1. SPACE PLASMAS

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STUDY OF CHARGED PARTICLE MOTION IN PERIODICAL MAGNETIC FIELD CONFIGURATIONS - M. ROTH, IASB

1 ABSTRACT

The effect of a spatial modulation in the magnetic field on the invariance of the magnetic moment of a charged particle ($\mu = V_\perp^2/B$) has been studied. We have investigated whether an invariant still exists when the wavelength of the modulation is comparable to the gyroradius of the particle. Two different magnetic field configurations were used: (a) an axially symmetric magnetic field with a square-wave modulation and (b) a sine-wave magnetic field modulation. For the latter configuration, we have shown, using a perturbation theory with the relative amplitude of the magnetic modulation (h) as a small parameter, that an invariant exists. To zero order in h this invariant reduces to the first adiabatic invariant (μ). For the square-wave modulation an invariant exists for most of the particle orbits (those which are regular in phase space), at least if h is not too great; the other particle orbits in phase space were shown to be quasi-ergodic. This type of quasi-ergodic orbits predominates in phase space when h is great.

2 INTRODUCTION

The motion of a charged particle in a magnetic field can be described quite accurately by a superposition of a gyration and a drift motion[1]. If both the Larmor radius and drift velocity change slowly during a Larmor period, the dynamics of the particle can be characterized by quantities which are approximate constants of motion. These *adiabatic invariants* approach a constant value in the limit of infinitely weak variations of the magnetic and electric fields. For motion in sufficiently smooth fields, an important adiabatic invariant is the magnetic moment[2] $\mu = V_\perp^2/B$, where $V^2_\perp$ is the particle velocity transverse to the magnetic field **B**.

The invariants of motion play an important role both in the trapping and containment of charged particles in magnetic-confinement systems. In the magnetosphere and in the solar wind, the applicability of the classical adiabatic invariants is quite restrictive. Violation of the invariants can be caused by non-adiabatic time variations of the fields, but also by interactions with electromagnetic or hydromagnetic waves (gyroresonant interactions). Interest in a possible invariant in modulated magnetic fields arose out of situations incorporating such fields, like the magnetic interaction of a charged particle with Alfvèn waves. Such studies were first performed for the case of fusion laboratory plasmas, e.g., in investigations of the containment properties of magnetic traps incorporating modulated magnetic fields[3, 4].

3 SEARCH FOR A GENERALIZED INVARIANT

Two kinds of magnetic field modulations were used in this study:
(a) an axially symmetric magnetic field with a square-wave modulation of amplitude h and wavelength λ around a uniform magnetic field $\boldsymbol{B_0}$·[5]
(b) the magnetic component of a monochromatic transversal hydromagnetic wave linearly polarized along the x-axis and propagating along an uniform magnetic field $\boldsymbol{B_0}$[6]. In the frame of reference moving with the wave, the electric field vanishes and the magnetic configuration is that of a sine-wave modulation, perpendicular to $\boldsymbol{B_0}$ of amplitude h and wavelength λ.
In both configurations, the magnetic moment of the particle is not an invariant near gyroresonance, i.e. when λ is comparable to the distance the particle travels in a Larmor period. This appears when the resonance condition:

$$V_{II} = \frac{\omega\lambda}{2\pi} \qquad (1.1)$$

is satisfied. In (1.1), $V_{\parallel}$ is the particle velocity in the direction of the field $\mathbf{B}_0$ and $\omega = qB_0/m$ is the angular frequency of gyration in the field $\mathbf{B}_0$. To investigate whether an invariant still exists when the particle velocity satisfies (1.1), we have studied the particle motion numerically—for configuration (a)—and both numerically and analytically—for configuration (b). A useful representation of the particle orbits for different initial conditions is the two dimensional phase space (ϕ, ξ), where ϕ is the zero-order (in h) Larmor phase angle and $\xi = V_{\perp}^2/V^2$ is a quantity evaluated at the points $z_n = n\lambda$ ($n = 0, 1, 2, \ldots$).
At $z = z_n$, ξ is proportional to the magnetic moment since the magnetic field intensity is periodical and therefore has the same values at $z = z_n$ (V, the amplitude of the particle velocity is a constant of motion since the kinetic energy is conserved in a static magnetic field).
In the analytic investigation we have searched for invariants using a perturbation theory, with h as a small parameter. A canonical transformation was first performed where ϕ and ξ are canonically conjugated variables. Any constant of motion $J = J_0 + hJ_1 + h^2J_2 + \ldots$ is in fact solution of the equation $(J, H) = 0$ where the left hand side is the Poisson bracket of J with the Hamiltonian H. In the new canonical variables, we have shown that all the differential equations determining J_i have the same form and can be integrated immediately.
Figure 1 summarizes the results of our study. The results obtained with configuration (a) (square-wave modulation) are similar to those obtained by Dunnett et al·[4], i.e. the numerically computed orbits fall into two classes: (1) regular orbits corresponding to the existence of an invariant; and (2) quasi-ergodic orbits. Provided the modulation h of the field is not too great, the regular orbits predominate. In the frame of configuration (b) (sine-wave modulation), the comparison of the invariant curves obtained by a perturbation method (first order invariant[6] or second order invariant[7]) with the exact results calculated by integrating the equations of motion, proves the validity of the approach, even when the resonance condition (1.1) is satisfied.

4 CONCLUSIONS

It is interesting to note that the search for motion invariants, in the case of a charged particle moving in non uniform magnetic field configurations, has gained today a new impulse; and that the results described here and obtained 20 years ago bear many similarities with the results of recent investigations. Indeed, studies of charged particle motion in magnetotail-like field reversals[8, 9] have shown that the particle orbits are of two types: regular and chaotic. In particular, the particle motion becomes stochastic when the minimum radius of curvature of the magnetic field tends to the maximum Larmor radius in it for a particle of given energy.

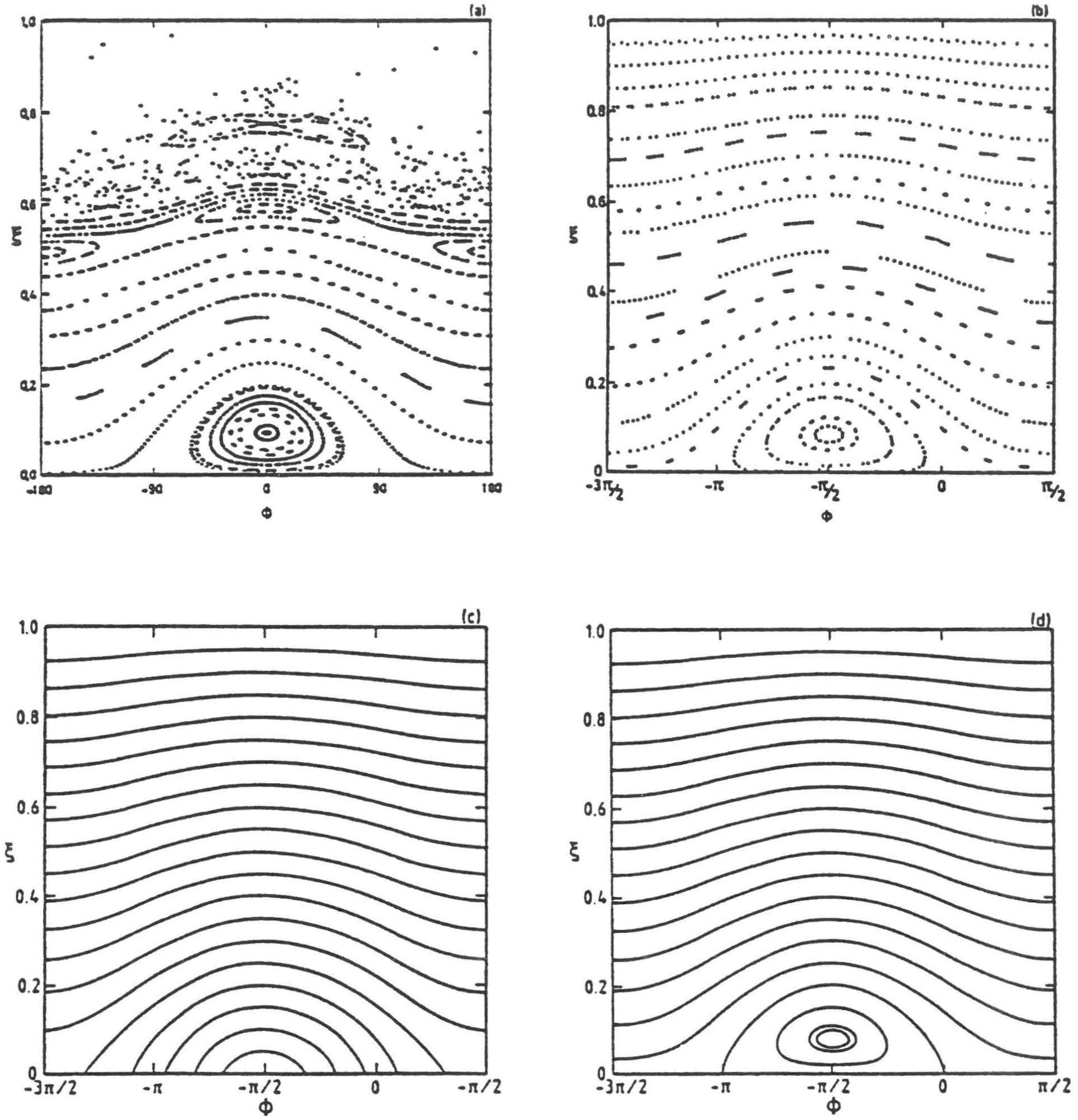


Figure 1 : (a) Integrated orbits in the phase plane (ϕ, ξ) for h=0.025, $V = V_{||} = \omega\lambda/2\pi$, in the case of the SquaK-WaUe modulation[5].

(b) Idem (a) but for the case of the sine-wave modulation[6].

(c) Invariant curves $J_o + hJ_l = C$, h=0.025, $V = V_{||} = \omega\lambda/2\pi$, sine-wave modulation[6].

(d) Invariant curves $J_0 + hJ_l + hJ_2 = C$, h=0.025, $V = V_{||} = \omega\lambda/2\pi$, sine-wave modulation[7]. Regular curves in (a) and (b) prove the existence of an invariant. This invariant is analytically determined in (c) (first order in h) and (d) (second order in h) for the sine-wave modulation. Note the resonance phenomenon for the small values of ξ (as expected from equation (1.1)).

PLASMA KINETIC THEORY AND ITS APPLICATION IN SPACE PHYSICS

1 ABSTRACT

In the solar corona collisions are important up to 3-5 solar radii and determine the viscosity and thermal diffusion coefficients. These coefficients have been calculated for the solar plasma. Above this transition level the solar wind plasma is collisionless and expands with supersonic speed into the interplanetary medium. In addition to the mechanical reason given by Parker[10] for such a radial expansion (i.e. the subsonic solutions of the coronal expansion give a too high gas kinetic pressure at large distances in the interstellar medium), a supplementary physical reason for the existence of solar and stellar winds is proposed: in order to carry out of the corona all the energy deposited at its base, a supersonic expansion is necessary.

2 INTRODUCTION

The hydrodynamic transport equations describe the spatial and time evolution of the density, bulk velocity, pressure, temperature, heat flow of non-uniform gases when they are considered as fluids. The magnetohydrodynamic (MHD) equations are special approximations of these transport equations in the case of ideal ionized gases called "plasmas". In kinetic theory of plasmas, a gas is considered as an ensemble of particles with well defined positions, r, and velocities, v. The velocity distribution $f(r, v)$ of these particles is determined by the Boltzmann equation.

The ionosphere and solar corona are formed of collision dominated plasmas where the electrons and ions of the plasma interact strongly by binary Coulomb collisions. In the topside region of the Earth's ionosphere, also called the ion-exosphere, plasmas are collisionless: i.e. the electrons and ions move almost freely in the gravitational, magnetic and electric fields. Similarly, in the outer solar corona, beyond 3-5 solar radii, the mean free path of the electrons and protons is larger than the density scale height, H. The plasma is therefore collisionless in this region where the solar wind is blowing with supersonic velocities into the heliosphere.

