PLASMA PHYSICS GROUP

N72-31398

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November 1970 R-81

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RELATIVISTIC ELECTRON PRECIPITATION DURING MAGNETIC STORM MAIN PHASE

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ABSTRACT

Relativistic electrons can have cyclotron resonances with electromagnetic ion cyclotron waves. The resonant energy is generally well above 1 MeV throughout the magnetosphere, but it can fall to 1 MeV just within the plasmapause. This also corresponds to the region where ring current (10-50 keV) protons are expected to be strongly unstable. The resulting ion cyclotron wave amplitudes necessary to precipitate ring current protons leads to electron lifetimes near the strong diffusion limit (< 100 sec). Thus, > 1 MeV electrons whose drift orbits intersect the stormtime plasmapause should rapidly be precipitated in the region $3 < L < 5$ during the initial phase of a magnetic storm.

(1) Alfred P. Sloan Faculty Fellow.

1. INTRODUCTION

Early geiger tube measurements of trapped relativistic electrons found pronounced flux depletions in the outer radiation belts during magnetic storms (Forbush et al.,1961, 1962; Rosser, 1963). Somewhat later, this characteristic drop in relativistic electron flux was shown to coincide with a pronounced injection of lower energy particles (Frank et al.,1964; Craven, 1966; Frank, 1966; Owens and Frank, 1968; Van Allen, 1969). This storm-time anticorrelation is typically most pronounced near $L = 4$, where the relativistic electron fluxes can decrease by factors of 10 to 100, coincident with a low energy $E_e \lesssim 1$ MeV electron flux increase by a similar factor.

As an illustration of the relativistic flux dropout we have enlarged in Figure 1 a section of the $E_e > 1.6$ MeV electron flux contours of Owens and Frank (1968). With the onset of a moderate geomagnetic storm, the relativistic electron flux rapidly decreased in the region $3.5 < L < 5$, whereas it remained relatively constant for $L > 5$. A further example of this behavior is shown in Figure 2. Here we have replotted the data of Pfitzer et al. (1966) over a magnetic storm period in September 1964. In Figure 2a the ratio J_{st}/J_q between the main phase (Sept. 29) and pre-storm (Sept. 20) electron fluxes is plotted against L for three energy channels. For $L > 5$, the fluxes at all energies increase by approximately an order of magnitude. However, at lower L values these curves show a striking energy dependence. The lower energy electron flux is considerably enhanced during the storm, whereas the relativistic electrons decrease for $L < 4$ and fall below threshold near $L = 3.5$. The electron "slot", $2 < L < 3.5$, is devoid of relativistic electrons even at quiet-times (Pfitzer et al., 1966) and is therefore not of interest for the present discussion. Figure 2b explicitly shows the energy dependence of the main phase-prestorm flux ratios for three representative medium L-values. Once more we emphasize that between L = 4 and 4.5, the relativistic fluxes above 2 MeV were reduced during the storm, whereas the lower energy electron fluxes increased substantially.

Taking Figures 1 and 2 together, we may abstract the following conclusions: First, the region of relativistic electron loss is spatially localized to medium L-values ($3.5 \lesssim L \lesssim 5$); secondly, the spatial boundary between relativistic electron increases and flux dropouts is quite sharp; and finally in the range $3.5 \lesssim L \lesssim 5$, the energy at which the behavior switches from a storm-time increase to a decrease is near 1 MeV. In this paper, we propose a mechanism for this main phase loss of relativistic electrons. We attempt to explain neither the flux increases at lower energies, nor the post-storm recovery of relativistic electrons exhibited in Figure 1. These latter two effects are related to complexities of the radiation belt source and may be evidence for local energy diffusion (Kennel, 1969) or radial diffusion (Frank, 1965).

The low energy flux increases nevertheless imply a loss mechanism which is selective to high energies. This loss mechanism must be turbulent, since collisions are clearly unimportant. Let us therefore consider the most rapid type of turbulent loss: pitch angle diffusion due to resonant violation of the first adiabatic invariant. We first notice that the relativistic electron fluxes are typically not intense enough to exceed the stability limit for whistler mode emissions (Cornwall, 1965; Kennel and Petschek, 1966). Furthermore, they are reduced to very low values, a behavior inconsistent with the existence of a threshold for self-generated whistler turbulence. Thus, it seems likely that the relativistic electron precipitation is parasitic; in other words, it is driven by waves generated by a different group of particles.

One clue to the source of wave turbulence is given by the region of relativistic electron depletion, $3.5 < L < 5$, which corresponds to the range in L-values over which the plasmapause is detected during magnetic storms (Carpenter, 1966; Gringauz, 1969; Chappell, et al., 1970a) We may therefore ask whether any wave turbulence can be localized near the plasmapause. Because of the pronounced energy dependence exhibited in Figure 2 we immediately rule out whistler mode turbulence generated by lower energy electrons. Recently, Russell and Thorne (1970) demonstrated a strong coincidence between the instantaneous location of the plasmapause (Taylor et al., 1968) and the inner edge of the proton ring current (Frank, 1967). Cornwall et al. (1970a) then pointed out that ring current protons should be highly unstable to ion cyclotron turbulence in the high density region of the plasmasphere. Outer zone fluxes transported into the plasmasphere should thus be rapidly removed, producing the sharp inner edge of the ring current and a localized region of intense ion cyclotron turbulence just within the plasmapause.

