\right\}\end{aligned} \tag{1}$$

where $N$ is the electron density, $\epsilon = \gamma mc^2$ is tht total electron energy, and $p_\parallel(p_\perp)$ is the electron momentum component along (across) $B_0$. The quantity $\eta_\omega$ is the rate of spontaneous emission of synchrotron radiation by one electron at radius frequency $\omega$, and is equal to

$$\eta_\omega(\omega, v, \theta) = \frac{e^2\omega^2}{8\pi^2\epsilon_0 c}\left[\sum_1^\infty \left(\frac{\cos\theta - \beta_\parallel}{\sin\theta}\right)^2 J_m^2(x) + \beta_\perp^2 J_m'^2(x)\right]\delta(y) \tag{2}$$

where $x = \omega/\omega_0\beta_\perp \sin\theta$, $y = m\omega_0 - \omega(1 - \beta_\parallel \cos\theta)$, and $\omega_0 = |e|\, B_0/\gamma m$. In equation (2), the first term in the sum over $m$ is the contribution of the ordinary wave (electric field vector oriented along $\mathbf{B}_0$); the second term is associated with the extraordinary wave (electric field vector polarized perpendicular to $\mathbf{B}_0$). The ordinary wave contribution is negligible for mildly relativistic particles, and will not be considered here. (There is thus a net polarization of the radiation from one filament, though for a large number of filaments with varied orientations, the polarization should be random).

Note that, for a general electron distribution function $f(p_{\parallel}, p_{\perp})$, the absorption coefficient $\alpha_\omega$ in equation (1) can be negative. In this case, the wave is amplified, and a maser-like amplification of the synchrotron radiation can occur (Hirshfield & Bekefi 1963). This phenomenon appears to have first been applied to cosmic radio sources by Zhelezynyakov (1966). The amplification of synchrotron radiation by current filaments associated with double layers may be one possible source of the cosmic maser observations (Moran 1984) in the universe. The pump mechanism of these luminous extragalactic sources in such galaxies as NGC4258 (Claussen *et al.* 1984) are not yet understood; it is believed to be due to masing phenomena in newly-formed stars. However, even the most efficient pump cycles do not appear to account for the extreme luminosities observed. A more recent pump model (Strelnitskij 1984) does explain luminosities of $10^2 L_\odot$ but seems to require about a hundred newly-formed stars within a volume of dimension 2 pc.

Knowledge of the absorption coefficient $\alpha_\omega$ allows one to calulate the effect of self-absorption on the emission spectrum. Whereas the radiation spectrum of a single electron spiraling along a magnetic field is a set of descrete lines at $\omega = m\omega_0$ (the lines are typically broadened by the relativistic change in mass and other phenomena), a plasma with a distribution of particles will have a nondiscrete spectrum (figure 4). For the purposes of the calculation here we make the following assumptions: The plasma is a homogeneous slab of thickness $L$ with an isotropic distribution function. There is a static uniform axial magnetic field of strength $B_0$ parallel to the faces of the slab. All other magnetic field components are neglected. The azimuthal magnetic field is neglected. For simplicity, we compute the radiation intensity $I$ at right angles to $B_0$. In the absence of reflections at the plasma boundary, the radiation intensity is given by

$$\frac{dI}{ds} = -\alpha_\omega (I - S_\omega) \tag{3}$$

where $s$ is the coordinate along the direction of propagation to the observer. The source function is defined by $S_\omega = j_\omega / n_r^2 \times \alpha_\omega$, where