3 THE SOLAR CORONA AND ITS RADIAL EXPANSION

In a series of articles Lemaire has studied the effects of Coulomb collisions on the interaction terms between the components of a nonuniform gas[11 12-13]. He pointed out that for geophysical and astrophysical plasmas diffusion of particles due to temperature gradients may be as important as diffusion due to gravitational forces. In collaboration with Delcroix, Lemaire calculated the viscosity coefficient[12] and thermal conductivity coefficient[13] in the multiionic plasmas of the solar chromosphere and solar corona. These results have been quoted in *Astrophysical Quantities* by J.W. Allen.

Hydrodynamical models and the exospheric models of the solar corona and its radial expansion[14] have been compared. The asymptotic solutions at large radial distances of the supersonic solar wind of Parker[10] and the subsonic solar breeze of Chamberlain[15] are compared. It was pointed out that in both models the anisotropy of the kinetic pressure tensor increases with radial distances and that the assumption of pressure isotropy in the hydrodynamic solar wind models is questionable. Lemaire[16] also identified a nonstationary solution for a polytropic gas expanding in its own gravitational field. At large radial distance this solution is similar to the critical solar wind solution of Parker[10]. This time dependent solar wind model corresponds to a progressive shock wave whose velocity has been determined.

In his Ph. D. Thesis, Lemaire[17] established in 1969 that neither thermal conduction nor turbulent convection are efficient enough to transport out of the corona all the heat which enters into it from below across the chromosphere. Only a supersonic hydrodynamic expansion like the solar wind flow carries a maximum energy out of the Sun into the interplanetary medium. This work demonstrates that a supersonic expansion of the solar corona is a phenomenon necessary to evacuate all the energy deposited in the lower corona. This appears then to be a new physical reason for the existence of solar and stellar winds which supplements the mechanical reason proposed by E.N. Parker in 1958. In this unpublished Ph. D. thesis, the 20-moments transport equations of Grad[18] were also applied for the first time to the plasma expanding out of a gravitational field. The asymptotic expansion for the solution of these 20-moments equations was compared with that of Parker's critical solution of the solar wind.

4 CONCLUSIONS

The conclusion of this series of contributions are that collisions are important in the solar corona up to 3-5 solar radii. They determine the viscosity and thermal diffusion coefficients. However, above this transition level the solar wind plasma is collisionless and expanding with supersonic speed into the interplanetary medium. In addition to the mechanical reason given by Parker for such a radial expansion (i.e. the subsonic solutions of the coronal expansion give too high gas pressure in interstellar medium), a supplementary physical reason for the existence of solar and stellar winds is proposed: to transport out of the corona all the energy deposited at its base, a supersonic expansion is necessary.

KINETIC MODELS OF POLAR AND SOLAR WINDS

1 ABSTRACT

The polar wind and solar wind ions are accelerated to supersonic speeds by a charge separation electric field which maintains the quasineutrality of the plasma flowing out of the polar cap along "open" magnetic field lines and out of the solar corona. This ambipolar electric field intensity has been shown to be larger than the Pannekoek-Rosseland *E*-field which polarizes any plasma in hydrostatic equilibrium in the gravitation field. The polar breeze and solar breeze models failed to predict the correct supersonic speeds at large radial distances because the too weak Pannekoek-Rosseland electric field was adopted in these kinetic models. With the appropriate polarisation electric field the values of the exospheric model densities and plasma temperatures are, however, in satisfactory agreement with the observations, except for the anisotropy of the kinetic pressure tensor.

2 INTRODUCTION

The polar ionosphere is like the solar corona an "open ion-exosphere", indeed magnetic field lines emerging from high latitudes are considered to be "open", or, more correctly, extend to large radial distances in interplanetary space. Along these extended magnetic field lines the ionospheric ions which have velocities larger than the critical velocity can escape or evaporate out of the ionosphere. This forms a flow of plasma out of the polar ionosphere which was described in 1968 by Banks and Holzer[19] as a hydrodynamical flow. This model was called "the polar wind model", by analogy with Parker's solar wind hydrodynamical model. But Dessler and Cloutier[20] challenged the validity of this hydrodynamical model and argued that above about 2000 km altitude the escaping plasma is collisionless. Indeed, beyond this altitude corresponding to the ion-exobase, the average mean free path of thermal ions and electrons is larger than the characteristic density scale height, and collisions are no longer frequent enough to maintain a velocity distribution close to a Maxwellian distribution. Consequently, the usual hydrodynamic approximations of the general moments equations, are not valid beyond the exobase altitude. Therefore, beyond the exobase, one should prefer a kinetic approach rather than a hydrodynamical approximation of any order (including the 20-moments equations of Grad[18]). As a matter of consequence, Dessler and Cloutier[20] suggested a simple kinetic model for the polar wind (called polar breeze model) similar to Chamberlain's solar breeze model.

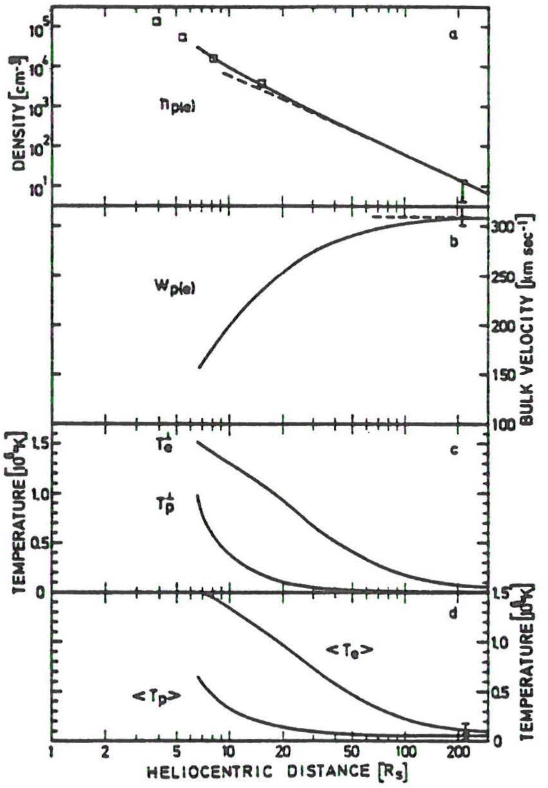


Figure 2 : Distribution of density (a), bulk velocity (b), perpendicular temperatures (c) and average temperatures (d) of electrons and protons in a kinetic model of the solar wind. The observed coronal density distribution reported by Pottasch[153] is shown by squares. The range of observed solar wind properties at 1 A U are taken from Hundhausen et al.[154] and are indicated by vertical bars.

3 KINETIC POLAR AND SOLAR WIND MODELS

Based on his past experience with exospheric theories of the solar wind, Lemaire became involved in this controversy between the polar wind/breeze modellers. He showed that when the correct ambipolar electric field is adopted (instead of the classical Pannekoek-Rosseland one), the polar breeze exospheric model of Dessler and Cloutier gives supersonic bulk velocities for the light H^+ and He^+ ions evaporating out of the Earth's polar ionosphere[21]. Furthermore, taking into account that the velocity distributions of the ions and electrons have finite temperatures, a supersonic plasma flow was determined from the new kinetic polar wind models implemented at IASB by Lemaire and Scherer[22, 23, 24]. This demonstrated that appropriate kinetic models are as able to predict supersonic polar wind expansion as the hydrodynamical models of Banks and Holzer. But the development of these kinetic models showed more clearly than hydrodynamical models how the charge separation electric field (ambipolar or polarization electric field) accelerates the ions to supersonic velocities and how it avoids the electrons to evaporate out of the ionosphere at a rate larger than the rate of escape of the positive ions.

On the basis of these encouraging results, the same authors applied their kinetic theory to describe the evaporation of protons and electrons out of the solar corona. They found that the solar breeze model of Chamberlain[25] would have given supersonic expansion velocities, if the correct ambipolar electric field would have been assumed in the solar ion-exosphere[25]. The proton and electron bulk velocity, density, mean temperature and heat flux predicted by the Lemaire-Scherer kinetic models are in satisfactory agreement with the satellite measurements for quiet solar wind regime. Figure 2 shows the radial distribution of the solar wind density (a), bulk velocity (b), perpendicular temperature (c) and average temperature of the electrons and protons (d) in a kinetic model of the solar wind for which the exobase is

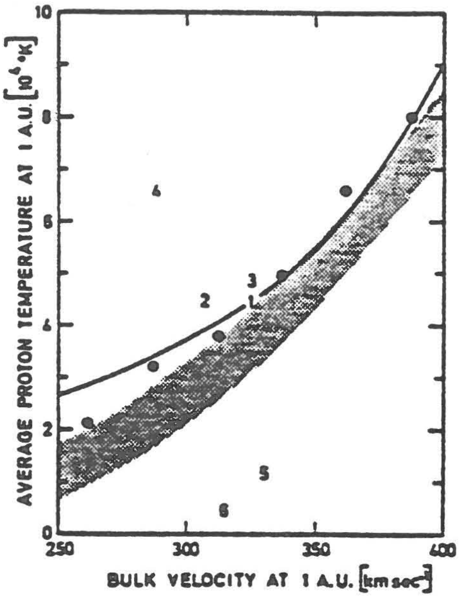


Figure 3 : Correlation between the solar wind velocities and the average proton temperature at 1AU. The solid dots correspond to Vela3 measurements. The shaded area corresponds to EXPLORER observations . The point I gives the quiet solar wind conditions[156]. Points 2-6 give the results from different kinetic and semikinetic models of Lemaire and Scherer. The solid line shows the relationship deduced by Lemaire[157].

located at 6.6 solar radii and the exobase temperature is 1.52 x 10^6 K. By varying the exobase temperature from 0.58 x 10^6 K to 1.8 x 10^6 K in the exospheric model, the authors recovered the relationship between the wind speed and the average proton temperature observed at 1 AU in the quiet solar wind. This is illustrated in Fig. 3. However, in all exospheric models, too large ion and electron temperature anisotropies are predicted. Lemaire and Scherer[25] attributed this discrepancy to the assumed absence of pitch angle scattering by Coulomb collisions in these ion-exosphere models. A detailed study of the asymptotic behaviour of the wind speed and density near the exobase level, as well as at large radial distances, was published by Lemaire and Scherer[26] .

A fitting procedure of exospheric models with hydrodynamical models across the exobase surface was proposed[27, 28]. It was then applied to the polar wind[29] and solar wind[30]. More recently, Monte Carlo simulations of the evaporation of thermal ions out of the polar ionosphere have been published[174 175~173]. Two invited review papers on the results of these kinetic results were published in *Reviews of Geophysics and Space Physics*[31] and in *Space Science Reviews*[32]. According to the citation index, these contributions on kinetic polar wind models were very often quoted in international journals, even in 1993.

4 CONCLUSIONS

The controversy between Banks-Holzer and Dessler-Cloutier about the validity of hydrodynamical polar wind models versus kinetic polar breeze models has been resolved by Lemaire and Scherer. They showed that when the Pannekoek-Rosseland ambipolar electric field intensity is replaced by a field of higher intensity (as needed to maintain the quasineutrality in the expanding polar wind plasma), one obtains supersonic bulk speeds which are consistent with observations. The same reason explains why the Chamberlain solar breeze model could not predict the observed supersonic solar wind velocities like in Parker's hydrodynamical models: the electric field intensity in the former breeze model was too low and erroneous.

KINETIC MODELS OF AURORAL ELECTRON PRECIPITATION

1 ABSTRACT

When the density of precipitating magnetospheric electrons exceeds a certain level, double layers are formed in the multicomponent plasma confined in an auroral magnetic flux tube. Steady-state models of such double layers have been obtained using the exospheric theory of Lemaire and Scherer. The flux of auroral electrons accelerated in these double layers contributes a field aligned current whose intensity is proportional to the positive potential difference, *V*, between the ionosphere and magnetosphere. This observed linear relationship between *J* and *V* has been explained by using the kinetic theory first developped by Lemaire and Scherer in the early seventies. This kinetic theory is also able to explain the other experimentally observed linear relationship between V^2 and q, the downward energy flux carried by the precipited auroral electrons.

