A MECHANISM FOR PRODUCING PLASMA RADIATION IN THE GIGAHERTZ RANGE BY PRECIPITATING HIGH-ENERGY PROTONS

D. F. SMITH

Berkeley Research Associates and Department of Astrophysical, Planetary and Atmospheric Sciences, University of Colorado, Boulder, CO 80306 U.S.A.

and

A. O. BENZ

Institute of Astronomy, ETH, 8092 Zürich, Switzerland

(Received 27 August, 1990)

Abstract. Gamma-ray observations are discussed to determine the density of protons of about 1 MeV precipitating to the photosphere. It is shown that Coulomb collisions will produce a positive slope in the proton distribution for energies less than 0.1 MeV for traversed column depths greater than $10^{18}$ cm$^{-2}$. This could lead to plasma wave emission and radiation near the plasma frequency for densities $\sim 3.1 \times 10^{10}$ cm$^{-3}$ and temperatures $\sim 4.0 \times 10^4$ K where collisional and collisionless damping of the plasma waves is sufficiently weak. It is expected that these conditions will only be satisfied sporadically which leads to stationary radio emission limited in frequency and time. Recent radio observations of impulsive phase non-drifting patches in the 1–3 GHz range with duration 2–4 s are presented which could be produced by this mechanism.

1. Introduction

Recent observation made with the Phoenix spectrometer at Zürich now operating from 0.1 to 3 GHz have shown sporadic 3–4 s wide features without drift in the microwave band. The corresponding densities for emission at the plasma frequency $\omega_{pe}$ are $1.6 \times 10^{10} - 10^{11}$ cm$^{-3}$. While emission at such frequencies is usually interpreted as gyrosynchrotron emission or some electron instability, we consider an alternate possibility. The implications from $\gamma$-ray observations for the number of protons with energies greater than 1 MeV that must be involved are reviewed. These protons are known to have a monotonically decreasing distribution function of Bessel form in interplanetary space (Ramaty and Murphy, 1987; hereafter referred too as RM).

However, most of these protons are trapped in loops at the Sun and produce $\gamma$-rays by nuclear interactions in the photosphere (RM). In traversing the atmosphere between their acceleration site, presumed here to be the corona, and the photosphere the proton distribution changes for at least three reasons. A fairly moderate proton density and anisotropy will lead to the excitation of Alfvén waves which will make the distribution almost isotropic (Melrose, 1980). An increasing magnetic field strength $B$ will cause any initial angular distribution to broaden as the protons descend. Coulomb collisions will preferentially scatter the slower protons and form a beam from an initially monotonically decreasing distribution in the same manner as in Emslie and Smith (1984). Some of the

details are different for protons in comparison to electrons, but the basic physics is the same.

For simplicity we consider only the last possibility since this is a case that has not yet been studied in the literature. We discuss in detail the restriction that this places on the applicability of the results in Section 5. It turns out that the most likely place for excitation of electron plasma waves near $\omega_{pe}$ is the upper transition region (TR) where Alfvén waves are already heavily damped by ion–ion damping. As shown by Hénoux et al. (1990), Coulomb collisions also restore directivity to a proton distribution which tends to offset the effect of increasing $B$. Finally, the results of Emslie and Smith (1984) have been criticized by McClements (1989) who showed that density variations or reverse currents would change their results considerably. Because of the lower densities and velocities of protons, none of these objections are important for protons in the 0.01–1 MeV energy range.