We now inquire into the consequences of this localized region of intense ring current generated, ion cyclotron wave turbulence. The parasitic interactions of electrons with ion cyclotron waves have been discussed by Kennel and Wong (1967). When the waves propagate obliquely to the magnetic field, a Landau resonant interaction with electrons of a few eV energy is possible. In a companion paper, Cornwall et al. (1970b) propose that this Landau damping provides a heat flux to the ionosphere sufficient to create an SAR arc. Ion cyclotron waves also have Doppler-shifted cyclotron resonance interactions with electrons in the MeV range. We propose here that the latter interaction is responsible for the spatially localized and energy selective losses of relativistic electrons during magnetic storms. Thus, if this set of ideas is correct, we expect to find a coincident precipitation of ring current protons and relativistic electrons correlated with the position of the plasmapause.

In Section 2, we review the resonant cyclotron interaction between relativistic electrons and left hand ion cyclotron waves, and show that only electrons above MeV energies are likely to be affected. Furthermore, the large ion cyclotron wave amplitudes required to precipitate the ring current protons lead to extremely short relativistic electron lifetimes. We then use these results in Section 3 to describe the main phase removal of relativistic electrons within a narrow region along the dusk to midnight bulge in the plasmasphere.

2. TURBULENT INTERACTION OF RELATIVISTIC ELECTRONS WITH ION CYCLOTRON WAVES

The condition for Doppler-shifted cyclotron resonance with relativistic electrons is

$$\omega - K_{\parallel} v_{\parallel} = \frac{n\Omega_-}{\gamma_E} \tag{1}$$

where ω is the wave frequency, $K_{\parallel}$ and $v_{\parallel}$ are the wave propagation vector and the electron velocity components parallel to the ambient magnetic field, respectively; n is an integer denoting the harmonic order of the resonance; Ω_- is the non-relativistic electron cyclotron frequency; $\gamma_E = (1 - v^2/c^2)^{-1/2}$ is the relativistic mass enhancement factor and c is the velocity of light. In terms of the wave refractive index $\mu = Kc/\omega$ and the normalized electron velocity $\beta = v/c$, (1) can be rewritten

$$1 - \mu_{\parallel}\beta_{\parallel} = \frac{n}{\gamma_E}\,\frac{\Omega_-}{\omega} \quad . \tag{2}$$

For cyclotron interactions ($n \neq 0$) between low frequency ion cyclotron waves ($\omega < \Omega_+$) and $\beta \simeq 1$ relativistic electrons, we may drop the factor of unity in (2). Using the ion cyclotron wave dispersion relation

$$\mu \approx (c/c_A)(1 - \omega/\Omega_+)^{-1/2} \tag{3}$$

where c_A is the Alfven speed, $c_A^{\,2} = B^2/4\pi NM_+$ we then obtain

$$(\gamma_E^{\,2} - 1)^{1/2} \simeq \frac{n}{\cos\alpha}\left\{\frac{2E_M}{E_o}\,\frac{M_+}{M_-}\right\}^{1/2}\frac{\Omega_+}{\omega}\left(1 - \frac{\omega}{\Omega_+}\right)^{1/2} \tag{4}$$

where α is the pitch angle, $E_M = B^2/8\pi N$ is the magnetic energy per particle, $E_o = M_-c^2$ is the electron rest energy, and M_+/M_- is the ion to electron rest mass ratio. Using the relation $E_R/E_o = \gamma_E - 1$, where E_R is the kinetic energy of the resonant electrons, and knowing the spatial variation of $E_M = B^2/B\pi N$ we can estimate E_R at each point in the magnetosphere.

Cornwall et al. (1970b) estimate that ring current protons would generate ion cyclotron waves with $\omega/\Omega_+ \simeq \frac{1}{2}$ just inside the plasmapause. In Figure 3 we combine this frequency estimate with a measured profile of E_M (Burton et al.,1970) and plot the first order (n = 1) equatorial resonant energies, assuming $\alpha = 45°$, as a function of L. We see that throughout the magnetosphere only electrons with energies $E_R \gtrsim 1$ MeV can resonate with ion cyclotron waves. Furthermore, the resonant energy is near 1 MeV only in the equatorial region just inside the plasmapause. Outside the plasmapause the resonant energy is a factor of 10 to 30 larger. Thus, even if ion cyclotron waves existed beyond the plasmapause, they would not interact with MeV electrons. The MeV electron precipitation region should therefore lie near but within the plasmapause, and have a sharp outer boundary at the plasmapause.