2 INTRODUCTION

Particles of ionospheric origin and magnetospheric particles are both present in auroral magnetic flux tubes. The ionospheric ions are accelerated upwards and the plasmasphere electrons are accelerated downwards by parallel electric fields and field aligned potential drops. The accelerated electrons precipitated into the upper atmosphere produce the aurorae borealis.

3 CURRENT-VOLTAGE CHARACTERISTICS FOR AURORAL MAGNETIC FLUX TUBES

Lemaire has shown that when low energy electrons and ions of ionospheric origin (< 1 eV) are mixed with photoelectrons (> 5 eV) or with hot electrons and ions of magnetospheric origin (> 100eV), the ambipolar electric field distribution which satisfies local quasineutrality of the multi-ionic plasma is quite different from the Pannekoek-Rosseland electric field corresponding to diffusive equilibrium in the gravitational field. When the concentration of warm plasma is small compared with that of the colder one, Lemaire has shown that the electric field and potential distributions are not significantly different from that corresponding to the polar wind models mentioned above[33, 34]. However, when the number density of the hot plasma becomes too large compared to the colder ionospheric one, large charge separation electric fields build up in a narrow region of the auroral flux tube. A double layer is then formed to satisfy local quasineutrality of the plasma[35]. Figure 4 shows the electrostatic potential distribution in a flux tube when the field total potential difference between the exobase and the magnetosphere is equal to 25 Volt. Within the double layer located at 20000 km altitude, a large upward directed field is formed with a peak intensity of 0.1 V/m. The associated potential drop accelerates plasmasheet electrons downwards and ionospheric ions upwards. This double layer may be as thin as one Debye length and separates two regions of plasma: the lower one where magnetospheric electrons are penetrating and the upper region where the colder ionospheric electrons are almost excluded. Figure 5 shows the density distributions of the cold (c) and warm (w) electrons as well as those of the ionospheric ions (H^+, O^+) and magnetospheric protons (p^+). Furthermore, when the thickness of the double layer becomes comparable to the Debye length, Lemaire has shown that the quasineutrality of the plasma fails to be satisfied. In these extreme cases, Poisson's equation must be solved instead of the quasineutrality equation generally used in current polar wind models and postulated in all MHD magnetospheric models[176].

In our earlier polar wind models it was generally assumed that the total electrostatic potential drop along a magnetic field line has the appropriate value to guarantee that the number of electrons escaping from the ionosphere is equal to the number of ions, i.e. that the field aligned current (FAC) is precisely equal to zero. This zero-current condition is satisfied in the polar wind when the electric potential is equal to about 1.5 Volt. But in the auroral region field aligned Birkeland currents have been observed by satellite measurements, and this zero-current condition needs not to be satisfied in all cases. Further-

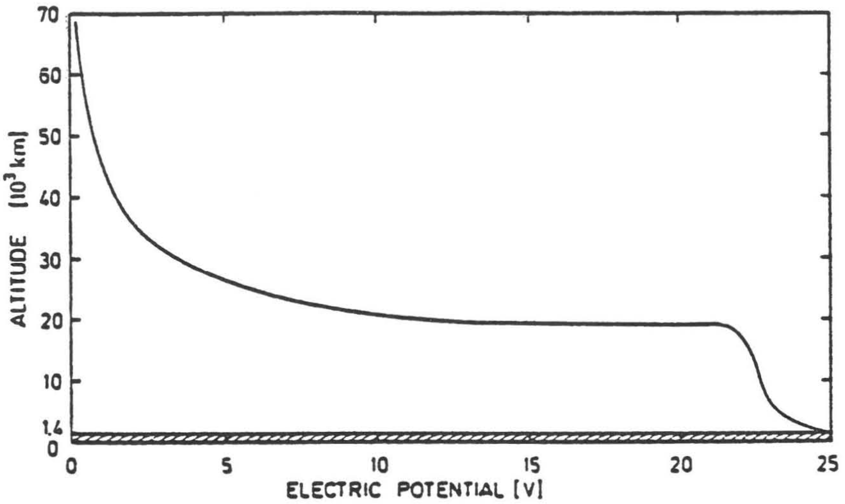


Figure 4 : Electrostatic potential distribution along a polar cusp magnetic flux tube filled with escaping polar wind ions (H^+, O^+), cold (c) ionospheric electrons, as well as with precipitating magnetosheath loarm (w) electrons and protons. An electrostatic double layer is formed at an altitude of 20000km. The peak intensity of the electric field is 0.1 V/m.

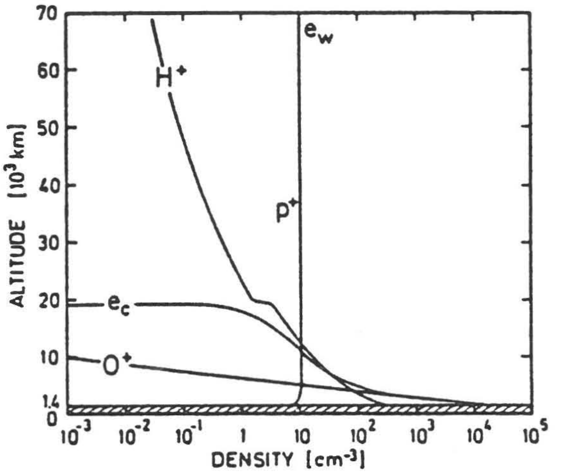


Figure 5 : Exospheric density distributions along a polar cusp magnetic flux tube filled with escaping polar wind ions (H^+, 0^+), cold (c) ionospheric electrons, as well as with precipitating magnetosheath warm (w) electrons and protons. The electrostatic double layer formed at an altitude of 20000km separates two regions: the lower one where accelerated electrons are precipitated, and the upper region where the ionospheric electrons are excluded. The density jump of the H^+ at 20000km is due to the upward acceleration of these ions.

more, in 1979, Lyons, Evans and Lundin[36] discovered experimentally the existence of a linear relationship between the field aligned current potential drop (*V*) and the intensity of the field aligned current density (*J*) carried by precipitating auroral electrons. They also found that the energy flux (*q*) carried by the same electrons was proportional to V^2. The kinetic theory introduced by Lemaire has been able to explain both experimental relationships from a theoretical point of view[37]. Figure 6 illustrates a series of current-voltage characteristics of magnetospheric flux tubes for six sets of plasma densities and temperatures in the plasmasheet source region. Note that this relationship was first predicted by Knight[38] in 1973. But this author only considered the currents carried by the hot plasmasheet electrons and cold ionospheric electrons. However, Lemaire and Scherer[39 40] pointed out that the currents carried by the ions of the ionosphere cannot be neglected when the positive field aligned potential difference *V* becomes smaller than 23 Volt. This occurs in the return current region outside the auroral precipitation region. Lemaire emphasizes that in the return current region the electric potential difference, *V*,

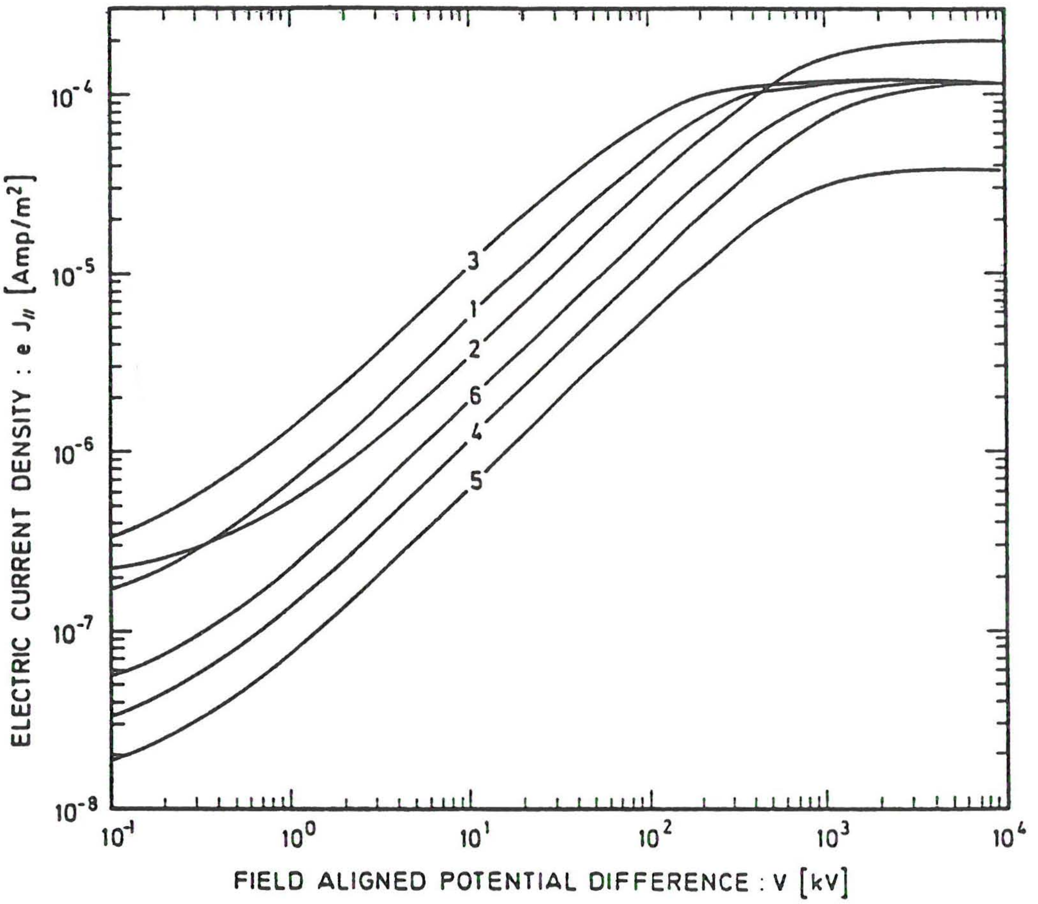
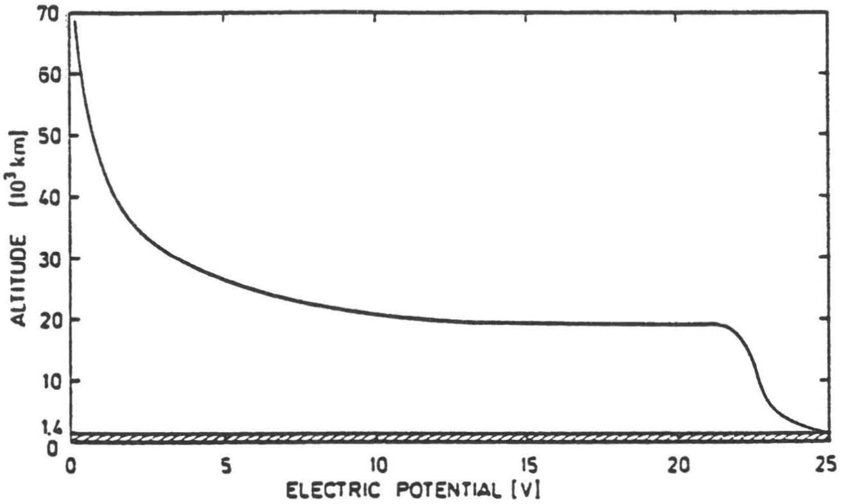


Figure 6 : Six current-voltage characteristics of auroral flux tubes for six sets of plasma densities and temperatures in the plasmasheet and ionospheric source regions.

between the ionosphere and magnetosphere needs not to be reversed (negative), but that a large downward current can easily be carried by an excess of escaping ionospheric electrons provided that the value of *V* is slightly below $V_0 = +1.5$ Volt, i.e. the value corresponding to the zero-current condition discussed above.

4 CONCLUSIONS

Field aligned electric potential differences and parallel electric fields can become large in the auroral and polar cusp regions where a relatively large number of hot electrons and ions coexist with the colder ionospheric plasma in the same magnetic flux tube. When the density of precipitating magnetospheric electrons exceeds a certain level, double layers are formed to satisfy local quasineutrality of the multicomponent plasma. Under extreme conditions, quasineutrality can no more be satisfied and Poisson's equation must be solved (see below). The flux of precipitating electrons contributes a field aligned current whose intensity is proportional to the positive potential difference *V* between the ionosphere and magnetosphere. This linear relationship between *J* and *V* has been explained by using the kinetic theory first developed by Lemaire and Scherer. This exospheric theory is also able to explain the experimentally observed linear relationship between V^2 and *q*, the downward energy flux carried by the precipitated auroral electrons.