Thus our aim is to investigate the following possibility. Is it possible for the same protons which cause $\gamma$-ray bursts or their low-energy extension to develop a region of positive slope in their distribution by their transport to the photosphere which could excite electron plasma waves? These plasma waves would convert by well-known processes (Smith, 1974; Melrose, 1980) to produce radiation in the gigahertz range. The electron plasma waves which we designate as $l$ waves are also subject to collisional damping at a rate (Lang, 1974)

$$v_e = 3.6n_iT_e^{-3/2} \ln A,$$

where $n_i$ is the ion density, $T_e$ is the electron temperature, and $\ln A$ is the Coulomb logarithm (Lang, 1974) where

$$A = \begin{cases} 
3.0 \times 10^6 T_e n_e^{-1/2}, & T_e \geq 3.6 \times 10^5 \text{ K}, \\
3.1 \times 10^3 T_e^{3/2} n_e^{-1/2}, & T_e < 3.6 \times 10^5 \text{ K},
\end{cases}$$

and $n_e$ is the electron density. Clearly for the $l$ waves to grow to a significant level, their growth rate must exceed the damping rate.

In Section 2 we present the radio observations and review the $\gamma$-ray observations and their implications. In Sections 3 the theory of propagation of protons in the presence of Coulomb collisions is discussed. In Section 4 we consider possible regions where $l$ waves could be excited and the resulting radiation. In Section 5 the limitations of our analysis and directions for further research are discussed.

## 2. Observations

We begin with the radio observations that motivated our analysis and then consider the $\gamma$-ray observations.

### 2.1. Radio Observations

The new frequency-agile radio spectrometer PHOENIX of the Institute of Astronomy of ETH in Zürich is ideally suited to survey a broad range of frequencies of solar flare
emission with high spectral resolution. It has completed an observing run in the 6–8 GHz range (in cooperation with the University of Berne) and is currently observing the 1–3 GHz region. It is the first time these spectral bands have been spectrally observed at high resolution and digitally recorded. A detailed description of the instrument and first results can be found in Benz et al. (1991).

A very frequent type of emission noted in the 1–3 GHz microwaves are relatively narrow-band patches. A typical example is shown in Figure 1. The diffuse emissions have half-power widths of 2–4 s and 400–500 MHz. They occurred during a GOES C1.9 flare and had flux densities between 20 and 50 s.f.u. A similar feature has been reported at 7 GHz by Bruggmann et al. (1990). These patches show no drift in the frequency-time plane and typically last more than an order of magnitude longer than type III bursts at the same frequencies.

2.2. Gamma-ray observations

Gamma-ray observations have been reviewed by Chupp (1984, 1987) and their implications have been reviewed by Ramaty (1986) and RM. Protons of energy > 10 MeV
descending a loop excite nuclear levels in the low chromosphere and photosphere. The de-excitations of these levels lead to $\gamma$-ray lines. This nuclear $\gamma$-ray component is dominant in the 4–7 MeV range. The protons also produce neutrons by $p - p$, $p - \alpha$, and $\alpha - \alpha$ interactions. The neutrons propagate diffusively in the photosphere and about 100 s later are captured on H which produces the 2.223 MeV $\gamma$-ray line.

Interplanetary protons distributions from $\sim 1$ to 400 MeV fit the Bessel function form

$$f(E) \sim I_2(x_0)K_2(x),$$

where $x = (12p/m_p c zT)^{1/2}$, $p$ is the proton momentum, $m_p$ is the proton mass, and $zT$ is a measure of the hardness of the distribution with a larger $zT$ corresponding to a harder distribution. $I_2$ and $K_2$ are modified Bessel functions. Assuming that this form also characterizes the protons in the lower chromosphere and using the $\gamma$-ray fluences from 4–7 MeV and at 2.223 MeV, Ramaty (1986) derived $zT$ and the energy $W$ ($> 1$ MeV) for several flares using Monte-Carlo simulations. His results are presented in Table 3 (see also Hua and Lingenfelter, 1987). We shall use as an example the 1980 June 7 flare which has a $zT = 0.021 \pm 0.003$ and $W (> 1$ MeV) $= 2 \times 10^{29}$ erg.