Electron lifetimes

Since the resonant relativistic electrons Doppler-shift the low frequency ion cyclotron waves to their own gyrofrequency we can use an approximate estimate of the quasi-linear diffusion coefficient given by Dungey (1965) or Kennel and Petschek (1966) for weak pitch angle scattering

$$D_\alpha \simeq \frac{\langle(\Delta\alpha)^2\rangle}{\Delta t} \simeq \left(\frac{B'}{B_o}\right)^2 \frac{\Omega_-}{\gamma_E} f \quad . \tag{5}$$

Here B' is the ion cyclotron wave amplitude, B_o is the ambient magnetic field strength and f is the fraction of the electron bounce period spent in resonance with the ion cyclotron waves. During the main phase of a geomagnetic storm, Cornwall et al. (1970a) have estimated that an ion cyclotron wave amplitude $B' \simeq 1$ gamma is needed to remove the ring current proton within one hour. At $L = 4$ we take $\mathcal{A} = 1/4$, $\Omega_- = 10^5$ rads sec^{-1} and $B_o = 500$ gammas to give a rough estimate for the effective electron loss time as

$$\tau_{loss} \sim D_\alpha^{-1} \sim 10\ \gamma_E \text{ secs} \quad . \tag{6}$$

The resonant electrons just within the plasmapause have $\gamma_E \sim 5$ which implies $\tau_{loss} \simeq 50$ sec. This, however, is comparable to the minimum lifetime τ_{min} expected from strong pitch angle diffusion (Kennel and Petschek, 1966; Kennel, 1969) of relativistic electrons at $L = 4$;

$$\tau_{min} = \frac{2\tau_B}{\alpha_o^2} \simeq 20 \text{ sec} \quad . \tag{7}$$

Here τ_B is the quarter bounce time for the electrons and α_o is the size of the atmospheric loss cone. We therefore conclude that the intense ion cyclotron turbulence generated by ring current protons should remove relativistic electrons near the maximum rate. Such a rapid removal of relativistic electrons should produce a nearly isotropic precipitation flux J_P . The ratio of precipitated to trapped fluxes J_P/J_T (Coroniti and Kennel, 1970) is

$$\frac{J_P}{J_T} \simeq \frac{\tau_{min}}{\tau_{loss}} \simeq 0.4 \quad . \tag{8}$$

The observed omnidirectional prestorm fluxes of 10^5 to 10^6 electrons cm^{-2} sec^{-1} measured by Pfitzer et al. (1966) and Owens and Frank (1968) for $E_e > 1$ MeV indicate that precipitation fluxes the order of a few times 10^5 cm^{-2} sec^{-1} might be observable during the initial phase of a magnetic storm. This precipitation would be localized to a region just within the plasmapause.

Electron wave absorption

The resonant interaction between electrons and ion cyclotron waves causes an energy transfer which results in wave damping. Kennel (1969) has estimated the relative magnitude of the resulting energy diffusion compared to pitch angle scattering. His analysis implies that the ratio of time scales for energy and pitch angle scattering is approximately

$$\frac{\tau_E}{\tau_\alpha} \simeq \left(\frac{\Omega_-}{\gamma_E \omega} \right)^2 \quad . \tag{9}$$

Using $\omega/\Omega_+ = \frac{1}{2}$ and $\gamma_E = 5$ we find $\tau_E/\tau_\alpha = 10^6$. Thus, in the process of scattering to the loss cone a typical relativistic electron will gain energy by a factor of 10^{-6}, or about 1 eV. This energy is removed from the ion cyclotron waves.

The predicted precipitation flux then implies a reduction of the wave energy flux to the ionosphere of about 10^5 eV cm^{-2} sec^{-1}. We can compare this to the total wave energy flux $(B'^2/8\pi)c_A$. Using equatorial values, $B' = 1$ gamma and $c_A \sim 10^3$ km/sec , and taking account of the geometrical reduction in the size of the geomagnetic flux tube we find a wave flux into the ionosphere slightly larger than 10^{10} eV cm^{-2} sec^{-1}. Cornwall et al. (1970b) show that if one half of this energy flux can be Landau absorbed by the thermal electrons in the plasmasphere an SAR arc will result. However, the wave damping due to relativistic electrons is lower by a factor of 10^{-5} and is thus clearly insignificant. Thus the relativistic electrons should not affect the stability of the ion cyclotron waves, which is controlled by ring current protons.

3. MORPHOLOGY OF ELECTRON REMOVAL

It remains for us to consider the morphology of the region of rapid electron removal. In Figure 4, we sketch the drift orbits and the expected spatial distribution of ring current protons during **main-phase.** The proton lifetimes estimated by Cornwall et al. (1970a) imply that protons are only able to drift the order of 2/3 R_E into the plasmasphere before they are precipitated. Assuming a storm-time injection of protons from the magnetospheric tail we thus expect intense ion cyclotron turbulence along the outer edge of the bulge region (Carpenter, 1966; Chappell et al., 1970b) of the plasmasphere. This is shown by the heavily hatched region in Figure 4. Relativistic electrons have roughly circular drift orbits for $L < 6$. Because of the asymmetry of the plasmasphere in the bulge region, electron drift orbits between $L \sim 2.5$ and $L \sim 5$ can pass through the storm time region of ion cyclotron turbulence. The short electron lifetimes estimated in Section 2 suggest that the relativistic electrons on these drift orbits should be completely removed after a few drifts across the turbulent region. This expected L range of electron loss compares favorably with that found experimentally (Figures 1 and 2). It should however be emphasized that the region of electron precipitation is determined by the region of ion cyclotron turbulence and is probably confined to the dusk to midnight quadrant.