$$j_\omega = \int \eta_\omega(\bar{p}) f(\bar{p}) d^3\bar{p} \tag{4}$$

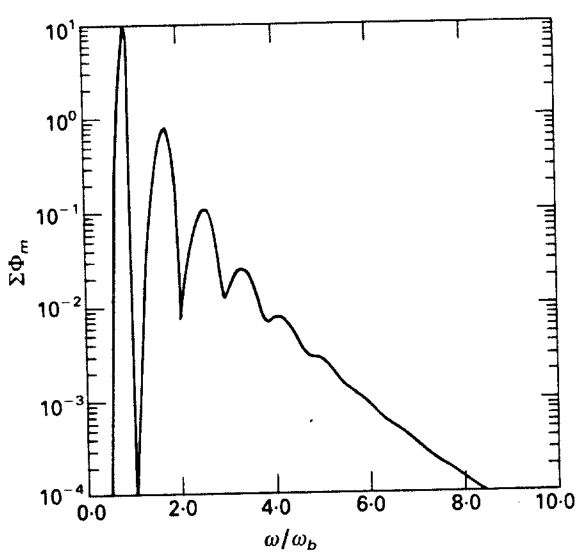


FIGURE 4. Calculated spectrum of radiation emitted by a plasma with electron temperature of 30 keV. Self-absorption effects are included.

and $n_r$ is the refractive index of the plasma. For $\omega \gg \omega_p$, the index of refraction can be taken to be unity. If the electron distribution function is Maxwellian, the source function $S_\omega$ is the blackbody intensity $B_0(\omega, t) = \hbar\, \omega^3/8\pi^3c^2[\exp(\hbar\, \omega/kT) - 1]$, which in the classical limit reduces to the Rayleigh-Jeans relation,

$$S_\omega = \frac{\omega^2}{8\pi^3c^2} kT \tag{5}$$

In the absence of thermal equilibrium, the radiation temperature is not equal to the electron temperature, the above relation can be taken to define the radiation temperature (Bekefi 1966).

Integrating equation (3) and applying the initial condition $I(s = 0) = 0$ we obtain

$$I_1 = S_\omega(1 - \exp(-\alpha_\omega L)) \tag{6}$$

where $I_1$ is the intensity for one filament. If there are now two Birkeland filaments a distance $\delta$ apart (figure 5) the radiation intensity seen by an observer from equation (3) is

$$I_2 = S_\omega[1 - \exp(-2\alpha_\omega L)]. \tag{7}$$

We have used the initial conditions for the second filament $I_2(s = L + \delta) = I_1$. Similarly, for $M$ filaments a distance $\delta$ apart, the radiation intensity can be shown to be equal to

$$I_M = S_\omega[1 - \exp(-M\alpha_\omega L)] \tag{8}$$

Note that the radiation intensity increased for larger $M$ because of each additional Birkeland current source. The parameter $\tau = M\alpha_\omega L$ can be identified as the optical depth of the system of $M$ currents. When $\tau \gg 1$ the observer sees a blackbody spectrum (if the current filament is in thermal equilibrium, which we assume); that is, $S_\omega$ is given by equation (5). When $\tau \ll 1$, the optically thin spectrum of the particle distribution $f(\bar{p})$ is observed, determined by equation (4).

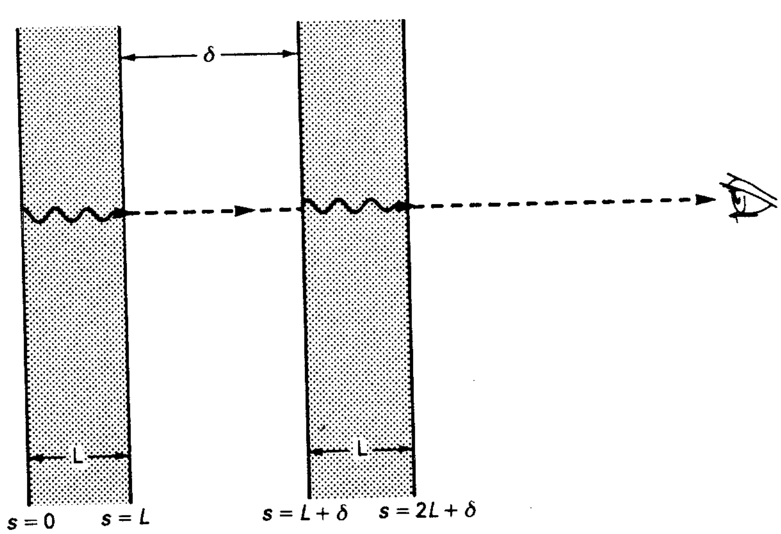


FIGURE 5. Radiation intensity seen by an observer through two successive Birkeland currents of width $L$ and distance $\delta$ apart.

