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The quiet and disturbed plasmasphere

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## FOREWORD

This paper "The quiet and disturbed plasmasphere" has been presented at the Agard Meeting on "The Aerospace Environment at high altitudes and its implications for spacecraft charging and communications" held in The Hague (The Netherlands) from 2 to 7 June 1986. It will be published in the proceedings of this symposium.

## AVANT-PROPOS

Ce texte "The quiet and disturbed plasmasphere" a été présenté au Meeting Agard intitulé "The Aerospace Environment at high altitudes and its implications for spacecraft charging and communications" qui s'est déroulé à La Haye (Pays-Bas) du 2 au 7 juin 1986. Il sera publié dans les comptes-rendus de cette réunion.

## VOORWOORD

Deze tekst "The quiet and disturbed plasmasphere" werd voorgesteld tijdens de Agard Meeting over "The Aerospace Environment at high altitudes and its implications for spacecraft charging and communications" die gehouden werd in Den Haag (Nederland) van 2 tot 7 juni 1986. Hij zal in de verslagen van de vergadering gepubliceerd worden.

## VORWORT

Dieser Text "The quiet and disturbed plasmasphere" wurde vorgestellt während der Agard Tagung über "The Aerospace Environment at high altitudes and its implications for spacecraft charging and communications" der stattgefunden hat im Haag (Holland) von 2 bis zum 7 Juni 1986. Er wird in den Mitteilungen dieser Konferenz herausgegeben werden.

# THE QUIET AND DISTURBED PLASMASPHERE

by

J. LEMAIRE

## Abstract

The plasmasphere and its outer surface, the plasmopause, are described from an observational point of view. The main properties of this inner magnetospheric region are briefly recalled. The dynamical response of the plasmasphere to enhancements of geomagnetic activity has also been considered. The peeling off of the nightside plasmasphere at the onset of enhanced magnetospheric convection events is discussed. The dayside refilling mechanism has also been addressed.

## Résumé

La plasmasphère et sa surface extérieure, la plasmopause, sont décrites d'un point de vue observationnel. Les caractéristiques principales de cette région magnétosphérique intérieure sont rappelées brièvement. La réponse dynamique de la plasmasphère à l'augmentation de l'activité géomagnétique a également été considérée. L'épluchage du côté nuit de la plasmasphère lors d'une augmentation de la vitesse de convection magnétosphérique est discuté. Le problème du remplissage diurne de la plasmasphère est également pris en considération.

## Samenvatting

De plasmasfeer en haar buitenste oppervlak, de plasmapauze, worden beschreven vanuit een waarnemingsstandpunt. De voornaamste eigenschappen van dit binnenste magnetosferisch gebied worden bondig opgesomd. De dynamische reactie van de plasmasfeer t.o.v. een vermeerdering van de geomagnetische activiteit werd eveneens in beschouwing genomen. Het "ledigen" van de nachtzijde van de plasmasfeer tijdens een vermeerdering van de magnetosferische convectiesnelheid wordt besproken. Het vulmechanisme van de dagzijde van de plasmasfeer wordt eveneens behandeld.

## Zusammenfassung

Die Plasmasphäre und ihre äusserste Oberfläche, die Plasmapause, werden beschrieben aus einem Beobachtungsstandpunkt. Die vornehmste Eigenschaften dieses innerlichen magnetosphärischen Gebietes werden bündig aufgezählt. Die dynamische Reaktion der Plasmasphäre mit Rücksicht auf eine Vermehrung der geomagnetischen Aktivität wurde auch betrachtet. Die "Leerung" der Nachtseite der Plasmasphäre während einer Vermehrung der magnetosphärischen Konvektionsgeschwindigkeit wird besprochen. Der Füllmechanismus der Tagseite der Plasmasphäre wird auch behandelt.

The ionosphere of the Earth extends deeply into the magnetosphere. In the F-region and above (i.e. in the exosphere), the distribution of ionization is controlled by the magnetic field line distribution. The distribution of the electron and ion densities is organized along magnetic field lines. Ionospheric plasma density irregularities are stretched out along magnetic flux tubes to higher altitudes into the protonosphere-magnetosphere. The filaments of plasma form preferential ducts for Very Low Frequency (VLF) whistlers wave propagation.

The cold ionospheric plasma (0.25-0.5 eV ; 3000-6000 K) is gravitationally bound to the Earth. Its density decreases above the F-region with a scale height which is proportional to the plasma temperature  $(T_e + T_i)/2$ , and inversely proportional to the gravitational force (mg).