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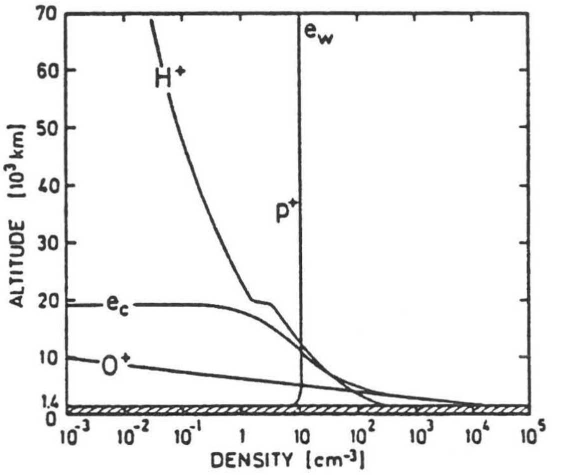

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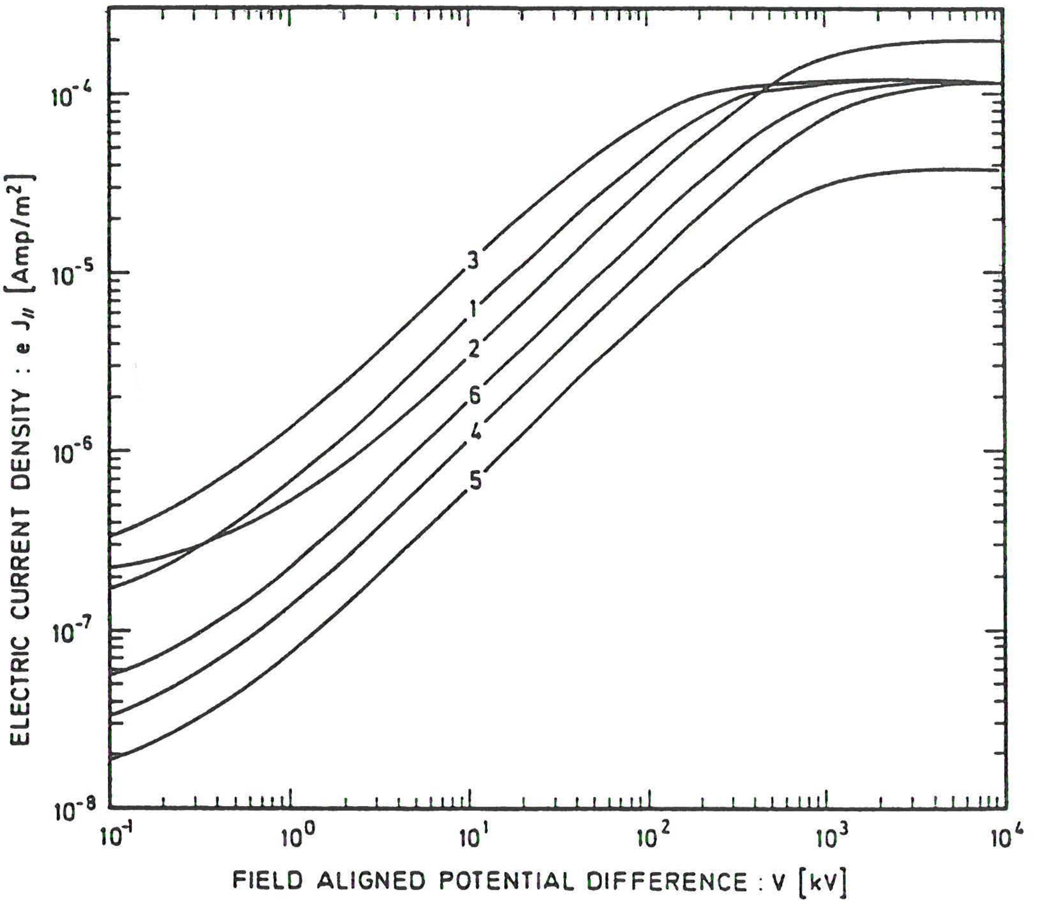

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4 CONCLUSIONS

Field aligned electric potential differences and parallel electric fields can become large in the auroral and polar cusp regions where a relatively large number of hot electrons and ions coexist with the colder ionospheric plasma in the same magnetic flux tube. When the density of precipitating magnetospheric electrons exceeds a certain level, double layers are formed to satisfy local quasineutrality of the multicomponent plasma. Under extreme conditions, quasineutrality can no more be satisfied and Poisson's equation must be solved (see below). The flux of precipitating electrons contributes a field aligned current whose intensity is proportional to the positive potential difference V between the ionosphere and magnetosphere. This linear relationship between J and V has been explained by using the kinetic theory first developed by Lemaire and Scherer. This exospheric theory is also able to explain the experimentally observed linear relationship between V^2 and q, the downward energy flux carried by the precipitated auroral electrons.

OUTER IONOSPHERE - M. ROTH

1 ABSTRACT

The total electron content of flux tubes and the electron densities, in both the equatorial plane and at the altitude of 1000 km, have been calculated for different models of electron distributions. The results for these different models are compared with those obtained when an empirical r^{-4} model for the electron density distribution along a geomagnetic field line (where r is the geocentric radial distance) is used in the interpretation of whistler observations. The results obtained have been shown to be useful for the analysis of a whistler whose propagation path cannot be experimentally specified as being definitely inside or definitely outside the plasmapause. They have also provided a strong support for the validity of the kinetic theory of ion-exospheres.

2 INTRODUCTION

From the measurements of the nose frequency f_n and propagation time t_n of a whistler one can determine $n_{eq}(L)$, the equatorial density of electrons in the magnetosphere, $n_0(L)$, the electron density at an ionospheric altitude of 1000 km, and $N(L)$, the total electron content of a flux tube (where L is the McIlwain parameter). These values will depend on the model adopted for the electron density profile along the magnetic field lines. An empirical r^{-4} radial dependence is often used for this density distribution and has been shown to fit the observations beyond the plasmapause[46]. In our study[47], we have compared the results obtained when different physical and empirical models are used for the whistler analysis .

3 EFFECTS OF FIELD-ALIGNED IONIZATION MODELS ON THE ELECTRON DENSITIES AND FLUX TUBE CONTENTS DEDUCED FROM WHISTLERS

The different models considered were: (1) the r^{-4} model, r being the geocentric radial distance along a geomagnetic field line[46]; (2) the constant density model; (3) the diffusive equilibrium model[48]; (4) the gyro frequency model[49]; (5) the collisionless model of Eviatar, Lenchek and Singer[50] for a nonrotating planet (ELS model); (6) a variant of the ELS model developed by Lemaire[51], including a finite planetary rotational rate.

These models were first used to compute the theoretical whistler nose frequency (f_n) as a function of the nose time delay (t_n) as well as the variations in the McIlwain parameter L of the whistler path. From these results, $n_{eq}(L)$, $n_0(L)$ and $N(L)$ were deduced for each model.

4 CONCLUSIONS

The L-value deduced from an observed whistler depends on the choice of the ionization model, but the L-values deduced with exospheric models are nearly the same as those obtained with the r^{-4} reference model. The equatorial density depends only moderately on the model. The ELS and Lemaire models give results quite comparable to the empirical r^{-4} model.

The choice of the model has much more influence when the density at 1000 km is deduced from a specific whistler observation. The exospheric models give values of $n_0(L)$ which are not very different from those deduced with the r^{-4} reference model. These results are useful for the analysis of a whistler whose propagation path cannot be experimentally specified as being either definitely inside or definitely outside the plasmapause.

The total electron content as deduced from a set of (f_n- t_n) values is rather insensitive to the model adopted to describe the ionization distribution in the field-aligned propagation duct of the whistler.

MAGNETOSPHERIC ELECTROMOTIVE FORCE AND THE FORMATION OF AURORAL ARCS - M. ROTH, J. LEMAIRE

1 ABSTRACT

In the framework of a kinetic theory for tangential discontinuities we modelled the electrical structure of the sheath which separates magnetospheric particle populations of different densities and temperatures. The model can equally be applied to the plasmasheet boundary layer (PSBL) in the tail or to the boundary of some plasmasheet cloud immersed in the central plasmasheet (CPS). For plasma parameters pertinent to the Earth's outer magnetosphere and plasmasheet, the electric potential differences across the transition layer are consistent with those required to account for the energized electrons associated with discrete aurora—much enhanced by the large scale potentials applied across the magnetosphere. These electric potential differences can be identified with the source of the electromotive force (EMF) required to create auroral arcs.

2 INTRODUCTION

Lyons et al.[52], Lyons[53], and Lyons and Evans[54] found evidence from coordinated auroral and magnetospheric particle observations that discrete auroral arcs are often located along magnetic field lines which mark the separation between different magnetospheric plasma populations. It is generally believed that these arcs arise because of magnetic field-aligned potential differences which energize and precipitate magnetospheric electrons. In addition to such field-aligned double layers, an ElectroMotive Force (EMF) located high in the magnetosphere is needed to drive the auroral current system.

3 ON THE FORMATION OF AURORAL ARCS

The EMF source that we suggest[55, 56, 57] is schematically illustrated in Fig. 7. It represents the projection in the terrestrial ionosphere of a plasma boundary layer located in the geomagnetic tail. This boundary sheet constitutes an EMF.

The EMF located in the magnetosphere, remote from the atmosphere, is an essential part of a current system that threads both the ionosphere and the source of EMF by means of field-aligned currents. These field-aligned currents have been discussed above.

The EMF electric potential difference is produced by thermo-electric charge separation at the interface between the two magnetospheric plasmas. This potential is distributed transverse to the magnetic field. This electric potential difference is identified with the EMF or in other words with a magnetospheric DC generator. Lyons[53] has shown that the existence of large electric potential differences over small dimensions transverse to the magnetic field is a necessary and sufficient condition to account for electric potential differences distributed along the magnetic field lines connecting that region with the ionosphere. Such potential differences along the magnetic field lines are responsible for accelerating magnetospheric electrons downwards to produce the discrete aurora. Due to pitch angle scattering associated with wave turbulence in the transition region and the presence of a conducting ionosphere, currents are allowed to flow to and from the ionosphere and close through the region of EMF.

4 CONCLUSIONS

The existence of two plasma populations that interface with one another leads directly to the creation of a space-charge separation and electrostatic potential difference in a direction normal to **B**. The potential distribution is highly stuctured with essentially two different scale lengths of variation: the average ion Larmor radius (or some multiple of this length) for the broad ion-dominated layers located at the