The problem is thus reduced to determining the optical depth of each galactic filament. A relativistic Maxwellian distribution function for electrons of the form

$$f(p)=\frac{1}{4\pi(kT)(m_0c^2)K_2(m_0c^2/kT)}\exp(-\epsilon/kT), \tag{9}$$

is assumed, where $K_2(x)$ is the modified Hankel function of second order. The absorption coefficient now reduces to its isotropic particle distribution form (Trubnikov, 1958),

$$\alpha_\omega=-\frac{8\pi^3c^2}{\omega^2}n\int\eta_\omega(p)\frac{\partial f(p)}{\partial\epsilon}d^3p. \tag{10}$$

Substituting equations (2) and (9) into equation (10), and approximating $m_0c^2 \gg kT$, the absorption coefficient at $\theta=\pi/2$ can be derived to be (Trubnikov 1958)

$$\alpha_\omega=\frac{\omega_p^2}{\omega_b c}\sum_m\Phi_m(x,\mu) \tag{11}$$

The quantities $\Phi_m=\Phi_m(x,\mu)$ are defined by

$$\Phi_m=\sqrt{2\pi}\frac{\mu^{5/2}}{x^4}m^2\sqrt{m^2-x^2}\,e^{-\mu(m/x-1)}A_m\left(\frac{m}{x}\right) \tag{12}$$

and we have used the notation of Bekefi (1966) where $\mu=m_0c^2/kT$, $x=\omega/\omega_b$, and $\omega_b=eB_0/m_0$. The quantities $A_n=A_n(\gamma)$ are given by

$$\begin{aligned} A_n(\gamma)&=\frac{(m\beta)^{2m}}{(2m+1)!}\quad\text{if}\quad m\beta\ll 1\\ A_n(\gamma)&=\frac{e^{2m/\gamma}}{\sqrt{16\pi m^3\gamma}}\left(\frac{\gamma-1}{\gamma+1}\right)^m\quad\text{if}\quad\gamma^3\ll m\end{aligned} \tag{13}$$

for nonrelativitic and mildly relativistic energies, respectively.

The optical depth for $M$ Birkeland currents is $\tau=\alpha_\omega ML$ or

$$\tau=\left(\frac{\omega_p^2LM}{\omega_b c}\right)\sum_m\Phi_m \tag{14}$$

The quantity $\omega_b$ corresponds to the nonrelativistic electron gyrofrequency and $\omega_p$ is the plasma frequency.

Summing the first one-hundred terms of the infinite series for $\Phi_m$ numerically yields the curve shown in figure 4. To determine $M$ to make the spectrum blackbody up to a frequency of 100 GHz (the highest measured frequency of cosmic blackbody radiation observations) it is convenient to use the approximate scaling formula (Bekefi 1966)

$$(m^*)^6=0{\cdot}57\left(\frac{20}{3}\frac{\omega_p^2}{\omega_b c}\right)LMT \tag{15}$$

where $m^*=\omega^*/\omega_b$ is the harmonic below which the frequency spectrum is blackbody. In figure 6 we plot the number of filaments of plasma density $n_e$ required to produce a blackbody spectrum up to 100 GHz versus magnetic field. For example, for $B_0=2\times10^{-4}\,G$, one finds $m^*=1{\cdot}8\times10^8$. Hence, the number of Birkeland filaments is $M=3{\cdot}4\times10^{31}$. Calculations for electrons with strongly relativistic energies do not differ significantly from these results.