The $\gamma$-ray emission in the 1980 June 7 flare lasted 50 s so that the average energy going into protons above 1 MeV was $4 \times 10^{27}$ erg s$^{-1}$. To find a proton beam density $n_p$ we can equate this release rate to $\frac{1}{2}n_p m_p v^3 A$, where $v$ is the photon velocity and $A$ is the area of the coronal loop in which the protons are traveling along field lines. Since for $zT = 0.03$ the proton distribution above 1 MeV is fairly steep (Figure 1 of RM, we can use $v = 1.4 \times 10^9$ cm s$^{-1}$ corresponding to 1 MeV for an estimate and with $A = 2.9 \times 10^{17}$ cm$^2$ corresponding to a loop radius of $3 \times 10^8$ cm, $n_p = 6.3 \times 10^6$ cm$^{-3}$. Because of the $v^3$ dependence, even a slight increase in $v$ lowers $n_p$ considerably so that we shall consider $n_p$ in the range $10^7$–$10^8$ cm$^{-3}$ for $v = 4.5 \times 10^8$ cm s$^{-1}$.

It is useful to compare the energy density $W_p$ in such a proton beam with the thermal energy density $W_T = \frac{3}{2}(n_i + n_e)kT_e$ in the plasma. For $n_p = 3.2 \times 10^7$ cm$^{-3}$ and $v = 4.5 \times 10^8$ cm s$^{-1}$ corresponding to 0.1 MeV, $W_p = 5.2$ erg cm$^{-3}$. For $n_i = n_e = 3.2 \times 10^{10}$ cm$^{-3}$ and $T_e = 10^5$ K, $W_T = 1.3$ erg cm$^{-3}$. Thus $W_p$ and $W_T$ are comparable and it should be possible to excite plasma waves of energy density $W_i \ll W_T$ with a negligible amount of energy from the protons.

3 Proton Propagation with Coulomb Collisions

Our analysis follows the one of Emslie and Smith (1984) with appropriate changes for a proton beam. We consider protons injected downward along the magnetic field of a loop which traverse a column depth $N$. The protons initially have a power-law energy flux spectrum,

$$F_0(E_0) = AE_0^{-\delta} \text{protons cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}.$$

In the range of interest around 1 MeV, $\delta = 1$ is a good approximation to the Bessel function distribution (3) with $zT = 0.03$ (cf. Figure 1 of RM). We consider the evolution of beam flux with depth allowing for scattering effects. Let $F(E)$ denote the component
of the proton flux along the field with values at injection denoted by the subscript zero. By continuity we have

$$F(E) \, dE = F_0(E_0) \, dE_0 .$$  \hfill (5)

Considering the effects of Coulomb collisions on energy alone, $E$ and $E_0$ are related by (Emslie, 1978)

$$E = E_0 \left(1 - \frac{2m_pKN}{\mu_0m_eE_0^2} \right)^{1/2} = E_0 \left(1 - \frac{\kappa N}{E_0^2} \right)^{1/2} ,$$  \hfill (6)

where $\mu_0$ is the cosine of the initial pitch angle which we set equal to zero ($\mu_0 = 1$), $K = 2\pi e^4 \ln \Lambda$ and $\kappa = 4\pi e^4m_p \ln \Lambda/m_e$.

Substitution of Equation (6) into Equation (5) leads to

$$F(E) = \frac{F_0(E_0)}{\left(1 + \frac{\kappa N}{E_0^2} \right)^{1/2}} ,$$  \hfill (7)

where $E_0(E)$ is the solution of the equation

$$E_0^2 = E^2 + \kappa N .$$  \hfill (8)

The proton beam’s phase-space distribution $f_b(v)$ (protons cm$^{-3}$ [cm s$^{-1}$]$^{-1}$, one-dimensional distribution) follows from

$$\nu f_b[v(E)] \, dv = F(E) \, dE ,$$  \hfill (9)

so that

$$f_b(v) = \frac{m_p}{\{1 - [v(E)/c]^2\}^{3/2}} \, F(E) .$$  \hfill (10)