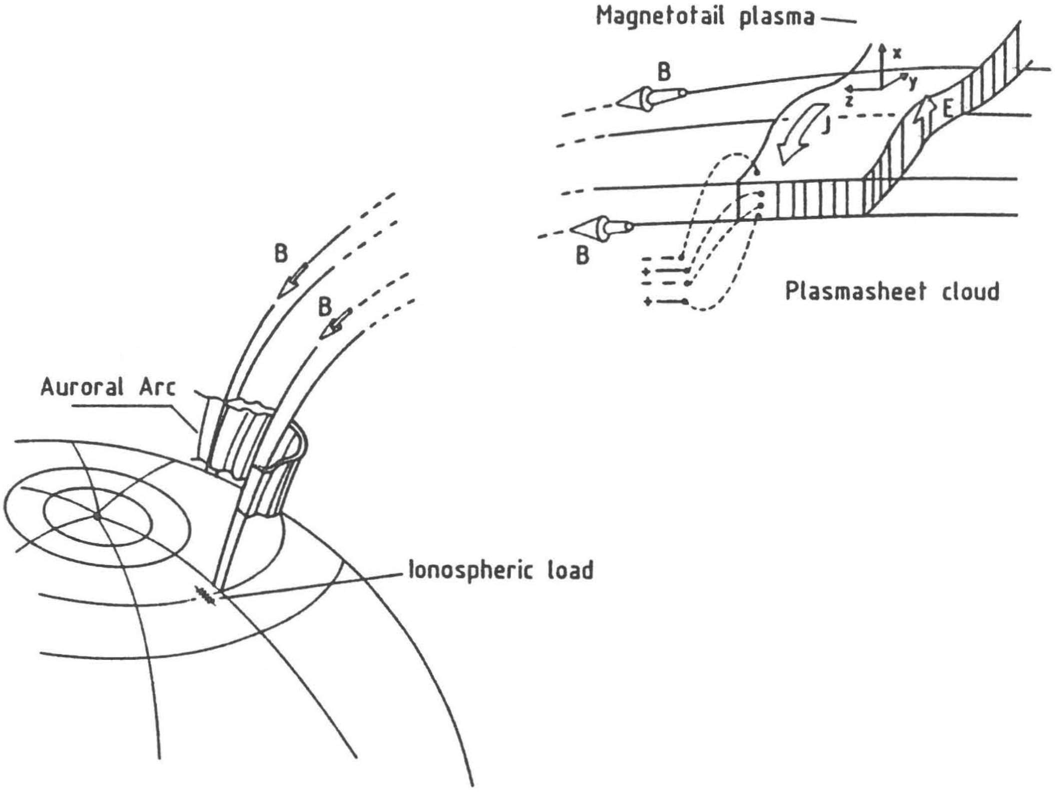

Figure 7 : Illustration of the plasma discontinuity (in this case a tangential discontinuity) generating an EMF at the surface of a plasmasheet density irregulartity (cloud or plasmasheet-lobe boundary), and its projection in the terrestrial ionosphere. Electric potential differences are produced by thermo-electric charge separation at the interface between the two plasma regions and are distributed transverse to the magnetic field in the x-direction. These potential differences map down into the ionosphere and drive Pedersen currents, provided the local ionospheric conductivity is large enough, i.e. that the system becomes loaded. Due to micro-instabilities in the interface region, electrons are scattered in the loss cone. Field-aligned double layers are formed as described in Section 4. The field-aligned potential drop accelerates the scattered and precipitating electrons to several keV. An auroral arc is formed by the bombardment of these electrons in the atmosphere. This auroral arc lasts as long as a large EMF is maintained in the magnetotail.

outer edges of the transition, and the average electron gyroradius (or some multiple of this length) for the central electron-dominated layer. For plasma parameters pertinent to the Earth's outer magnetosphere and plasmasheet, the largest scale size of the potential distribution transverse to the magnetic field is appropriate to auroral arc dimensions (10-50km), while the smallest scale size can account for the observed small scale structure within arcs (100 m).

When a large scale potential difference externally imposed across the transition layer is applied, the imposed electric field is concentrated at the interface. This gives rise to *localized* potential differences much larger than that produced by the contact between the two plasmas alone. Thus, the total available solar wind imposed potential difference is redistributed by the plasma populations to give rise to large potential differences appearing over small distances perpendicular to **B**—just the situation needed for the creation of an auroral arc.

For plasma parameters pertinent to the Earth's outer magnetosphere and plasmasheet, the electric potential differences across the transition layer are consistent with those required to account for the energized electrons associated with discrete aurora—much enhanced by the large scale potentials applied across the magnetosphere. These electric potential differences can be identified with source of EMF required to create auroral arcs.

Waves with spectrum near the lower hybrid frequency are generated. These waves scatter the pitch angles of electrons into the atmospheric loss cone. Dissipation processes will not change significantly the available potential and electric field intensities of the initially unloaded EMF, as long as the gradients in temperatures and densities are maintained, i.e. during a time interval of at least 1000 s: the estimated half lifetime of the transition.

THE PLASMAPAUSE FORMATION AND THE PLASMASPHERIC WIND

J. LEMAIRE

1 ABSTRACT

A sharp drop in the plasma density is observed at 4-6 R_E in the magnetosphere. It is called the plasmapause. The formation of the plasmapause surface is presented as a consequence of a peeling off mechanism occuring in the postmidnight sector during enhanced magnetospheric convection episodes. The physical mechanism of interchange motion, ignored in previous MHD theories for the formation of the plasmapause, is emphasized as a key physical process. The predictions of this model have been tested with whistler as well as with satellite observations. The existence of a continuous plasmaspheric wind, similar to the solar wind, has also been deduced from a series of plasmaspheric observations. A physical mechanism driving this continuous expansion of the inner magnetosphere has recently been proposed.

2 INTRODUCTION

The plasmapause is the outer edge of the plasmasphere. This boundary is located at an equatorial distance of 4-6 Earth radii (R_E) where the low energy (< 1eV) plasma density decreases abruptly by almost two orders of magnitude over a radial distance sometimes less than 0.2 R_E (≈ 1200km). This boundary was discovered in 1960 by K.I. Gringauz from LUNIK 2 measurements[53], and independently from whistler observations by Carpenter[59, 60] The position of this boundary was first assumed to be determined by the last closed equipotential (LCE) of the large scale magnetospheric convection electric field[61]. Although this MHD model has been able to explain certain features of the plasmapause surface, it failed to account for other main physical aspects. Alternative models were then proposed in 1970 by Grebowsky[62], and in 1972 by Chen and Wolf[63]. In 1974, Lemaire[64] suggested a different scenario for the formation of this sharp plasmapause boundary. This work has been published in a series of papers described below and was presented as a *Thèse d'agrégation de l'enseignement supérieur*[65].

3 THE PLASMAPAUSE AND PLASMASPHERIC WIND

The plasma trapped along closed magnetic field lines inside the plasmasphere is nearly corotating with the ionosphere. Therefore, the opposite gravitational and centrifugal forces are balancing each other at a synchronous orbit. This determines the position of the zero-radialforce (ZRF) surface, whose equatorial cross section is a circle at radial distance of 6.6 R_E in the case of solid corotation. Lemaire[64] suggested that it is at the point of deepest penetration of the ZRF surface that the plasmasphere is peeled off by plasma interchange motion[64, 66]

This peeling-off mechanism occurs preferentially after the onset of a substorm in the post-midnight local time sector where and when the eastward convection velocity is larger than the corotation velocity[67, 68]. Furthermore, since the growth rate of interchange instability is inversely proportional to the integrated Pedersen conductivity, it is in the post-midnight sector that this peeling-off mechanism is

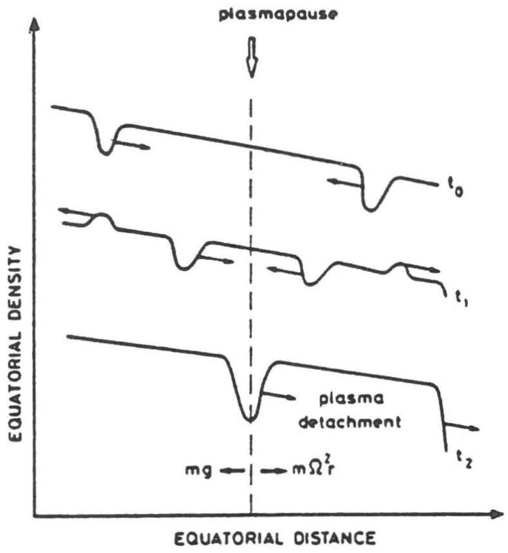

Figure 8 : Equatorial density distritbution with two plasma holes drifting toward a common asymptotic trajectory determined by the balance between the gravitational force and the radial component of the pseudo centrifugal force. All plasma holes collect along this trajectory wich is along the "zero-radial-force" surface. As a consequence, a trough is developing along this surface. The large plasma density enhancement formed beyond this surface drifts away from the main plasmasphere by interchange motion. A sharp "knee" in the equatorial density is left over when the block of plasma has separated from the core part of the plasmasphere which remains trapped in the gravitational potential well.

fastest and most efficient. Indeed, the integrated Pedersen conductivity has its mimimun value in this local time sector[69, 70, 71]. Density depressions in the magnetosphere are all moving towards a surface where the gravitational force is balanced by the pseudo centrifugal force. At that surface, a deep hole is developing in the plasma distribution in an unstable manner. The plasma layer located beyond that hole is breaking off from the plasmasphere. This loose element moves then away from the Earth, leaving at the surface of the "break" an important density gradient which is identified with the plasmapause by Lemaire.

This peeling-off mechanism is illustrated in Fig. 8 where a detached plasma element is drifting away from the main body of the plasmasphere which remains confined in the gravitational potential well. Beyond the newly forming plasmapause the gravitational pull is not large enough to balance the radial component of the enhanced inertial-centrifugal force.

Lemaire and Kowalkowsky[72] examined a large number of equatorial density distributions from the OGO-5 satellite to determine the local distribution of detached plasma elements outside the plasmasphere. Besides the population of detached plasma elements already identified in the afternoon sector by Chappell[73], Lemaire and Kowalkowsky[72] found a significant number of detached elements in the post-midnight sector. These nightside detached plasma elements were most often observed when K_p was high: i.e. during periods of disturbed geomagnetic conditions when the eastward convection velocity is expected to be large and therefore when Lemaire's peeling-off mechanism is expected to work in this local time region.

A computer model simulating the formation and deformation of the plasmapause has been developed by Lemaire using a *Kp* - dependent magnetospheric electric field model[74], i.e. McIlwain's E3H electric field model with an adhoc *Kp-dependence* of its parameters, similar to the *Kp* - dependence of the dawn-dusk *E* - field component in the Stern-Volland model[65]. Using this computer code, the positions of the plasmapause have been calculated for extended periods of time when whistler data were available from the Kerguelen station[75]. The comparison of plasmapause positions determined from these whistler observations and the calculated ones has shown interesting correspondences with Lemaire's model, as well as with an MHD model based on the Stern-Volland E-field. DYNAMIC EXPLORER observations have also been compared with the predictions of Lemaire's model for the formation of the plasmapause[76]. The results were supported by the observations in many cases. However, to improve the results of such simulation models of the plasmapause and plasmasphere motions, more comprehensive and time de-

pendent empirical models for the magnetospheric electric field distribution would be needed.[77, 78, 79]
The exospheric distribution of plasma along a corotating magnetic flux tube was studied in 1974 by Lemaire[80, 81] on the basis of a kinetic theory similar to that used in Lemaire-Scherer polar wind models. The existence of an equatorial potential well along corotating flux tubes was emphasized in this study as a means to trap cold (< 0.5eV) ions near the equatorial plane.

The existence of a slow radial outward expansion of the whole plasmasphere was postulated in 1992 by Lemaire and Schunk[82], on the basis of a series of plasmaspheric observations. This subsonic outward transport of plasma within the plasmasphere is called the "plasmaspheric wind". Lemaire and Schunk suggest that this plasmaspheric wind is due to interchange motion of plasma density irregularities driven by ∇B and curvature drifts[83]. Such a slow plasmaspheric wind flow would enable continuous transport of ionization from deep into the plasmasphere up to its outermost regions. From there, it is evacuated in a much faster and catastrophic manner during periods of substorms by the peeling-off mechanisms outlined above. The plasmaspheric wind contributes in the evacuation of Helium from the low latitude region. Therefore it helps to resolve the long-standing problem of the Helium budget in the Earth's atmosphere.

4 CONCLUSIONS

The sharp "knee" observed in the ionization profile at 4-6 R_E is explained as the consequence of a peeling-off mechanism occuring in the post-midnight sector during enhanced magnetospheric convection episodes. The physical mechanism of interchange motion, ignored in previous MHD theories for the formation of the plasmapause, is emphasized by Lemaire[65] as a key element. The predictions of this model have been tested with whistler as well as with satellite observations. The existence of a continuous plasmaspheric wind, similar to the solar wind, has been deduced from a series of plasmaspheric observations. This continuous expansion of the inner magnetosphere is driven by plasma interchange motion.

SPACE BOUNDARY LAYERS - M. ROTH, J. LEMAIRE

1 ABSTRACT

Different types of boundary layers may be formed in space plasmas. A first type may be classified as *tangential discontinuity* (TD). This type of discontinuity describes a structure where the field and flow are tangential to the boundary surface. *Inclined shocks* structures where both the plasma flow and the magnetic field cross the surface of discontinuity represent another type of discontinuity. Vlasov equilibrium models of tangential discontinuities in collisionless plasmas have been developed at the Institute of Space Aeronomy and have been applied to the description of the internal structure of the Earth's plasmapause, of TD's and magnetic holes in the solar wind, and of the Earth's magnetopause. The space charge separation electric field inside TD's has also been studied. The results of this study have led to a mechanism of formation of discrete auroral arcs as described previously.