4. SUMMARY

1) Ring current protons are strongly unstable to electromagnetic ion cyclotron waves near but within the plasmapause (Cornwall et al., 1970a), accounting for the coincidence of the plasmapause and the ring current inner boundary (Russell and Thorne, 1970).

2) During magnetic storms a region of intense ion cyclotron turbulence is therefore expected along the bulge region of the plasmapause.

3) Ion cyclotron waves can resonantly interact with $\sim$ MeV electrons near but within the plasmapause. The wave amplitudes required to precipitate the ring current protons lead to very short relativistic electron lifetimes, comparable with the minimum lifetimes. Electrons whose drift orbits intersect the region of ion cyclotron turbulence should thus be removed within a few drift periods or an hour or two after the storm onset. The longitudinal asymmetry of the plasmasphere indicates that the region of electron removal will be several R_E thick; typically between L = 2.5 to 5.

4) During the main phase, measurable precipitation fluxes of > 1 MeV electrons should occur near the plasmapause in the dusk to midnight quadrant. Within the first hour of the storm onset, these should be comparable with pre-storm trapped fluxes ($\sim 10^5$ cm^{-2} sec^{-1}).

5) Since the electron lifetimes approach the strong diffusion limit, the precipitation flux should approach isotropy across the loss cone.

6) Relativistic electron precipitation should also be correlated with more intense low energy (5-50 KeV) proton precipitation fluxes along the bulge region of the plasmapause.

7) The penetration of the plasmapause to $L \sim 2$ during very intense magnetic storms may account for the anomalously fast removal of artificially injected electrons at $L > 2$ (Van Allen, 1964, 1965).

8) The reduction in $B^2/8\pi N$ with increasing distance implies, following the reasoning of Cornwall et al. (1970a), that ion cyclotron waves can also be generated in the region of the proton aurora ($L \gtrsim 6$) (Eather and Carovillano, 1970). From Figure 3, we therefore expect $\gtrsim 7$ MeV electrons to resonate with these waves. This may account for the dropout in relativistic electrons which occurs well within the outer boundary of trapping for lower energy electrons.

9) Cornwall (1965), 1966), Kennel and Petschek (1966), and Cornwall et al. (1970a) have argued that Davis-Williamson (1963), $E_p > 100$ KeV, protons can be unstable beyond the plasmapause to ion cyclotron waves even at quiet times. These waves would resonate with ultrarelativistic electrons ($E_e \gtrsim 10$ MeV). This component should therefore be precipitated in association with energetic proton precipitation. Thus it is unlikely that ultrarelativistic electrons are present in the radiation belts.

ACKNOWLEDGMENTS

We would like to thank J.M. Cornwall, F.V. Coroniti, and L. M. Lyons for interesting conversations. This work was supported by NASA, NGR-05-007-190. C.F. Kennel was supported by an Alfred P. Sloan faculty fellowship. R.M. Thorne was supported by a summer faculty fellowship of the Academic Senate of the University of California.

FIGURE CAPTIONS

Figure 1. Contours of constant omnidirectional flux for electrons ($E > 1.6$ MeV) at the magnetic equator. Notice the pronounced dropout between $3.5 < L < 5$ at the onset of the geomagnetic storm.

Figure 2. The ratio J_{st}/J_q between the storm-time (September 29, 1964) and quiet-time (September 20, 1964) electron fluxes measured by Pfitzer, Kane and Winkler (1966) is plotted as a function of electron location (2a) and energy (2b) in the radiation belts.

Figure 3. The energy of electrons with 45° pitch angle resonant at the magnetic equator with $\omega/\Omega_{+} = 0.5$ ion cyclotron waves is plotted against L value. The sharp increase at $L \approx 4.5$ is caused by the pronounced drop in density at the plasmapause. Beyond the plasmapause, two curves have been plotted, one assuming typical thermal plasma densities ($N \approx 1$ cm^{-3}) and the other assuming ring current proton densities ($N \approx 10$ cm^{-3}).

Figure 4. The expected main-phase asymmetry of the ring current protons is shown in relation to the local time asymmetry of the plasmapause. Strong ion cyclotron turbulence, generated in the region of overlap, causes a rapid precipitation of both low energy protons (5-50 KeV) and relativistic electrons in the region just within the plasmapause between dusk and midnight.