Figure 2 shows the form of $f_b[v(E)]$ for different values of $N$ corresponding to an injected flux distribution

$$F_0(E_0) = 9.8 \times 10^9 \, E_0^{-1} \text{protons cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} ,$$  \hfill (11)

which leads to a beam density $n_p = 3.2 \times 10^7$ cm$^{-3}$ above 0.1 MeV. One immediately sees that the effect of collisions is more pronounced on the lower energy protons since the collisional cross-section is proportional to $E^{-2}$ (Spitzer, 1962). Thus an injected distribution that is a monotonically decreasing function of energy develops a positive slope at finite depths in the atmospheric target. By beam in this paper we mean a hump in $f(v)$ parallel to the magnetic field $\mathbf{B}$ with the distribution integrated over $v$ components perpendicular to $\mathbf{B}$. It is well known (Ch. 10 of Krall and Trivelpiece, 1973) that this is a sufficient condition for excitation of electron plasma ($l$) waves. Arguments and references are given as in Emslie and Smith (1984) to justify our neglect of dispersion in both energy and pitch angle; the main point is that a full Fokker–Planck treatment

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System
Fig. 2. Distribution function $f_b[v(E)]$ for the component of the proton velocity along the field for various values of $N$, the column depth (cm$^{-2}$) into the target.

of the problem yields remarkably similar results. In the same way the presence and location of a positive slope in $f_b(E)$ is insensitive to the form of $F_0(E_0)$ chosen since it is determined by the form of the collision cross-section (cf. Equation (7) here and Equation (10) of Emslie and Smith (1984)).

Thus we proceed to use the curves in Figure 2. One notes that for $N \leq 10^{18}$ cm$^{-2}$, the positive slope begins below 0.1 MeV and that the hump is relatively symmetric about 0.1 MeV. Hence, the beam density below 0.1 MeV relevant for $l$ wave excitation is about the same as above 0.1 MeV, namely $n_p = 3.2 \times 10^7$ cm$^{-3}$. It is also a simple matter to find the form of $f_b(v)$ completely in terms of $v$ since we note that for $KN \gg E^2$, $F(E) \sim E$ from Equation (7). Using this fact and normalizing using

$$n_p = \frac{1}{2} \int_{v_1}^{v_2} f_b(v) \, dv, \quad (12)$$

where $v_1 = 4.5 \times 10^8$ cm s$^{-1}$ corresponds to the energy (0.1 MeV) of the hump for
\[ N = 10^{18} \text{ cm}^{-2} \] and \( v_e \) is the electron thermal velocity, one finds
\[ f_b(v) = 5.4 \times 10^{-19} v^2 \text{ protons cm}^{-3} (\text{ cm s}^{-1})^{-1}. \] (13)

We shall use this form of \( f_b(v) \) in the next section to evaluate the possibility of amplifying \( l \) waves.

4. Plasma Wave Excitation and Emission from Proton Beams

Using Chapter 10 of Krall and Trivelpiece (1983), we derive the following formula for the growth rate of \( l \) waves by a proton beam:
\[ \gamma_l = \frac{\pi}{2} \frac{\omega_{pi}}{n_i} \frac{v_b^2}{v_e^3} \frac{\partial f_b}{\partial v} \bigg|_{v = \omega_{pe}/k}, \] (14)

where \( \omega_{pi} = (m_e/m_i)^{1/2} \omega_{pe} \) is the ion plasma frequency, \( v_b \) is the beam velocity, and \( k \) is the wave number of the excited \( l \) wave. One notes that Equation (14) is a factor \( (m_e/m_i)^{1/2} \) smaller than the growth rate for an electron beam (cf. Equation (10.4.2) of Krall and Trivelpiece (1973)). There is another requirement for amplification,
\[ \gamma_l > v_L = 0.14 \frac{\omega_{pe}^4}{k^3 v_e^3} \exp \left( -\frac{\omega_{pe}^2}{2k v_e^2} \right) \bigg|_{\omega_{pe}/k = v_b} = \]
\[ = 0.14 \omega_{pe} \frac{v_b}{v_e^3} \exp \left( -\frac{v_b^2}{2v_e^2} \right), \] (15)

where \( v_L \) is the collisionless Landau damping rate by the electrons of the background plasma (Schmidt, 1966).

