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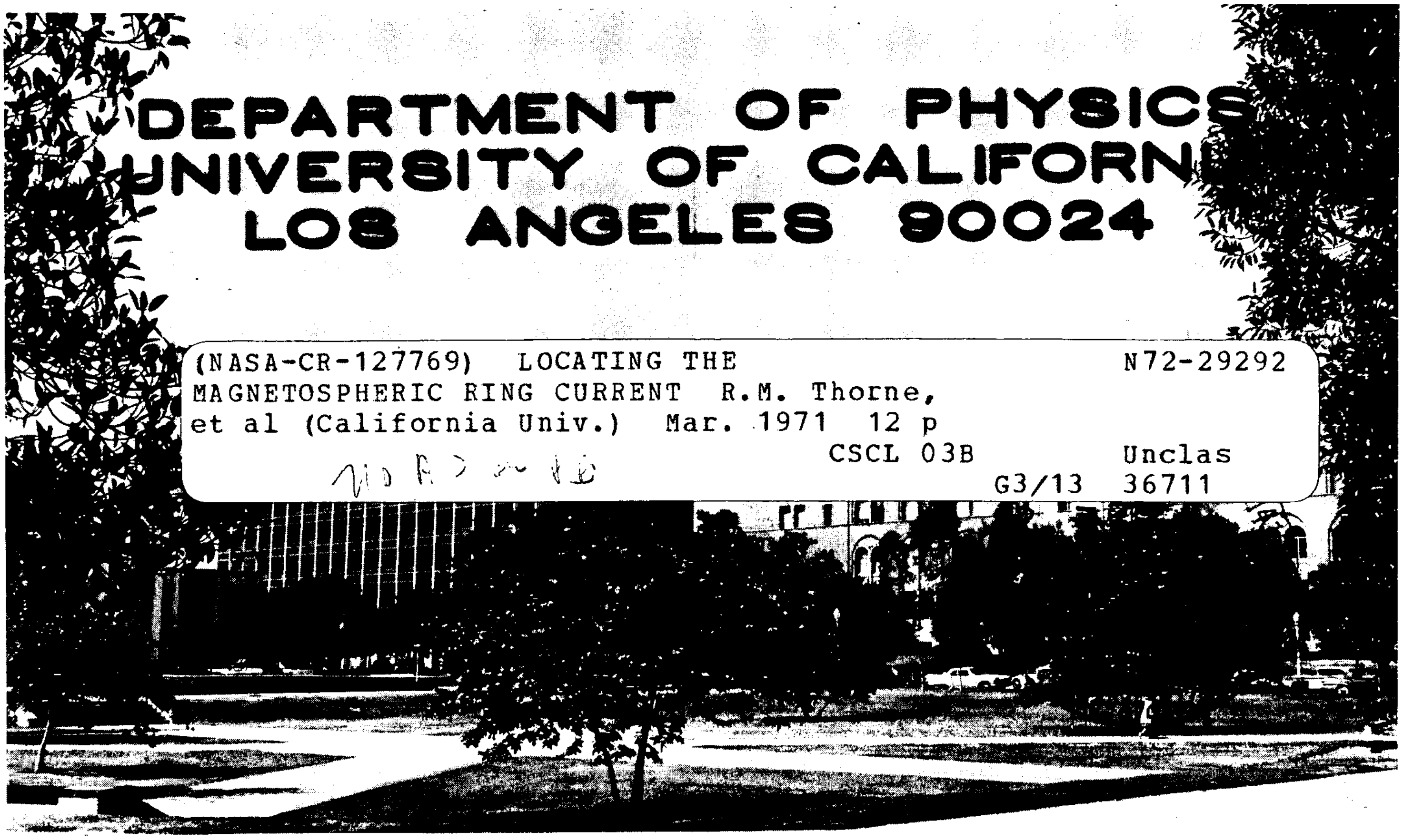

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Locating the Magnetospheric Ring Current

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LOCATING THE MAGNETOSPHERIC RING CURRENT

The most pronounced feature of a geomagnetic storm is the global depression of the Earth's horizontal magnetic field. This main phase decrease is generally considered to result from an enhanced injection of energetic plasma into the region of trapping within the Earth's radiation belts. Theoretical arguments have shown that the field depression ΔB measured at low latitudes on the ground depends almost entirely on one single property of the injected plasma; namely its total energy content ϵ_T (1). ΔB has been shown to be independent of the type of the injected charged particles, their individual energies, or their spatial distribution in the magnetosphere (2,3). The general solution for the main phase depression given by Sckopke (2) is

$$\frac{\Delta B}{B_o} = -\frac{2}{3}\frac{\epsilon_T}{\epsilon_M} \qquad (1)$$

where B_o (≈ 0.3 Gauss) is the equatorial magnetic field at the Earth's surface and ϵ_M ($\approx 10^{25}$ ergs) is the total geomagnetic energy contained above the Earth. This result has been extended to include the effects of a bounded magnetosphere (4,5,6) but the additional contributions (from boundary currents, etc.) are generally small.