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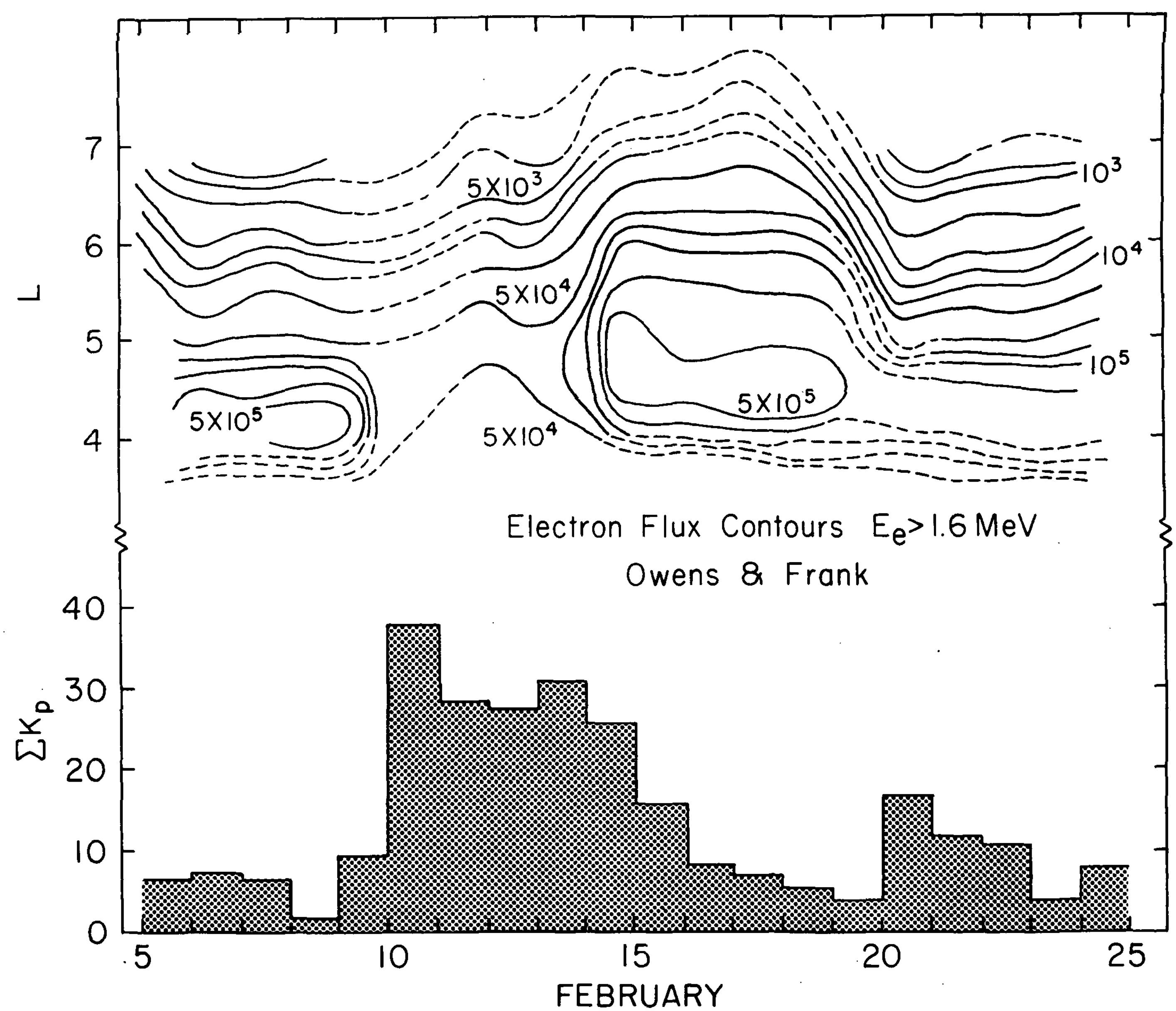

Electron Flux Contours E_e>1.6 MeV
Owens & Frank
L
7
6
5
4
10^3
10^4
10^5
5×10^3
5×10^4
5×10^4
5×10^5
5×10^5
ΣK_p
40
30
20
10
0
5
10
15
20
25
FEBRUARY