Upward diffusion and evaporation of charged particles contribute to replenish magnetic flux tubes as soon as they have been emptied at the onset of major geomagnetic perturbations. The maximum upward refilling flux is found to be of the order of  $3 \times 10^8$  ions and electrons per  $\text{cm}^2$  and per second. Empty flux tubes at low latitudes and mid-latitudes are refilled in less than a week with new plasma pouring out of the terrestrial atmosphere.

Catastrophic depletions of the plasmasphere are observed during large geomagnetic perturbations which often occur before the saturation level has been reached. The equatorial plasma density drops then from a near saturation value ( $300-500 \text{ cm}^{-3}$ ) to less than  $10 \text{ cm}^{-3}$ , in a rather short period of time starting at the onset of the geomagnetic substorm. The portion of the plasmasphere which is then peeled off depends on the strength of the geomagnetic perturbation as measured for instance by the  $K_p$ -index. During large storms, the plasmasphere can be depleted and peeled off along geomagnetic field lines as low as  $L = 2$ . However such

deep depletions are relatively rare events. Therefore, flux tubes at  $L < 3-4$  are most of the time close to saturation level while those beyond  $L = 4$  are usually in a dynamical state of refilling.

When the level of geomagnetic activity is steady for 24 hours or more, the thermal ion and electron densities remain almost unperturbed in all geomagnetic flux tubes located inside  $L = 4$ . When magnetic agitation has been at a same level for a day or more, and increases subsequently, a well developed sharp boundary is formed in the plasmasphere. This surface was called "plasmopause" by D.L. Carpenter (1963) who discovered it from VLF whistler observations. The sharp density gradient forming at the plasmopause surface has been observed with many different satellites since (Chappell et al., 1970a, 1970b, 1971, 1980). Actually, the plasmopause density "knee" had first been observed in 1960 by Gringauz with ion traps (Gringauz et al., 1960 ; Gringauz, 1963).

At a recently formed plasmopause the equatorial density decreases very abruptly by two orders of magnitudes from  $300-500 \text{ cm}^{-3}$  to less than  $10 \text{ cm}^{-3}$ , over an equatorial distance of  $0.1 - 0.3 R_E$ . These density gradients separate almost empty magnetospheric flux tubes just outside the plasmopause and those which are in the process of refilling just inside this boundary.

A three dimensional representation of the plasmasphere and of its outer boundary is illustrated in fig.1. The equatorial cross-section of the doughnut-shaped surface is a function of local time (LT). For steady and moderate geomagnetic activity the plasmopause has a bulge extending to  $L = 6-7$  in the dusk region as illustrated in fig.2.

During prolonged very quiet geomagnetic conditions the plasmasphere has a tendency to fill a maximum space in the magnetosphere. The sharp equatorial density 'knee' formed during the latest magnetospheric substorm onset, has the irreversible tendency to smooth out and to