Ground-based observations of the geomagnetic field give no clue about the location of the ring current as is clear from equation (1). Furthermore, we have little idea whether or not there is an upper limit to the total energy content, ϵ_T. From observational results it appears that the kinetic energy density of trapped particles does not exceed that of the geomagnetic field at the equatorial point on the field line where the particles are measured. This limitation of particle energy density may be due to such large scale instabilities as the interchange instability(8,9) or the finite β ballooning mode.(10) However, observations and theory have yet to converge on this point.

Microscopic instabilities, involving resonant interactions with waves whose frequency matches the cyclotron frequency or bounce frequency, cause trapped particles to diffuse in velocity space towards the atmospheric loss cone, whereupon they are removed from the magnetosphere by atmospheric collisions. It is the purpose of this note to point out that 10-100 KeV protons, which dominate ring current energetics, have two preferred regions of cyclotron instability, and consequently loss, which serve as stable trapping boundaries for ring current protons. The pertinent electromagnetic ion cyclotron instability therefore limits the ring current location, and, using the empirical notion that within the stable region the energy density does not exceed the geomagnetic energy density, also the ring current energy density, and therefore, the main phase depression.

Energetic protons resonate with electromagnetic ion-cyclotron waves when their motions parallel to the magnetic field Doppler-shift the wave frequency to the proton cyclotron frequency. This instability is believed to control the populations of energetic protons, $E_p > 100$ KeV.(11,12) As we shall see, energetic protons are likely to be unstable throughout the entire magnetosphere. Recently, in applying the above instability theory to lower energy (10-100 KeV) ring current protons, Cornwall, Coroniti and Thorne(13) have stressed the fact that the ion cyclotron instability only affects protons whose energy exceeds a threshold which depends upon the magnetic field strength B and plasma number density N. The threshold energy E_c is given by a relation of the form

$$E_c = E_M f(\omega, A) \tag{2}$$

where $f(\omega, A)$ denotes a weak dependence on wave frequency and pitch angle anisotropy A. For the exact form of $f(\omega, A)$, see Kennel and Petschek.(12) E_c is primarily controlled by the magnetic energy per particle

$$E_M = B^2/8\pi N \tag{3}$$

which has a strong spatial variation throughout the magnetosphere. E_M is smallest (hence permitting lower energy particles to participate in the instability) near the geomagnetic equatorial plane and in regions where the electron density is large or where the magnetic field strength is small, namely inside the plasmapause or at large radial distance in the auroral zone.

If, for simplicity, the arbitrary assumption is made that the pitch angle anisotropy is roughly constant, $f(A) \approx 1$, throughout the magnetosphere, several pronounced properties of the ring current are readily explained. Figure 1 shows schematically how the threshold energy for instability varies with geocentric distance along the geomagnetic equatorial plane. It is immediately clear that high energy particles, $E > 100$ KeV, are susceptible to the cyclotron instability at all locations in the magnetosphere. However, due to wave energy loss processes, the resonant interaction will be self-sustaining <u>only</u> if the particle flux also exceeds a critical value.(11,12) The cyclotron instability therefore limits the storm-time injection of <u>high</u> energy particles (E >100 KeV) to their stably trapped flux levels. The resulting total energy content (E > 100 KeV) in high energy electrons and protons is consequently limited to values which are insufficient to produce the observed main phase geomagnetic field depression. This conclusion agrees with observations of high energy radiation belt fluxes.(14,15,16) One can therefore theoretically and experimentally rule out high energy particles as important members of the ring current.