The last requirement for effective growth of \( l \) waves is that \( \gamma_l > v_e \), i.e., that the growth rate be larger than the collisional damping rate of Equation (1). Differentiating Equation (13) and substituting it into Equation (14) with \( v_b = 4.1 \times 10^8 \text{ cm s}^{-1} \) corresponding to \( E_b = 0.09 \text{ MeV} \) which is on the straight portion of the positive slope of Figure 1 for \( N = 10^{18} \text{ cm}^{-2} \), we find for \( n_b = 3.2 \times 10^7 \text{ cm}^{-3} \),
\[ \gamma_l = 7.6 \times 10^{10} n_i^{-1/2} \text{ s}^{-1}. \] (16)

The well-known relation \( \omega_{pi} = 1.3 \times 10^3 n_i^{1/2} \) was used in deriving Equation (16). In Table I we present values of \( v_e, v_L, \) and \( \gamma_l \) for various values of \( n_i, T_e, \) and \( n_b \) which are the most likely regime for \( l \) wave excitation by proton beams. It is of course implicit in Table I that the protons have traversed \( N = 10^{18} \text{ cm}^{-2} \) of material. The values of \( n_i \) and \( T_e \) could only occur in the upper TR of an active region and probably only sporadically.

It can be seen from Table I that for sufficiently low \( T_e \) and or low \( n_i \) it is possible to have \( \gamma_l > (v_e + v_L) \) with sizeable net \( (\gamma_l - v_e - v_L) \) growth rates. For example, for \( n_i = 3.2 \times 10^{10} \text{ cm}^{-3} \) which would lead to radiation at 1.6 GHz with \( T_e = 4.0 \times 10^4 \text{ K} \) and \( n_b = 3.2 \times 10^7 \text{ cm}^{-3} \), \( \gamma_l - v_e - v_L = 8.0 \times 10^4 \text{ s}^{-1} \). Thus 20-e folds requires a time of \( 2.5 \times 10^{-4} \text{ s} \) during which time \( l \) waves could grow up to a highly nonthermal level.
### TABLE I

<table>
<thead>
<tr>
<th>log(n_i)</th>
<th>log(T_e)</th>
<th>log(n_b)</th>
<th>(\gamma_l (s^{-1}))</th>
<th>(v_e (s^{-1}))</th>
<th>(v_L (s^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>4.9</td>
<td>7.0</td>
<td>2.4E+5</td>
<td>2.2E+4</td>
<td>4.1E+7</td>
</tr>
<tr>
<td>10</td>
<td>4.6</td>
<td>7.5</td>
<td>7.6E+5</td>
<td>5.6E+4</td>
<td>1.1E+5</td>
</tr>
<tr>
<td>10</td>
<td>4.3</td>
<td>8.0</td>
<td>1.5E+6</td>
<td>1.5E+5</td>
<td>4.0E-1</td>
</tr>
<tr>
<td>10.5</td>
<td>4.9</td>
<td>7.0</td>
<td>1.3E+5</td>
<td>7.0E+4</td>
<td>7.3E+7</td>
</tr>
<tr>
<td>10.5</td>
<td>4.6</td>
<td>7.5</td>
<td>4.3E+5</td>
<td>1.7E+5</td>
<td>1.8E+5</td>
</tr>
<tr>
<td>10.5</td>
<td>4.3</td>
<td>8.0</td>
<td>9.4E+5</td>
<td>4.7E+5</td>
<td>7.1E-1</td>
</tr>
<tr>
<td>11</td>
<td>4.9</td>
<td>7.0</td>
<td>7.5E+4</td>
<td>2.2E+5</td>
<td>4.1E+8</td>
</tr>
<tr>
<td>11</td>
<td>4.6</td>
<td>7.5</td>
<td>2.4E+5</td>
<td>5.6E+5</td>
<td>1.1E+5</td>
</tr>
<tr>
<td>11</td>
<td>4.3</td>
<td>8.0</td>
<td>4.7E+5</td>
<td>1.5E+6</td>
<td>4.0E+0</td>
</tr>
</tbody>
</table>