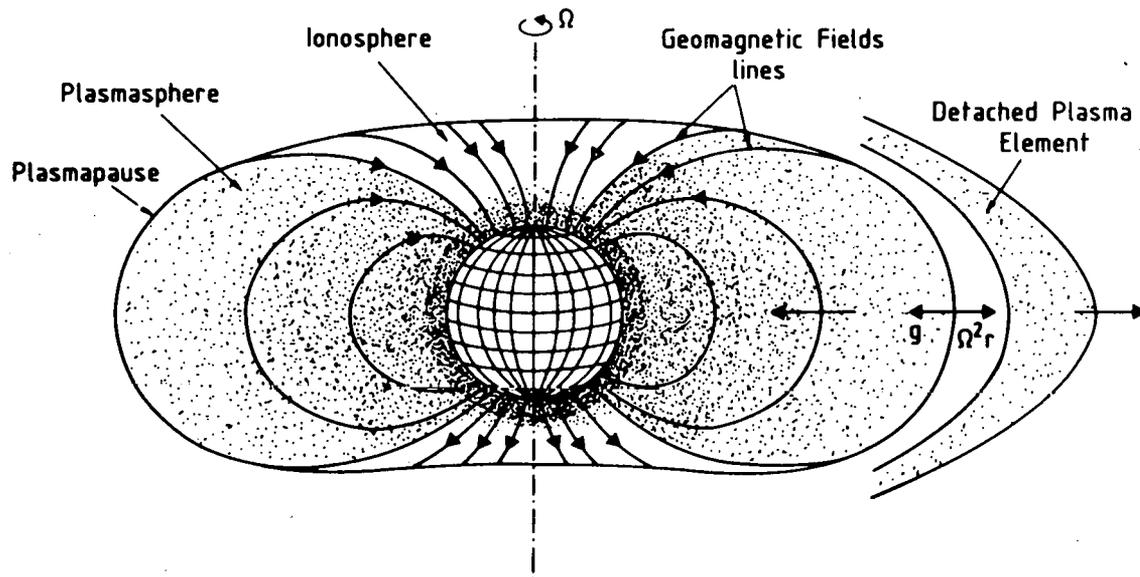


Fig.1: Three-dimensional illustration of the plasmasphere and of its outer boundary : the plasmapause. Under enhanced magnetospheric convection events, blocks of plasma can detach in the post-midnight local time sector as a consequence of the enhanced centrifugal effects. The electric resistivity of the lower ionosphere limits the growth rate of plasma interchange instability responsible for the plasma detachment and peeling off of the nightside plasmasphere.

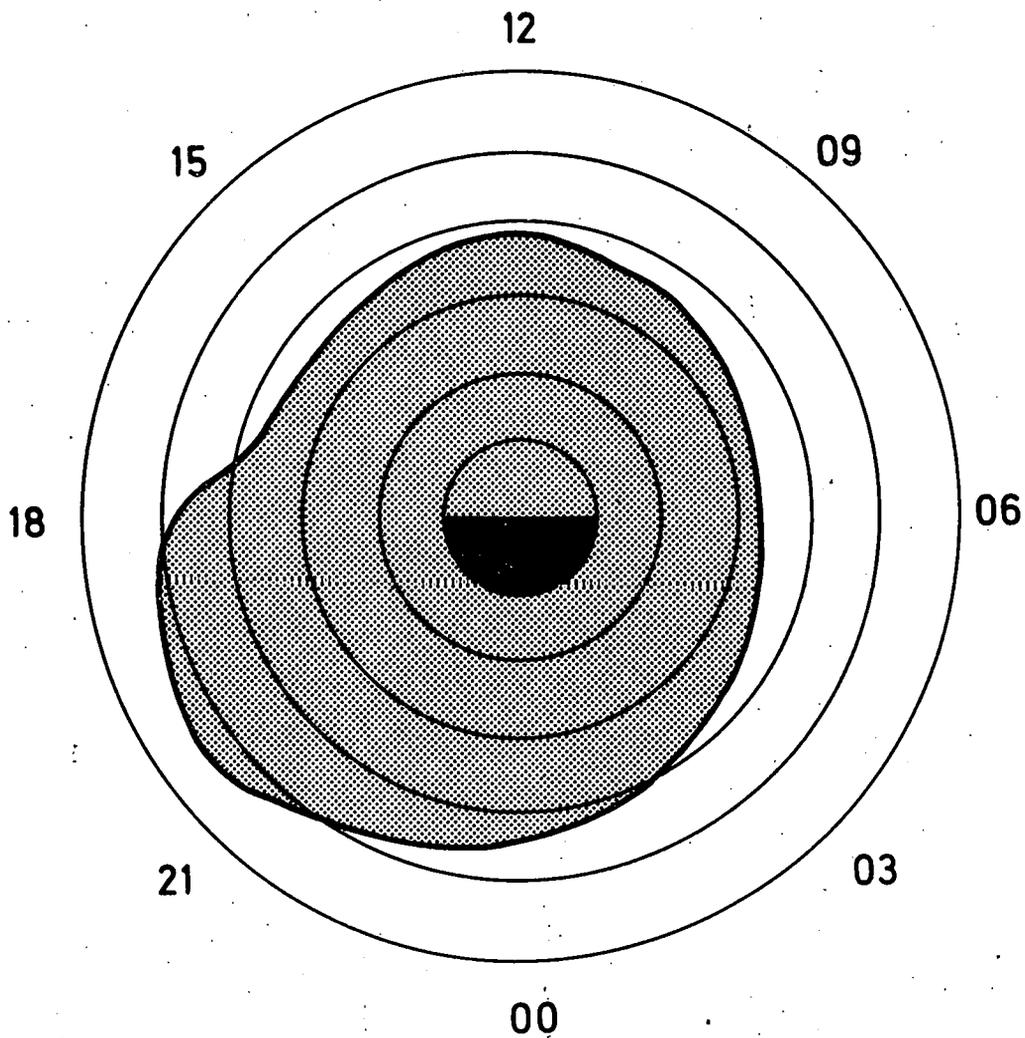


Fig.2: Equatorial radius of the plasmapause versus local time. The solid line represents a typical cross section of the plasmasphere during a period of moderate steady geomagnetic agitation ( $K_p = 2-4$ ) (Carpenter, 1966).