At lower energies, between 10 and 100 KeV, Figure 1 predicts two regions of cyclotron instability separated by a stable zone just outside the plasmapause. The two unstable regions have recently been associated with the location of the ionospheric SAR arc observed at midlatitudes and proton precipitation emissions observed at auroral latitudes.(17)

This simple description of the location and maximum energy of the ring current particles agrees well with the few direct observations of the particles responsible for the main phase depression during moderate geomagnetic storms.(7,18) A strong coincidence between the inner edge of the proton ring current and the plasmapause(19) has been noted during all phases of one geomagnetic storm(20) and interpreted in terms of the above cyclotron instability.(12) Furthermore, Figure 1 predicts that the energy of individual particles comprising the stable symmetric ring current are less at larger radial distance. Such a softening of the ring current energy spectrum has been observed.(7) Finally, the dominant energy of precipitating particles should also decrease with increasing covariant latitude; a trend which is becoming increasingly apparent from recent auroral zone observations.(21, 22)

In summary, figure 1 tells us where the intense 10-100 KeV proton ring current is allowed to exist and why it is that the observed ring current protons have the energy they do. (Higher energy protons, $E_p > 100$ KeV, are always stable in the ring current region.) Furthermore, by assigning an average ratio $\bar{\beta}$ between the plasma kinetic and magnetic energy densities in the ring current one can approximately relate the main phase magnetic depression to the location of the boundaries of the region of cyclotron stability:

$$\frac{\Delta B}{B_o} \simeq -\bar{\beta}\left(\frac{1}{L_{pp}^3} - \frac{1}{L_{AZ}^3}\right)\alpha \qquad (4)$$

The fudge factor α depends weakly on the pitch angle anisotropy of the plasma and lies between 1/2 to 1/4 for typical ring current conditions. Notice that ΔB is primarily controlled by the location of the plasmapause L_{pp} since the auroral zone is generally much further from the Earth. For a moderate magnetic storm [$\Delta B \sim 50\gamma$ and $L_{pp} \sim 3$] predicts $\bar{\beta} \sim 1/5$ to $1/10$ which agrees well with the inner edge observations of Frank.(7)

It is clear that magnetic storms, which involve large magnetic field depressions, require either that the plasmapause move inward or that $\bar{\beta}$ increase in the stable trapping zone. Significant inward penetration of the plasmapause has indeed been observed.(23,24) It is currently popular to associate injection into the stable trapping zone with magnetospheric substorms, which periodically squirt plasma Earthwards from the geomagnetic tail. In support of this we note that substorms are very frequent during the buildup phase of geomagnetic storms. A unified theory of the ring current and plasmapause may be possible, since the large electric fields associated with substorms, according to current thinking(25,26), also determine the position of the plasmapause.

Future models which utilize the enhanced substorm inward convection of the plasma must include the effect of rapid particle loss by strong pitch angle diffusion throughout the auroral zone(27), which is interpreted here as the unstable region between the ring current and tail. In order to build up a strong ring current the time scale for transport across this unstable zone must become less than the scattering loss time. Because electrons are more rapidly removed by pitch angle scattering(27), the convecting protons should form the most important constituent of the ring current in agreement with the observations of Frank.(7) Also, since the convection time scale depends on the electric field across the magnetosphere tail, the above injection model places a lower limit on the substorm electric field needed to produce a storm. Once the particles are convected into the zone of stability they are able to complete drift orbits around the Earth and thus contribute to the symmetric ring current depression. The only apparent means of removing this stably trapped belt of particles is by charge exchange interactions(28) or by waiting for the outward expansion of the plasmapause to erode the ring current along its inner edge.(13,17) Both of these processes require about two days, which is the characteristic decay period of the main phase depression.

Below are listed a few questions whose answers are necessary to formulate a quantitative theory of geomagnetic storms which relates main phase depression to solar wind parameters.

(a) For given solar wind conditions, what is the maximum electric field associated with substorms? What is the substorm repetition rate?

(b) For a given substorm amplitude and repetition rate, what is the plasmapause location? Rough estimates are possible here already.

(c) What shuts off substorms, stopping further proton injection, allowing the plasmapause to expand outward, and thereby initiating the recovery phase? Does a strong ring current moderate the substorm repetition rate, or is the recovery phase related to a relaxation of the solar wind?

(d) What process limits the proton energy density in the stable trapping region?

Such questions should not be interpreted as a sign of our ignorance; rather the mere fact that they can be asked so specifically indicates the considerable progress which has been made recently. Hopefully this will encourage renewed attacks on this, the oldest geophysical problem after the aurora.