Figure 1

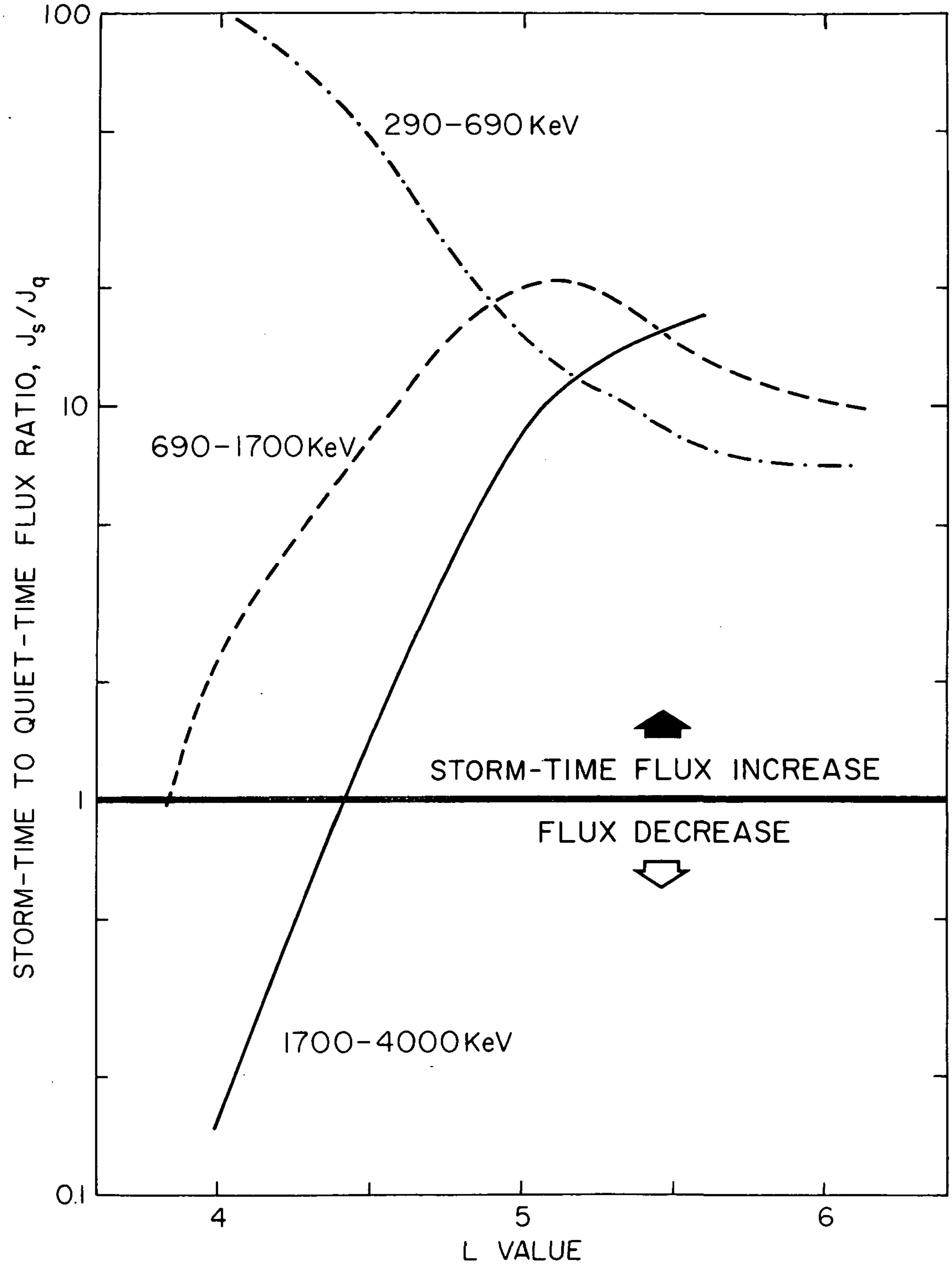
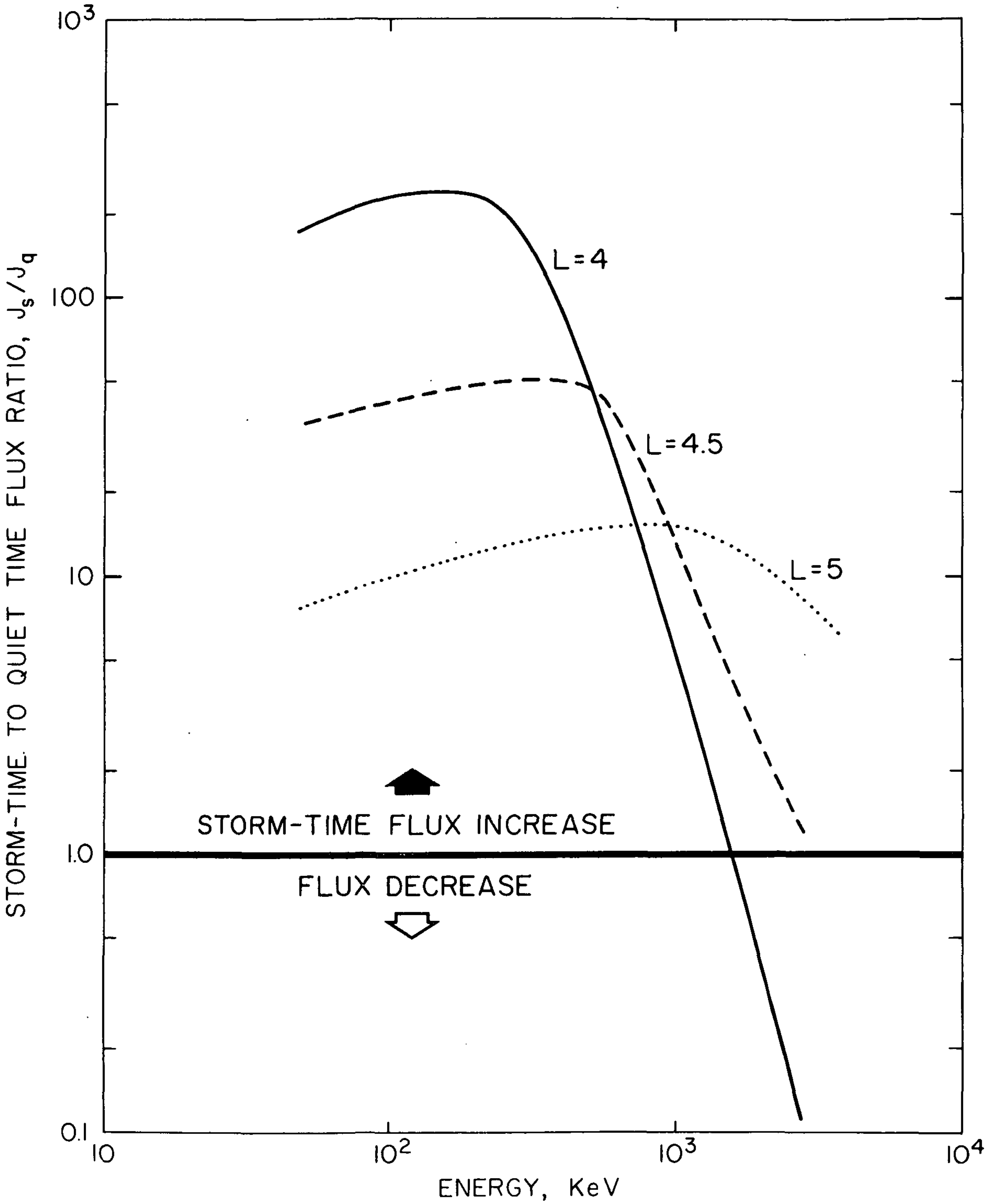