An interdisciplinary investigation of Directional Discontinuities in the solar wind was selected by ESA/NASA in the framework of the space mission *ULYSSES*. High amplitude electric field oscillations at very low frequencies, detected by the satellite *PROCNOZ-8* near the magnetopause were also analysed in collaboration with a team of the Space Research Institute (Russian Academy of Sciences, Moscow).

2 INTRODUCTION

Space plasmas have a general tendency to divide themselves into distinct regions by setting up a number of boundary surfaces[84]. These boundary layers separate plasmas possessing drastically different parameters and are due to electric sheet currents. Space exploration has shown that such layers are formed, e.g. at the magnetopause, and in the solar wind (directional discontinuities[95], magnetic holes[96]). Earth-like boundary layers resulting from the interaction of the solar wind with the intrinsic magnetic field of Jupiter, Mercury and Saturn have also been observed. On the interstellar and intergalactic scales, space in general is expected to have a "cellular structure"[85].

Observed current layers in space can be very thin, sometimes only a few ion Larmor radii. The plasma kinetic theory is therefore the most appropriate tool to study the equilibrium structure and stability properties of these collisionless plasma regions. Investigations of kinetic plasma processes within such layers are very important as the latter control the mass and energy exchanges between the different adjacent regions. Kinetic plasma processes in magnetospheric boundary layers control the overall dynamics of the Earth's magnetosphere, e.g. govern important phenomena like magnetospheric substorms and aurora.

The first kinetic description of the magnetopause was made by Ferraro[86], for the case of monokinetic solar plasma clouds impinging on the Earth's dipole magnetic field. Vlasov equilibrium models of tangential discontinuities in collisionless plasmas have been first discussed in the context of thermonuclear containment. Harris[87] considered a pinch configuration in which a charge-neutral layer (i.e. with no electric field) was confined between two oppositely directed magnetic fields produced by perpendicular flowing currents.Multidirectional currents—producing a rotation of the magnetic field—were also considered in the models of Kan[88], Alpers[89], and Channell[90], but only in the case of exact charge neutral layers. Sestero[91] was the first to consider the small charge separation electric field normal to the transition layer and obtained solutions which scale according to the electron/ion Larmor radius. In 1966, Sestero[92] generalized his first model taking into account shears of the plasma bulk motion across the magnetic field.

3 KINETIC MODELS OF TD'S IN SPACE PLASMAS

The models of Sestero[91, 92] did not take into account changes in plasma composition and temperatures nor the rotation of the magnetic field. In 1976, Roth[93] generalized Sestero's model[92] to include changes in plasma composition and temperatures. He obtained an electrostatic model characterized by an unidirectional magnetic field, in a multispecies plasma with velocity shear. This model was applied to the description of the plasmapause structure. Also in 1976, Lemaire and Burlaga[94] developed a similar kinetic model where the bulk velocity shear was replaced by a shear in the magnetic field distribution. They applied their model to the study of solar wind TD's[94, 95] and magnetic holes[96 ,97].

None of the previous models included simultaneous shears of the magnetic field distribution and plasma bulk velocity. In 1978, Roth[98] obtained such a generalized model of TD's. This model includes the charge separation effects, the bulk velocity shear, the changes in plasma composition (multispecies plasma with different temperatures and mean velocities), and the shear of the magnetic field. This model is called the IASB model[98, 100, 101]. It was applied to the study of the Earth's magnetopause[98, 99,100,102,103]. It was used in IASB contributions to the *ULYSSES* interplanetary space mission[104, 105], in the framework of an interdisciplinary study of directional discontinuities in the solar wind.

The validity of the so-called *charge-neutrality approximation* was verified by solving Poisson's equation to calculate the electric potential in kinetic models of TD's[106]. Charge separation effects were also studied in the framework of auroral electron precipitation[55, 56, 57]. Furthermore, observational data from ISEE and *PROGNOZ-8* satellites were used to analyse the structure of the magnetopause current layer[102, 107].

4 CONCLUSIONS

The IASB model describing tangential discontinuities in collisionless plasmas is based on the kinetic description of plasma. The magneto-hydrodynamic (MHD) theory is a rather different approximation in plasma physics. The latter is unable to describe the structure of thin current sheets and double layers.

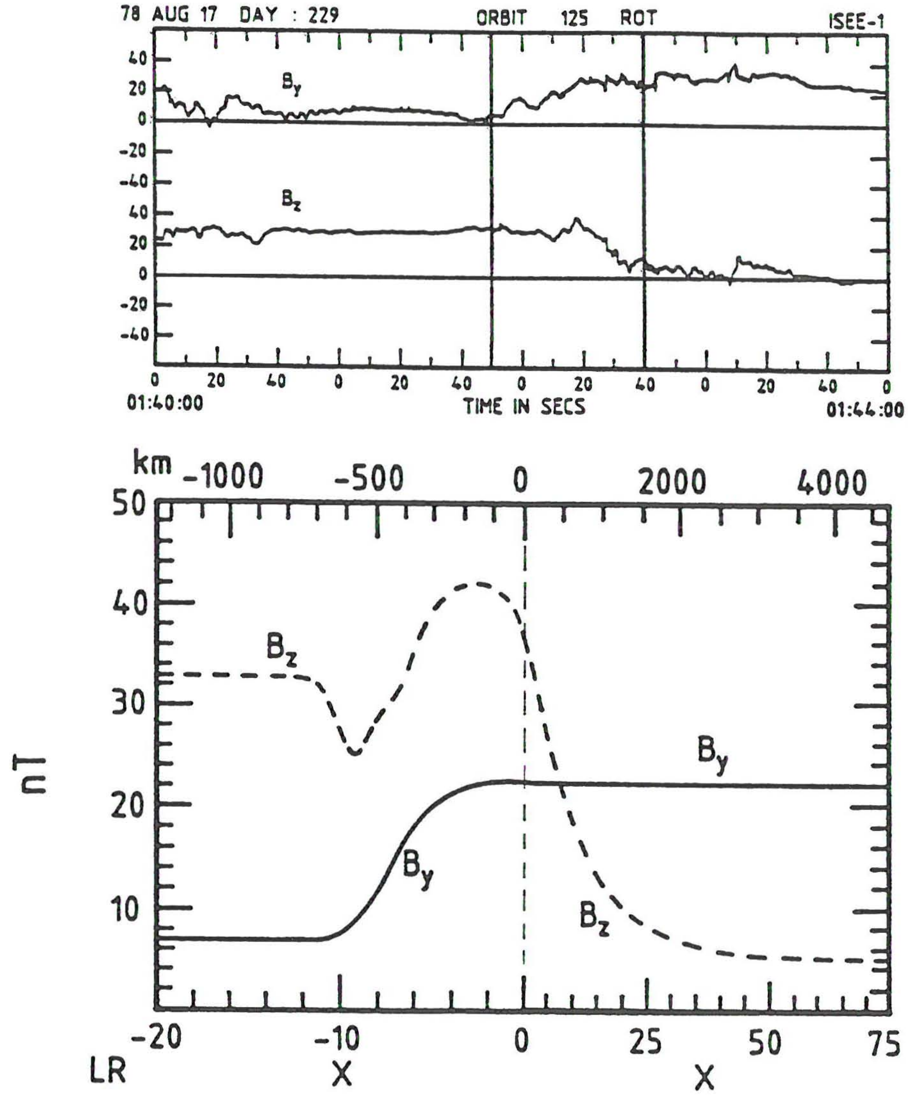

Figure 9 : Top panel: High-time resolution measurements of the magnetic field obtained on board the satellite ISEE1, during a magnetopause crossing (courtesy: C.T. Kussell, UCLA). A minimum variance analysis was carried out to illustrate the B_y and B_z components tangential to the magnetopause. The magnetopause crossing occurs between 01:41:50 UT and 01:42:40 UT. Corresponding plasma data were those obtained by the LEPEDEA experiment (courtesy of T.E. Eastman, University of Iowa).

Bottom panel: Computer simulation of this observed magnetic field variation using the kinetic model of Roth[98]. Plasma parameters pertaining to the velocity distribution functions were fitted to reproduce the observed plasma and field variations across the magnetopause.

Except for the small-scale time dependent fluctuations of the magnetic field, it can be seen that both profiles of B_y and B_z are well reproduced. Note in particular that the x-scale has been reduced on the magnetospheric side ($x > 0$) to reproduce the observed slow decrease of B_z. A J_y current component carried by high-energy magnetospheric particles is responsible for this B_z variation.

This inefficiency of MHD models was pointed out by Eastman[108] and Roth[109] in the case of the Earth's magnetopause. It has also been shown[103] that our model is more appropriate than the kinetic model of Lee and Kan[110] for configurations with large rotation angles of the magnetic field and non-zero flow velocity shear.

The most recent version of the IASB model[111] is a powerful tool to study the structure of tangential discontinuities in space (or even laboratory) collisionless plasmas. This includes some of the boundary layers resulting from the cellular structure of space plasmas, including planetary and pulsar magnetopauses, cometary tails and micro-structure of stellar winds.

It has been compared to experimental data[102] (see Fig. 9). In the future, it should become the most important theoretical tool of our interdisciplinary study of directional discontinuities in the solar wind[104], within the framework of the *ULYSSES* mission.

From the theoretical point of view, the problem of the non-uniqueness of the velocity distribution functions[112] should be taken into consideration. Kinetic models of directional discontinuities where both the normal components of the magnetic field and plasma flow are small can be considered as "slightly modified" 2-dimensional TD's.

STABILITY OF THE MAGNETOPAUSE - M. ROTH, IASB

1 ABSTRACT

Plasma microinstabilities are generated at the Earth's magnetopause by currents and beams existing in the current layer itself. We have argued that the modified two-stream instability and/or the lower-hybrid drift instability could explain the high frequency fluctuations observed at the magnetopause. The Vlasov kinetic approach was used to study the stability of the magnetopause with respect to low-frequency tearing-type electromagnetic perturbations. For this study, the IASB model of TD's is used for the unperturbed equilibrium state.

2 INTRODUCTION

Microinstabilities at the Earth's magnetopause have been observed using plasma wave detectors[113]. These waves are believed to be generated by currents and beams. The currents are necessary to sustain the jump in the magnetic field, whereas the beams may be generated by electric fields. Emissions are observed at a wide range of frequencies, ranging from a few Hertz up to 200-300 kHz. This ranges from the vicinity of the lower hybrid frequency to the electron plasma frequency. The thresholds for current-driven microinstabilities are well known[114] and usually require the plasma cross field drift to exceed a certain value. When this drift exceeds the ion thermal speed, generation of lower hybrid turbulence may be possible.

The conditions of spontaneous excitation of longwave perturbations (with wavelength much larger than the thickness of the current layer) depend not only on the local values of the plasma parameters near a given magnetic surface within the current layer but mainly on the global structure of the layer which determines the free energy of the perturbations. An important large-scale instability is the tearing instability which operates due to the free energy contained in sheared magnetic field configurations (like the Earth's magnetopause). The drift tearing mode is known to be responsible for the growth of magnetic islands. The growth of multiple tearing modes, the subsequent overlapping of magnetic islands and stochastic diffusion of magnetic field lines through the destructed magnetic surfaces has been imagined as a *magnetic field percolation* through the current layer (Galeev et al. [115])

When analysing these processes with the help of the kinetic Vlasov formalism, some problems arise related to the choice of the initial equilibrium configuration. In papers by Galeev and Zelenyi[116], Kuznetsova and Zelenyi[117, 118], Galeev et al.[115], the linear thresholds for the destruction of magnetic surfaces and the nonlinear evolution of the magnetic islands were investigated for the case of the exactly charge neutral Harris equilibrium model[87] (a symmetrical configuration separating two plasmas with equal densities, temperatures and absolute values of the magnetic field, while containing a shear property suitable to the magnetopause structure, i.e. the rotation of the magnetic field vector by an angle that is always less than 180°). Realistic boundary layers are however a mixture of plasmas of different origins having not necessarily identical plasma and field parameters on their outer edges. Furthermore, such realistic layers represent in general electrostatically non-equipotential configurations. We were the first using realistic asymmetrical TD's configurations as initial equilibrium stuctures to carry out the analysis of the collisionless tearing instability, using the Vlasov formalism.