The protons would only travel 1.0 km during this time and only extremely sharp density inhomogeneities could reduce the growth of \(l\) waves (McClements, 1989). The fact that the growth rate (14) is \((m_e/m_i)^{1/2}\) times smaller than for an electron beam is of no consequence since the net growth rate is still quite large. It is easy to see from Table I that condition (15) is well satisfied.

It should be emphasized that although there is considerable leeway in our estimates, we do not expect the conditions for \(l\)-wave growth by proton beams to be satisfied continuously. The number of flares with \(\gamma\)-ray emission is already relatively small. Of these flares, those that manage to have a column density of \(\gtrsim 10^{17} \text{ cm}^{-2}\) between the source of the protons and a relatively hot dense region may be even smaller. On the other hand, because less than 0.1 MeV protons are required, there could be a significant number of flares which produce no \(\gamma\)-ray emission, but which amplify \(l\) waves with proton beams. The condition for proton beam radio emission is that the beam (peak) velocity exceeds about 3 times the mean thermal electron speed. The beam only forms in an ionized gas.

This means for solar conditions that a beam energy of about 3 keV must be formed before the protons reach a region with a temperature below \(10^4 \text{ K}\). Figure 2 indicates that the protons must traverse a column depth of at least \(10^{17} \text{ cm}^{-2}\) to form a beam at \(> 3 \text{ keV}\) before reaching this level.

Models of the transition region can now be used to test whether the required column depth can be achieved between the acceleration region and the \(10^4 \text{ K}\) level. Models of Lantos (1972, radio observations) and of Vernazza et al. (1981, UV observations) for the quiet Sun yield \(8 \times 10^{16} \text{ cm}^{-2}\) and \(4 \times 10^{17} \text{ cm}^{-2}\), respectively, between the low density \((10^9 \text{ cm}^{-3})\) corona and the \(10^4 \text{ K}\) altitude assuming vertical propagation. The electron density at this height is \(4.5 \times 10^{10} \text{ cm}^{-3}\) corresponding to a plasma frequency of 1.9 GHz.

Active region models may be more relevant. In the transition region model of plages by Basri et al. (1979) the column depth reaches \(6 \times 10^{18} \text{ cm}^{-2}\) at a density of \(6.2 \times 10^{11} \text{ cm}^{-3}\) \((v_p = 7 \text{ GHz})\). Instability of a proton beam is thus predicted to occur already above this level suggesting the above model parameters of a column depth of.
10^{18} \text{ cm}^{-2}, \ T = 4 \times 10^4 \text{ K}, \text{ and } n = 3.2 \times 10^{10} \text{ cm}^{-3} \text{ yielding emission at 1.6 GHz. Flare-heated transition regions reach a column depth of } 9 \times 10^{18} \text{ cm}^{-2} \text{ (Machado et al., 1980, model F2). However, the region of instability moves to higher densities yielding radio emission at frequencies exceeding } 5 \text{ GHz (model F1) or } 15 \text{ GHz (model F2). Free-free absorption severely reduces plasma emissions at such frequencies (e.g., Bruggmann et al., 1990). We conclude that this model predicts observable proton beam emissions from the transition region above plages for the 1–3 GHz range and the flare heated transition region for much reduced emissions above 3 GHz.}