100
10
1
0.1
STORM-TIME TO QUIET-TIME FLUX RATIO, J_s/J_q
290-690 KeV
690-1700 KeV
1700-4000 KeV
STORM-TIME FLUX INCREASE
FLUX DECREASE
4
5
6
L VALUE

Figure 2a



10^3
100
10
1.0
0.1
10
10^2
10^3
10^4
STORM-TIME TO QUIET TIME FLUX RATIO, J_s/J_q
ENERGY, KeV
L=4
L=4.5
L=5
STORM-TIME FLUX INCREASE
FLUX DECREASE

Figure 2b

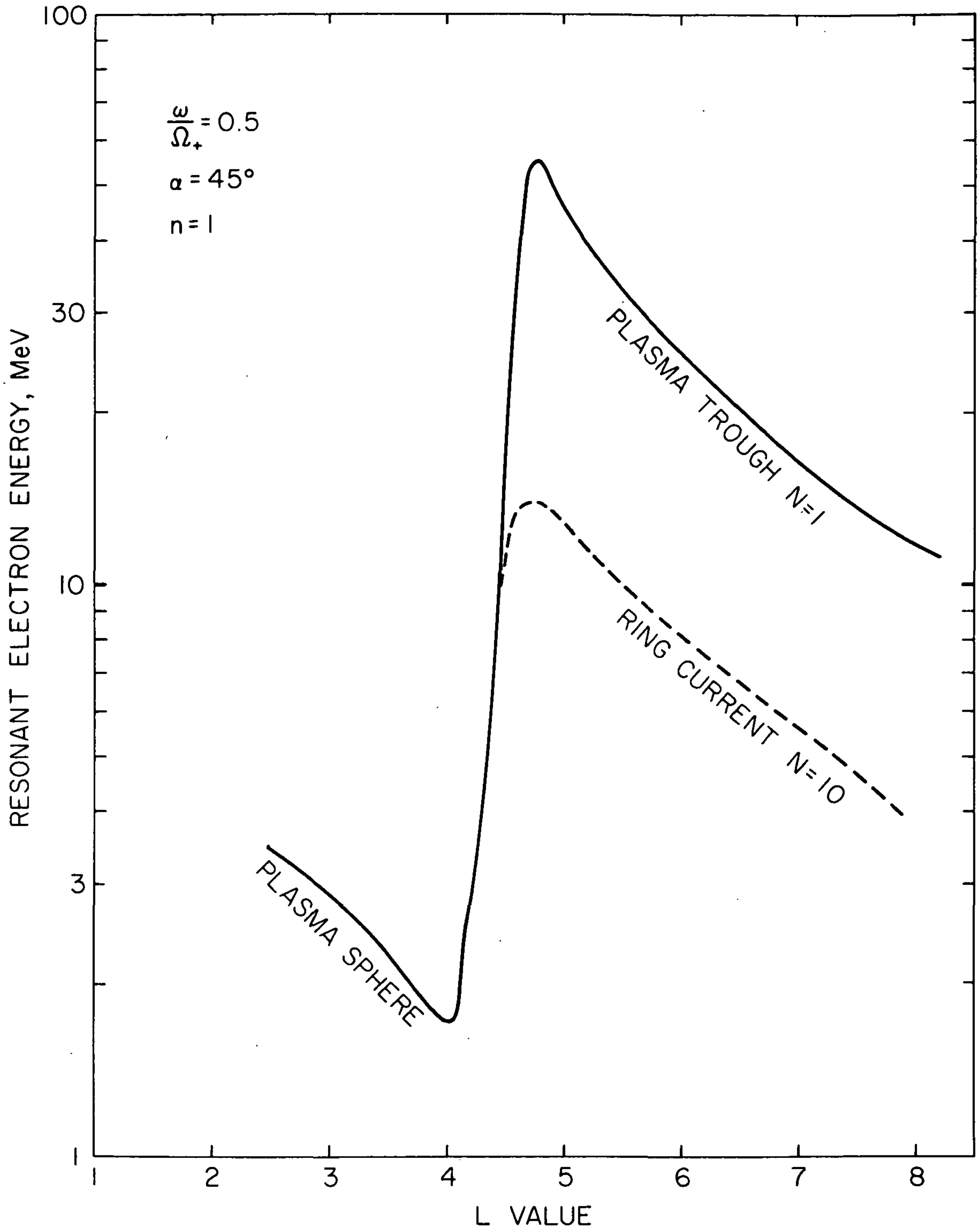

100
30
10
3
1