disappear gradually during the following prolonged quiet period of time. The plasmasphere relaxes then to a more axisymmetric shape, with, however, a characteristic bulge in the noon local time sector. However, when geomagnetic activity increases, the nearly symmetrical plasmasphere is compressed in the post-midnight local time sector, while, in the dayside, the thermal plasma is expanded in the sunward direction, as illustrated by the arrows in fig.3. A new plasmopause gradient is then formed in the post-midnight local time sector at an equatorial distance which is approximately given by

$$L_{pp} = 5.7 - 0.43 (K_p)_{-12}$$

where  $(K_p)_{-12}$ , is the maximum value of the geomagnetic index  $K_p$  during the 12 preceding hours (Carpenter and Park, 1973). Once formed in the nightside region, the new density 'knee' corotates toward dawn and toward later LT hours, as illustrated in fig.4. In the dayside local time sector, the equatorial position of the plasmopause is determined by the level of activity at an earlier Universal Time, i.e. when the corresponding plasma element was convecting past the post-midnight LT sector (see fig.4) (Chappell et al., 1971 ; Decreau, 1983 ; Decreau et al., 1982). While the new density gradient formed near midnight propagates toward later local time hours, its sharpness gradually decreases to become spread over much broader radial distances in the afternoon LT sector.

Following short duration  $K_p$  enhancements, small plasmaspheric bulges are formed in noon local sector as a result of the sunward plasma drift associated with enhanced dawn-dusk component of the magnetospheric electric field. Subsequently, these dayside bulges corotate toward the dusk local time sector as  $K_p$  decreases.

Detached plasma elements or plasma tails are often observed in the afternoon local time sector (Chappell, 1974), as well as in the post-midnight sector (Kowalkowski and Lemaire, 1979). This is shown in fig.5. For  $K_p > 2$ , the occurrence frequency of detached plasma elements has