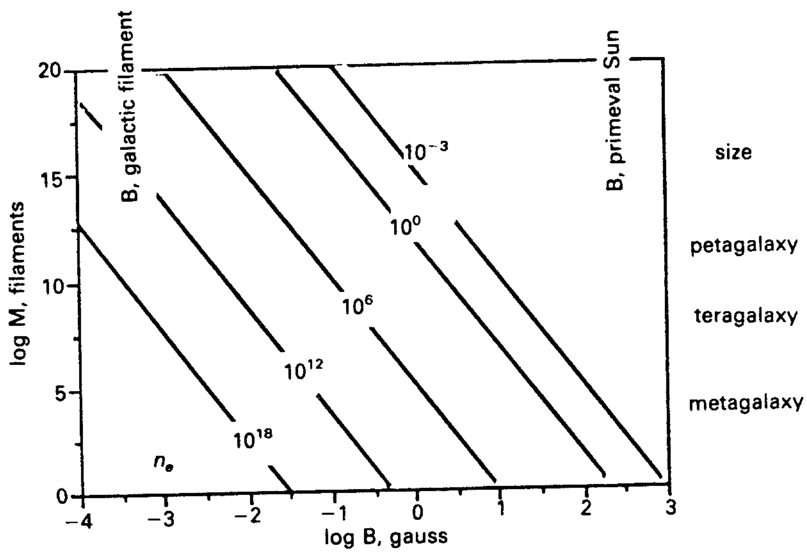


FIGURE 6. Number of filaments containing plasmas of density $n_e$ cm$^{-3}$ required to produce a blackbody spectrum to 100 GHz versus magnetic field. The graph pertains to mildly relativistic electron temperatures. The width of each galactic filament is $10^{23}$ cm. The right-hand scale denotes the size of the universe required to isotropize synchrotron radiation. The top scale denotes magnetic field magnitudes typical of cosmic objects.

## 3. Discussion

The results obtained in the preceeding section depend upon a specific form for the electron distribution function, and on specifically assumed values for the magnetic field and filament parameters. From equation (15), the thermalization of the synchrotron radiation depends on the magnetic field strength, the plasma density, electron temperature, and filament width. However, for a non-Maxwellian distribution, the functional dependence on these parameters may be different. A more appropriate distribution function for a mildly relativistic electron beam ($\gamma^2\beta^2 \ll 1$) is the bi-Maxwellian distribution function discussed by Sudan (1965).

$$f(p_{\parallel}, p_{\perp}) = n(\pi\alpha_{\perp})^{-1}(\pi\alpha_{\parallel})^{-1/2} \exp\left(-p_{\perp}^2/\alpha_{\perp} - p_{\parallel}^2/\alpha_{\parallel}\right) \tag{16}$$

where $\alpha_{\parallel}$ and $\alpha_{\perp}$ are related to the parallel and perpendicular electron temperatures $T_{\parallel}$ and $T_{\perp}$. This is a convenient form for $f(p)$ since it easily reduces to a Maxwellian or a delta function distribution under certain conditions. The temperature anisotropy can be determined from particle-in-cell simulations which we have conducted. These indicate that the particles are cold in the perpendicular and warm in the parallel direction. Hence, there is no equilibrium. The radiation temperature $T_r$ is not necessarily equal to either the parallel or perpendicular electron temperatures and Kirchoff's radiation law is not applicable (Bekefi *et al.* 1961). In this case, the absorption coefficient can be derived from a formula which replaces Kirchoff's law for an anisotropic Maxwellian, as was done by Trubnikov and Yakubov (1963).

The large number of filaments required to thermalize the synchrotron radiation into a blackbody spectrum up to the observed frequency of 100 GHz suggests that this process is inconsistent with a finite universe of Hubble radius dimensions. However, it appears to be consistent with the large-universe metagalaxy theories of Alfvén (1981). It is unclear if effects such as magnetoactivity or plasma refractivity can decrease the number of current filaments needs to thermalize the synchrotron radiation. It is also not obvious that the presence of such a large number of intergalactic structures are consistent with other astrophysical observations and measurements. These questions, and a more rigorous calculation of the emission spectrum including a non-Maxwellian distribution function and the effects of a thermal background plasma (Crusius 1987), are currently being considered.

In conclusion, three-dimensional particle-in-cell simulations of two interacting galactic-sized Birkeland currents predict a burst of synchrotron radiation very early in galactic formation time (Peratt 1986b). The energy density of this burst is measured to be $1{\cdot}2\times10^{-13}$ erg/cm$^3$ in the simulations, which compares with the cosmic radiation background of $1{\cdot}5\times10^{-13}$ erg/cm$^3$. Thermalization of the synchrotron radiation by filament self-absorption has been calculated to give a blackbody spectrum up to 100 GHz if a large number ($>10^{31}$) of filaments exist within the observational line-of-sight.

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