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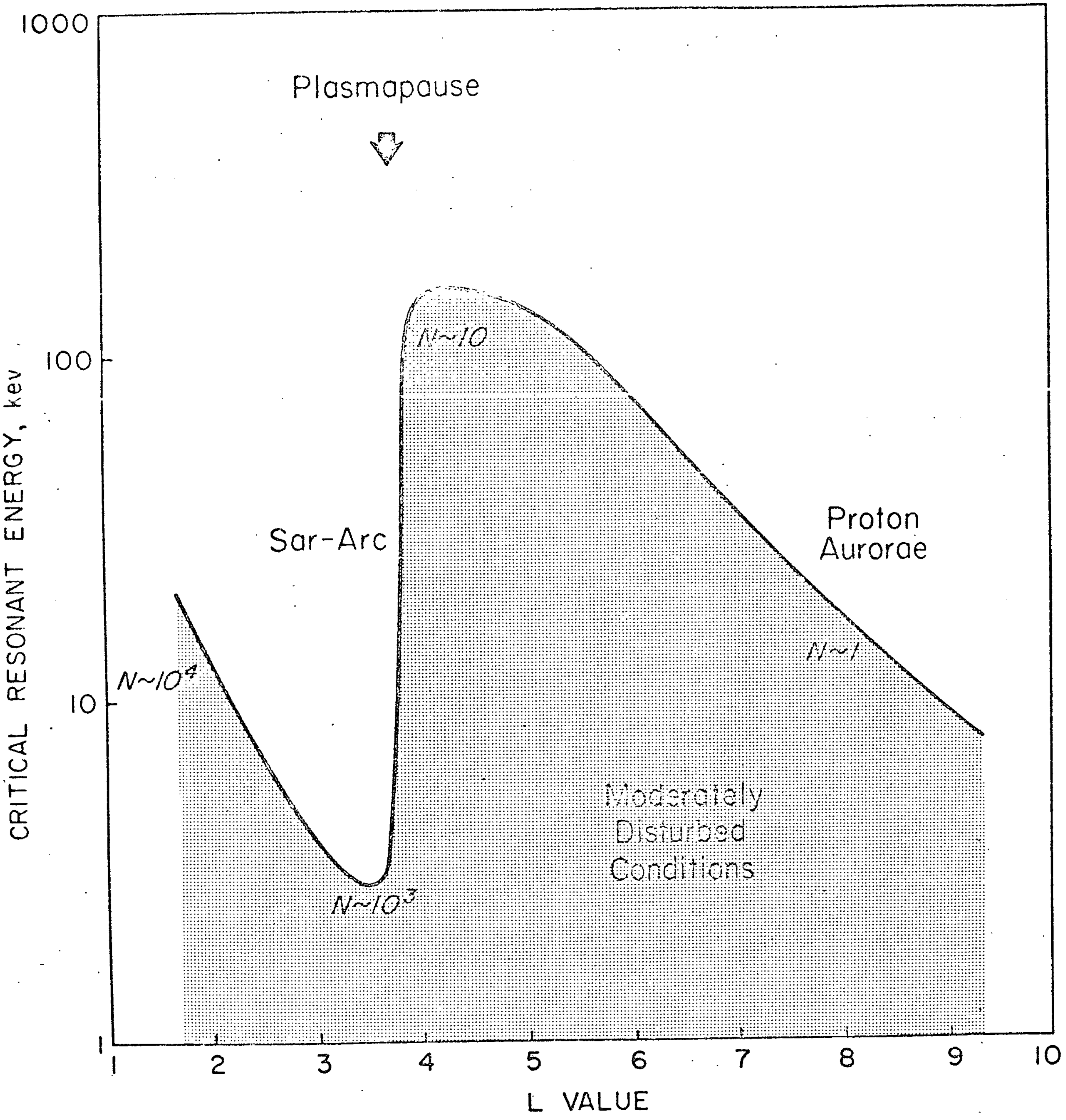
FIGURE CAPTION

The threshold energy for unstable cyclotron resonance $E_M = B^2/8\pi N$ is schematically plotted against radial distance along the equatorial plane. The curve is drawn for moderately disturbed conditions and the hatched area indicates stability.


1000
100
10
1
CRITICAL RESONANT ENERGY, kev
Plasmapause
$N \sim 10$
Sar-Arc
Proton
Aurorae
$N \sim 10^4$
$N \sim 1$
$N \sim 10^3$
Moderately
Disturbed
Conditions
1
2
3
4
5
6
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8
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10
L VALUE