Once there is a significant nonthermal level of l-waves, it is a straightforward matter to produce radiation by the scattering process (Smith, 1974)

\[ l + i \rightarrow t + i', \]

where \( t \) is a transverse electromagnetic wave near \( \omega_{pe} \) and \( i \) and \( i' \) are the polarization cloud of an ion before and after the scattering, respectively. Alternatively, \( l \) waves may couple to low-frequency waves (or other \( l \)-waves) to radiate (at the harmonic), or emit radiation by effects of strong turbulence. For a concrete mechanism for saturating the \( l \) wave instability at an energy density in plasma waves \( W_c \), we take the conservative strong turbulence estimate of Galeev et al. (1977; see discussion in Emslie and Smith (1984)) so that

\[ \frac{W_c}{n_e k T_e} \simeq 3 \frac{n_i}{\omega_{pe}}. \]

Using Table I for \( \log n_i = 10.5, \log T_e = 4.6 \), and \( \log n_e = 7.5 \), we find from Equation (18) that \( W_c/n_e k T_e = 1.3 \times 10^{-4} \) in comparison to the \( W_p/n_e k T_e = 2.5 \times 10^{-4} \) used in Smith and Emslie (1984) for their radiation calculations which led to a harmonic flux of \( 3.2 \times 10^3 \) s.f.u. (their Equation (51)). Thus the expected harmonic flux in our case would be \( 1.7 \times 10^3 \) s.f.u. which could be very easily detected at about 3.1 GHz. We note that because of the increase of \( \lesssim m_p/m_e \) in energy per particle, quasi-linear relaxation will be \( \lesssim m_e/m_p \) times slower than for electrons and other processes associated with density and/or magnetic field inhomogeneities may play an equally important role. However, there is no reason in principle why radiation near \( \omega_{pe} \) or its harmonic with a high \( T_B \) could not be produced and, considering the large density gradients present, escape from the source.

5. Discussion

We have presented a simplified analysis of a possibly important mechanism for producing gigahertz plasma radiation in order to elucidate the basic physics. It is now necessary to consider the limitations of our analysis. First of all we derived beam fluxes on the basis of the analysis of Ramaty (1986) which assumes a Bessel function proton distribution all the way to the photosphere. It was shown that Coulomb collisions will modify the low energy part of this distribution. The really important parameter
here is the energy flux of the beam, $\frac{1}{2}n_b m_p v^3$, which equals $2.3 \times 10^9$ erg cm$^{-2}$ s$^{-1}$ for $n_b = 3.2 \times 10^7$ cm$^{-3}$ and $v = 4.5 \times 10^9$ cm s$^{-1}$ corresponding to 0.1 MeV. While this is below the range of energy fluxes of electron beams considered relevant in thick target models, it should be kept in mind that each proton carries $10^2$ times more energy than a corresponding electron so that reverse current and other problems are eased considerably. This fact together with the above maximum beam energy flux implies that there is no problem with distorting the low energy part of the Bessel function distribution which has not been observed.

We noted that Alfvén waves could be excited (Melrose, 1980). However, there are cases in which such excitation does not occur (Hénoux et al., 1990; Smith et al., 1990) due to Alfvén wave damping in the upper TR. Since we are only proposing that this mechanism operates in the upper TR, we do not expect Alfvén wave excitation to be a problem.

Finally there is the problem of magnetic field convergence and mirroring. As noted above, it was shown by Hénoux et al. (1990) that collisions also tend to restore anisotropy. The physical mechanism is simple. Those protons with large pitch angles traverse a considerably larger $N$ in going a certain distance along $B$ than those going directly along $B$. Thus the protons with large pitch angles are more rapidly removed by collisions. Whether this effect is sufficient to counteract the effect of increasing $B$ in a converging field is the subject of further research. Again, there are most likely circumstances where the increase in $B$ is sufficiently mild that the above effect will counteract the increase in $B$. It is in just such cases that the analysis presented here applies.

Acknowledgements

This work was supported by the Swiss National Science Foundation Grant 2000–5.499 and by NSF Grant ATM-8909845. We would like to express our gratitude to Prof. Donat Wentzel for many helpful comments.

References


© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System