3 STABILITY ANALYSIS OF THE MAGNETOPAUSE

The study of current-driven microinstabilities at the Earth's magnetopause has been studied in two papers by Roth[99, 100]. Such microinstabilities are expected to relax the strong gradients in both the plasma density and flows. Potential candidates are lower-hybrid instabilities like the modified two-stream instability[119] or the lower-hybrid drift instability[120, 121]. In large ion-dominated layers, the lower-hybrid drift instability which is driven by the ion diamagnetic current, can contribute to a wave spectrum near the lower-hybrid frequency. Modes driven by the electron cross-field current are expected to be unstable in thin electron-dominated layers, where the electron cross-field current largely exceeds the ion diamagnetic current. In these electron layers, the modified two-stream instability, which is driven by relative streaming of electrons and ions across the magnetic field, can be expected to contribute most to the electrostatic noise near the lower-hybrid frequency. In our kinetic models of the magnetopause, we argued that the modified two-stream instabilty[119] or the lower-hybrid drift instability[121] could explain the observed high frequency fluctuations. We found[99, 100] that the thickness of stable layers should depend on the ion to electron temperature ratio and the density jump. For a typical range of plasma parameters at the dayside magnetopause, the variation was not found significant, and a constant 2.5 ion gyroradii thick layer was predicted.

The possible occurrence of the tearing mode instability[122] at the magnetopause was inspired by magnetotail studies. However, since the magnetic field does not vanish at the centre of the magnetopause current layer, Landau resonant electrons are forced to follow a guiding centre motion. Hence, the tearing process occurs in the guide-field limit. It was shown that the approach by Galeev et al.[115] was not appropriate for the case of nearly opposite directions of magnetosheath and magnetospheric magnetic fields. Using realistic equilibrium models of the magnetopause current layer, we have investigated, using the Vlasov formalism, the influence of the flow asymmetry on the structure and stability of the layer for the case of nearly oppositely directed asymptotic magnetic fields[103]. We have also investigated the stability of magnetic surfaces due to excitation of collisionless tearing perturbations within the magnetopause with asymmetric magnetic field profiles, modelled by a self-consistent Vlasov equilibrium[123]. Such an approach has enabled us to take into account the electric field normal to the magnetopause, to obtain more accurate expressions for the "free energy" of tearing perturbations that could be excited at a given magnetic surface within the layer, to consider effects dealing with the finiteness of the ion Larmor radius and the stabilizing influence of the field-aligned ion oscillations. On the basis of this study, the Galeev et al.[115] approach was reconsidered and generalized.

4 CONCLUSIONS

An important topic in the study of TD's is their stability to infinitesimal perturbations. We have shown that lower hybrid modes are important. This conclusion was also found in hybrid numerical simulations of TD's for parameters representative of both the solar wind and magnetopause[124].

To illustrate the physical mechanism of the tearing instability, we have used the IASB equilibrium kinetic model depending on parameters characterizing different asymmetry factors proper to the magnetopause. The presence of a shear flow strongly influences the adiabatic interaction of the plasma with low-frequency tearing-type electromagnetic perturbations, as well as the non-adiabatic response of the particles near the centre of the magnetopause. This results in a reduction of the growth rate of the tearing mode[103]. The presence of asymmetrical magnetic field profiles significantly modifies the free energy of the perturbations, controlled by the global plasma and field distributions, and the singular current, controlled by the local values of the plasma density and magnetic field near the centre of the magnetopause[123].

NON-STEADY STATE SOLAR WIND-MAGNETOSPHERE INTERACTION

J. LEMAIRE, M. ROTH

1 ABSTRACT

The idea that solar wind plasma-field irregularities (i.e. plasmoids) with an excess momentum density penetrate deeper into the geomagnetic field was introduced in 1976 by Lemaire and Roth. This new concept was based on magnetic field observations showing that most of the time the solar wind is patchy over distances smaller than the diameter of the magnetosphere. Transient and impulsive interaction processes between the solar wind and the magnetosphere have now become an important and highly debated topic.

2 INTRODUCTION

Two classes of theories describing the interaction of the solar wind and the geomagnetic field have been debated until the mid-seventies. The first theory introduced by Dungey[125] assumes that steady state reconnection occurs continuously at the front side of the magnetosphere. This first class of models, based on the loosely defined paradigm of reconnection or merging of magnetic field lines, leads to open magnetospheric models. On the other hand, the second class of interaction models, called the "viscous interaction models[126], leads to a closed magnetospheric model within which all geomagnetic fields are confined like in a closed nutshell. According to this type of models, the magnetosphere is bounded by a closed magnetopause surface similar to the tangential discontinuities discussed previously and illustrated in Fig. 10a. Both classes of models are steady-state interaction models, since the solar wind impinging on the geomagnetic field was assumed to be quasi-uniform over distances larger than the diameter of the magnetosphere, and quasi-steady over times long compared to the time of propagation of the solar wind along the magnetopause surface.

However, the paradigm of a uniform and steady-state solar wind and steady-state magnetospheric models was questioned by Lemaire[127, 128], in 1975, when he visited the Laboratory for Extraterrestrial Physics at Goddard Space Flight Center for a six month leave of absence from IASB. Indeed, in collaboration with Burlaga and Turner, Lemaire examined and analysed high resolution solar wind magnetic field and simultaneous plasma observations from EXPLORER-43. They studied the general characteristics and frequency of observations of directional discontinuities[95] and discovered the existence of "magnetic holes" in the interplanetary magnetic field distribution[96]. On the basis of these observations, Lemaire inferred that the solar wind contains almost all the time small scale diamagnetic currents and plasma irregularities. Lemaire and Burlaga[97, 94] developed at GSFC the kinetic theory of these diamagnetic magnetic holes and interplanetary current sheets. The presence of these irregularities indicates that the solar wind momentum density is not uniform over distances much smaller than the diameter of the magnetosphere, and that the dynamic pressure of the solar wind upon the magnetosphere is patchy, non-uniform, and continually changing rapidly in time.

This new idea and the non-steady interaction mechanism between the solar wind are illustrated in Fig. 10b. They were presented for the first time[132] at the symposium on "Physics of the Magnetopause", organized in 1976 by Lemaire and Rycroft[129], in Amsterdam, at the EGS general assembly.`

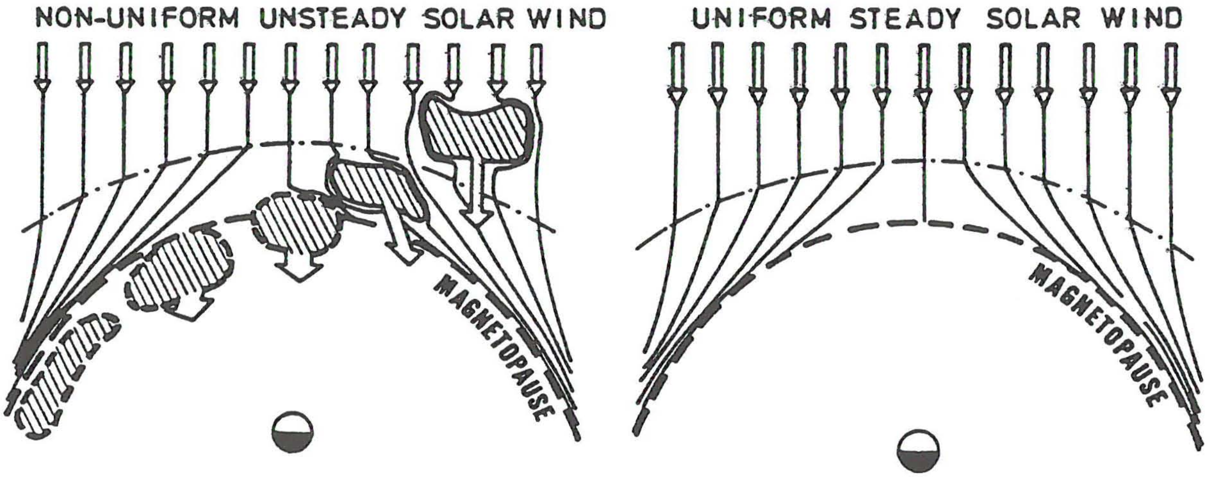

Figure 10 : (a) When the solar wind is steady and uniform, the magnetopause is a smooth surface along which the solar wind slips without penetration. (b) When the solar wind is nonuniform and unsteady, plasmoids carried in the solar wind will be able to penetrate deeper in the geomagnetic field provided they have an excess momentum density. Both drawings represent equatorial sections of the magnetosphere (after[132]).

3 ON IMPULSIVE PENETRATION OF SOLAR WIND PLASMOIDS INTO THE GEOMAGNETIC FIELD

The solar wind plasma irregularities are "plasmoids", a word which means "plasma-magnetic entities"[130]. These plasmoids can penetrate inside the geomagnetic field beyond what is considered to be the mean position of the magnetopause. These plasma elements penetrate deeper when they have an excess momentum density with respect to the background solar wind plasma. Collisionless solar wind plasmoids are thrown into the geomagnetic field, just like rain droplets penetrate impulsively through the surface of a lake[131]. This idea is illustrated in Fig. 10b showing a series of plasmoids at different depths inside the magnetosphere.

The theory of impulsive penetration and its consequences have been explained in a series of papers[128], [131]-[142]. The distance of penetration of plasma elements in the Earth's magnetosphere is calculated by Lemaire[136], and applied to the magnetosphere of Jupiter. He showed that due to electrodynamic coupling of the intruding plasma droplet with the resistive ionosphere the stopping distance is inversely proportional to the integrated Pedersen conductivity along dayside cusp magnetic field lines[136]. The excess kinetic energy of these solar wind plasma irregularities is dissipated by Joule heating in the ionosphere. This dissipated energy produces the observed plasma temperature peak in the ionospheric trough region[132, 138]. Other geophysical consequences of this non-steady state theory are suggested in the references[131, 136].

The adiabatic and non-adiabatic deceleration mechanisms of plasmoids impulsively penetrating in the non-uniform geomagnetic field were presented in detail by Lemaire[139]. In this article, Schmidt's theory[143] for the motion of plasma-magnetic entities was generalized for the case where the magnetic field distribution is sheared. These theories are supported by laboratory experiments[144, 145] which have been discussed by Lemaire[135].

It has been shown that the interaction of a solar wind plasmoid having an excess density with the magnetosphere depends upon the orientation of the IMF[137, 140]. It has been shown[141, 134] that the actual entry mechanism differs from ideal MHD entry mechanisms like those proposed by Schindler[146] and by Heikkila[147].

In these alternative scenarios, the plasmoids are infinitely long flux tubes, while those in the Lemaire-Roth theory have a finite extent, and the magnetic flux inside the plasmoids is interconnected with the

external magnetic flux. More importantly, the electric field distribution E in the vicinity of Lemaire-Roth's plasmoids may have a component parallel to the magnetic field direction $\mathbf{B}$, i.e. $\mathbf{E}\,\mathbf{B} \neq 0$.
A video montage available at IASB has been produced to illustrate the time dependent interconnection of interplanetary magnetic field lines with geomagnetic field lines, when a diamagnetic solar wind plasmoid is injected impulsively into the magnetosphere[142, 148].
Recently, Lemaire and Roth[133] presented a comprehensive review of their theory in *Space Science Reviews*. Shorter versions of this review were also prepared elsewhere[149, 134].

4 CONCLUSIONS

High-time resolution interplanetary magnetic field[95] and plasma[150] measurements indicate that plasma irregularities are present in the solar wind. These irregularities can penetrate impulsively into a closed magnetosphere across a tangential discontinuity[139], transferring energy, mass, and momentum to the magnetosphere and to the coupled ionosphere. Measurements of magnetic field and plasma irregularities in the magnetosphere support this scenario and provide evidence that "plasmoids" in the solar wind have penetrated into the magnetosphere across closed magnetic field lines[151, 138].
The interaction models of a patchy solar wind with planetary magnetospheres and comets[152] challenged the early steady-state ideal MHD descriptions. They take into account the time variations in Maxwell's and Vlasov's equations. A new controversy has now replaced the early one concerning the openness and closeness of the magnetosphere. The current issue is now whether the plasma and field signatures commonly observed in the magnetopause region are either explosive events produced locally by some instability, or 3-D diamagnetic plasmoids convected in from the solar wind.