RESONANT ELECTRON ENERGY, MeV
$\frac{\omega}{\Omega_+} = 0.5$
$\alpha = 45°$
$n = 1$
PLASMA TROUGH N=1
RING CURRENT N=10
PLASMA SPHERE
1
2
3
4
5
6
7
8
L VALUE

Figure 3

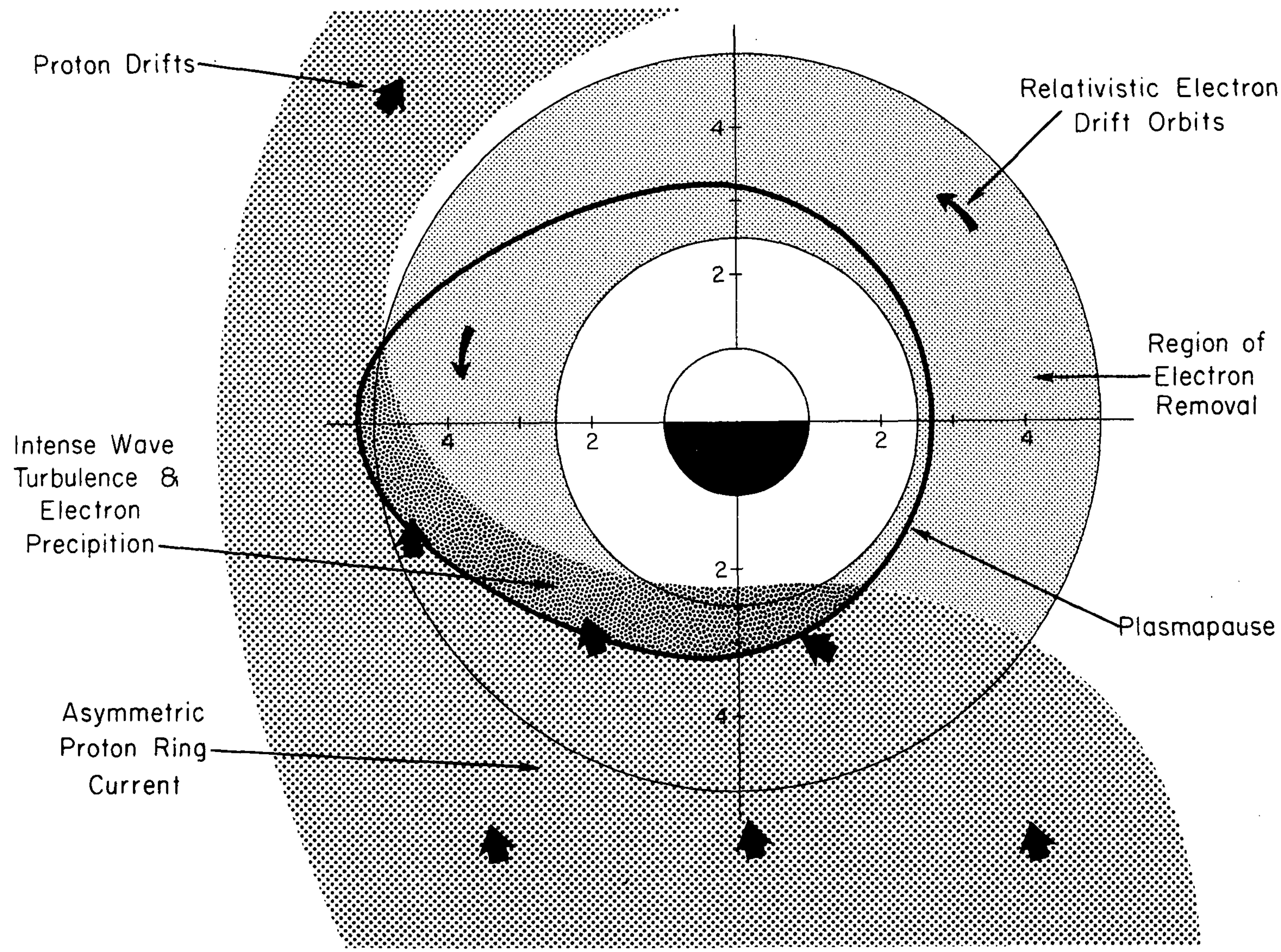

Proton Drifts
Relativistic Electron
Drift Orbits
Region of
Electron
Removal
Intense Wave
Turbulence &
Electron
Precipition
Plasmapause
Asymmetric
Proton Ring
Current
4
2
2
4
4
2
2
4

Figure 4