CONTRIBUTIONS TO THE STUDY OF THE VAN ALLEN BELTS

J. LEMAIRE, D. HEYNDERICKX, M. ROTH, V. PIERRARD

1 ABSTRACT

The velocity distribution of relativistic electrons trapped in the geomagnetic field can be represented by the superposition of two maxwellian populations. The soft and hard electrons have different concentrations in the inner and outer radiation belts. The spatial distribution of the energetic electrons and protons in the Van Allen belts changes due to the secular variation of the geomagnetic field. When the empirical AE-8 and AP-8 models[158] are used to predict the radiation doses along the orbit of a future satellite, the original Jensen & Cain[159] and GSFC 12/66[160] magnetic field models (for epochs 1960 and 1970, respectively) should be used to determine the corresponding B,L coordinates, instead of the modern International Geomagnetic Reference Field (IGRF) models. New updated empirical models are currently being designed at IASB/BIRA. They are based on more recent and comprehensive particle flux measurements from CRRES and other modern satellites.

2 INTRODUCTION

The magnetospheric Van Allen zones are populated with energetic electrons and ions with energies from 100keV to 100MeV. These particles are trapped in the Earth's magnetic field for long periods of time and are damaging for electronic spacecraft components and astronauts. Their distribution in space usually has been mapped in terms of the B, L coordinate system which was introduced in 1961 by McIlwain[161].

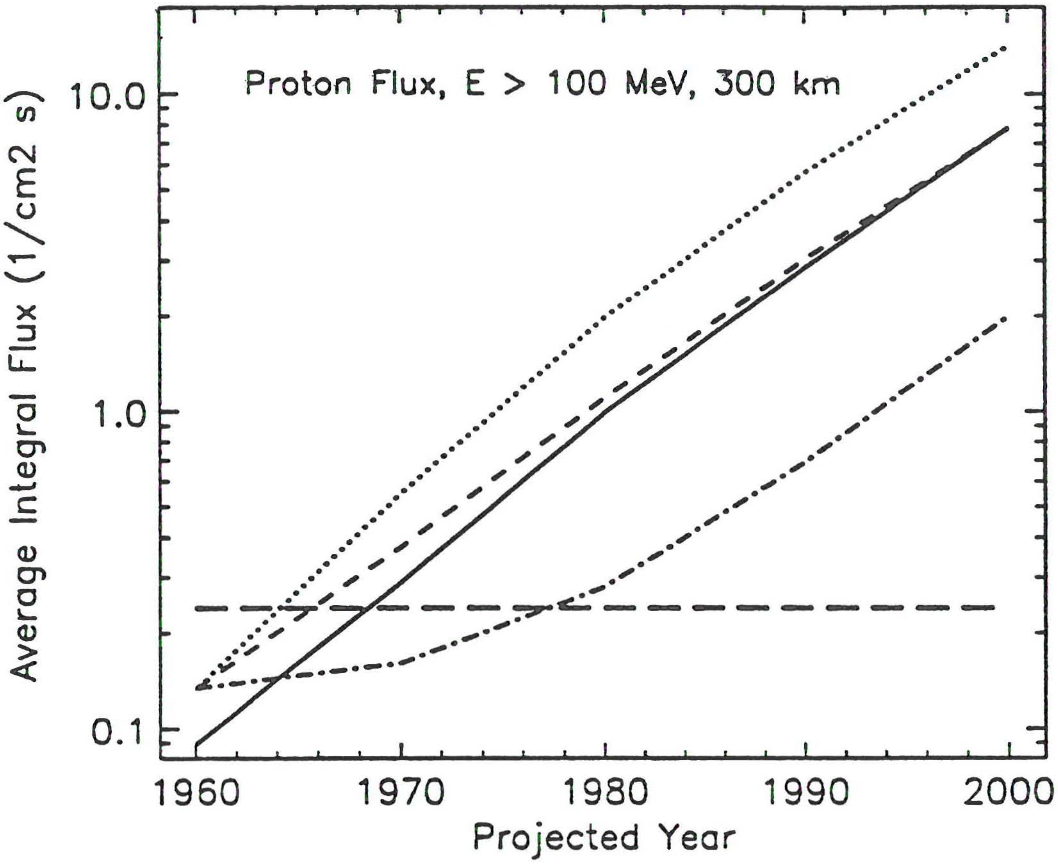

Figure 11 : Average integral proton flux for E > 100 MeV over 13 circular orbits at altitude 300km and inclination 28.5°, obtained with the AP8MIN model. The different lines represent the results obtained by successive cancellation of the secular variations of the multipole terms representing the Earth 's magnetic field distribution. The artificial increases of the average flux values as a function of epoch (projected year) are the consequence of the secular decrease of the Earth's magnetic dipole, as well as of the secular variation of higher order multipole terms in the harmonic expansion of the International Geomagnetic Reference Field (IGRF) model.

3 STUDY AND RESULTS

In 1962, Lemaire[162] studied the trapping conditions of charged particles in the geomagnetic field. He calculated W_{max}, the maximum energy below which ions of charge Ze and mass m can be trapped in the geomagnetic field: i.e. the energy above which the Alfvèn conditions are not satisfied (see also[163] and[164]).

Since 1989, IASB/BIRA gained renewed interest for models of the Van Allen zones and participated with other European Laboratories (Mullard Space Science Laboratory, MATRA, Space Technology Ireland) in a Development Study of Improved models of the Earth's Radiation Environment. This study, also called TREND (TRapped Radiation ENvironment Development), was commissioned by ESA/ESTEC. Lemaire was the project manager of the TREND project. Within the framework of this ESA contract, the AE-8 and AP-8 models were reviewed and evaluated. Recommendations concerning future studies, model developments, and flight requirements were proposed in a series of Technical Notes, reports and articles[165, 166, 167].

The TREND study showed, for instance, that the secular evolution of the Earth's dipole moment and of its eccentric distance has a sizeable long term effect on the distribution of energetic charged particles trapped in the geomagnetic field above the atmosphere. Figure 11 illustrates the artificial increase of the predicted average flux along a low altitude circular orbit when the secular variation of the geomagnetic field is taken into account. The large increase in the predicted average flux (dotted curve) between 1960 and 2000 is a consequence of the secular variations of the dipole, quadrupole, octupole and higher order components of the geomagnetic field. When the secular variations of the multipole terms are successively inhibited, the predicted average flux becomes less and less sensitive to the epoch. As a consequence of this result, the TREND team recommended not to use updated IGRF magnetic models to compute the B,L coordinates when the AE-8 and AP-8 particle flux models are used. The original Jensen & Cain[159] and GSFC 12/66[160] magnetic field models should be used with AE-8 and AP-8 since these magnetic field models were employed to build the latest NASA particle flux models[168]. TREND also recommended that minimally intrusive energetic particle detectors be incorporated in all spacecraft orbiting in the harsh environment of the radiation belts.

In a follow-up TREND-2 study, also commissioned by ESA/ESTEC, Lemaire and Heynderickx[169, 170] have proposed and implemented an adhoc rotation of the satellite coordinate system to shift the South Atlantic Anomaly of the geomagnetic field by about 0.3°/year in the eastward direction in order to replace it were it was located in 1960 or 1970 according to the appropriate magnetic field model. This change in the ESA-UNIRAD software minimizes the errors made in the predictions of radiation fluxes, especially along low altitude orbits like those of the Space Shuttle and the Space Station.

The PROTEL measurements of the CRRES satellite are being analysed by Heynderickx[171] at BIRA/IASB in order to update the AP-8 model. A new model based on a coordinate system taking into account the effect of the Earth's atmosphere will also be investigated.

Pierrard and Lemaire[172] have studied the energy spectrum of Van Allen electrons in the range between 100 keV and 4 MeV. They showed that the velocity distribution of these relativistic electrons can be represented by the superposition of two maxwellian functions. The temperatures and densities of these two electron populations vary with the radial distance. The soft electrons with the lowest temperature (70-90 keV) dominate the inner electron zone, while the harder electron spectra corresponding to higher

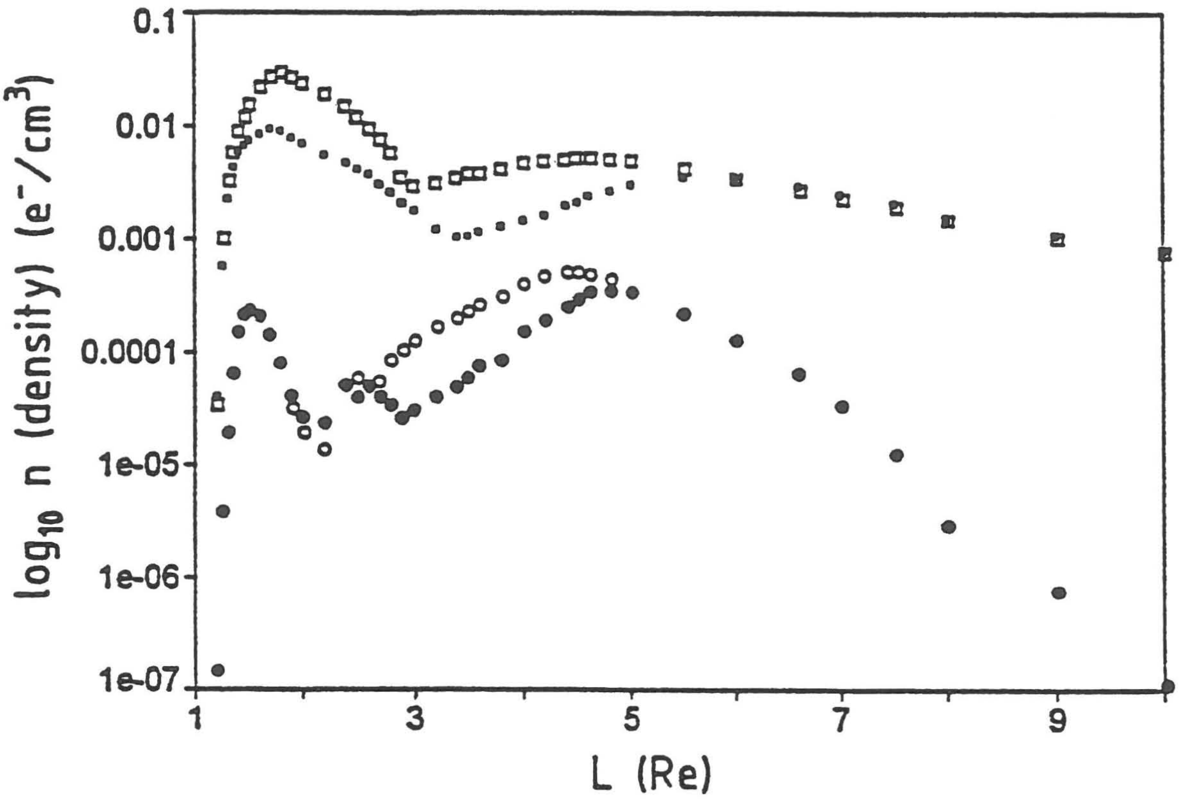

Figure 12 : Equatorial distribution as a function of L of the densities of the soft electrons and of the hard electrons o. These electron densities correspond to the AE8MIN model (solid symbols) for minimum solar activity conditions, and to the AE8MAX model (open symbols) for maximum solar activity conditions.

temperatures (250-450keV) dominate in the outer electron zone. This is illustrated in Fig. 12 which shows the number densities of both electron populations as a function of L.

4 CONCLUSIONS

The velocity distribution of relativistic electrons trapped in the geomagnetic field is the superposition of two maxwellian populations which have different concentrations in the inner and outer radiation belts. The spatial distribution of the longterm average fluxes of the energetic electrons and protons in the Van Allen belts changes due to the secular variation of the geomagnetic field. When the empirical AE-8 and AP-8 models are used to predict the radiation doses expected along the orbit of a future satellite, the original Jensen & Cain and GSFC 12/66 magnetic field models (corresponding to epochs 1960 and 1970, respectively) should be used to determine the B, L coordinates. New updated empirical models are currently built based on more recent and comprehensive particle flux measurements from CRRES and other modern satellites.

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