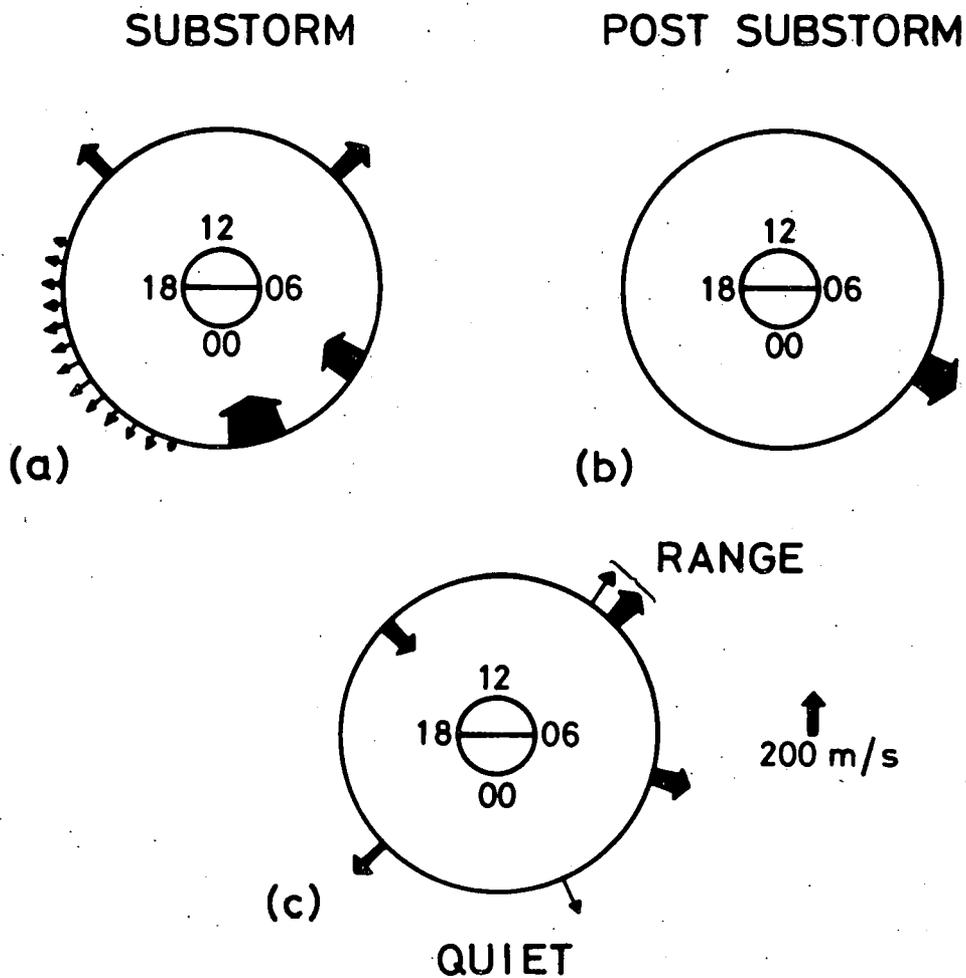


Fig.3: Typical cross-L equatorial flow velocities near  $L = 4$  deduced from whistlers recorded during (a) substorm periods, (b) post-substorm periods, and (c) quiet times (Carpenter and Seely, 1976).

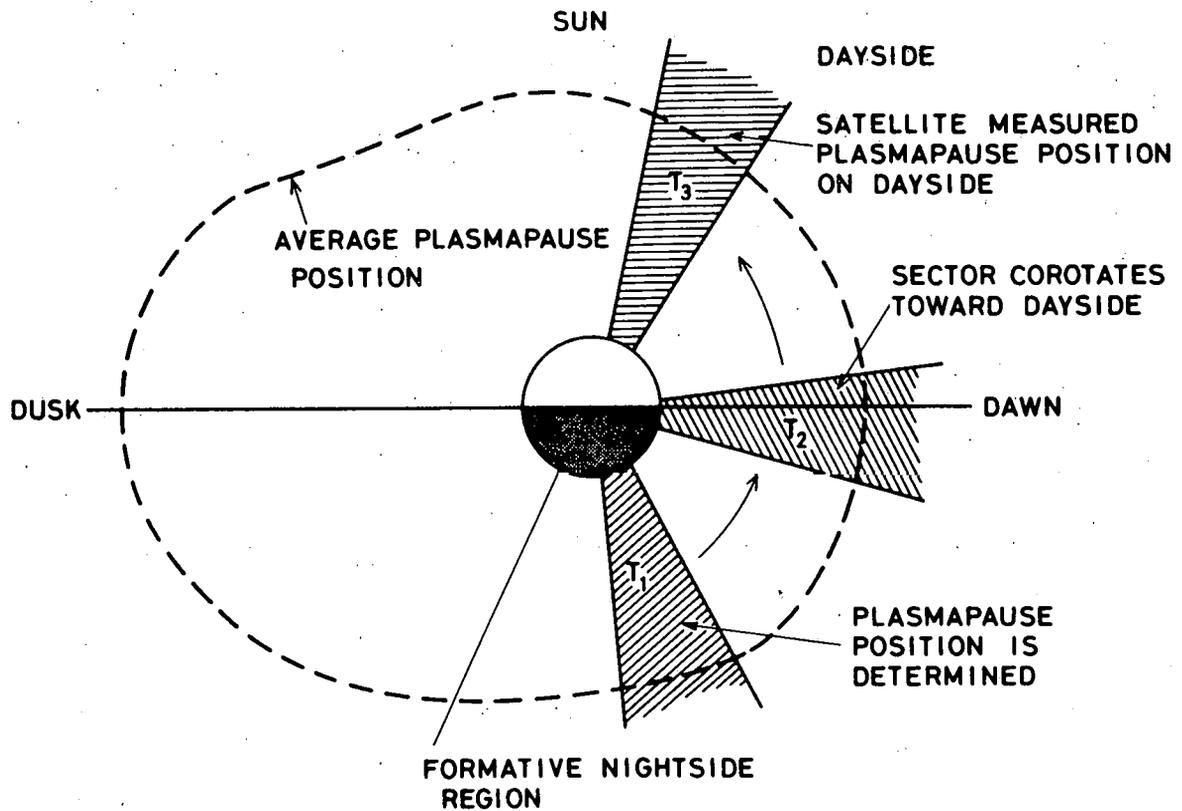


Fig.4: An illustration of the plasmapause formation in the nightside region. The plasmapause position is determined by the magnetic activity level present during its corotation through the nightside. The sector subsequently corotates to the dayside (Chappell et al., 1971).

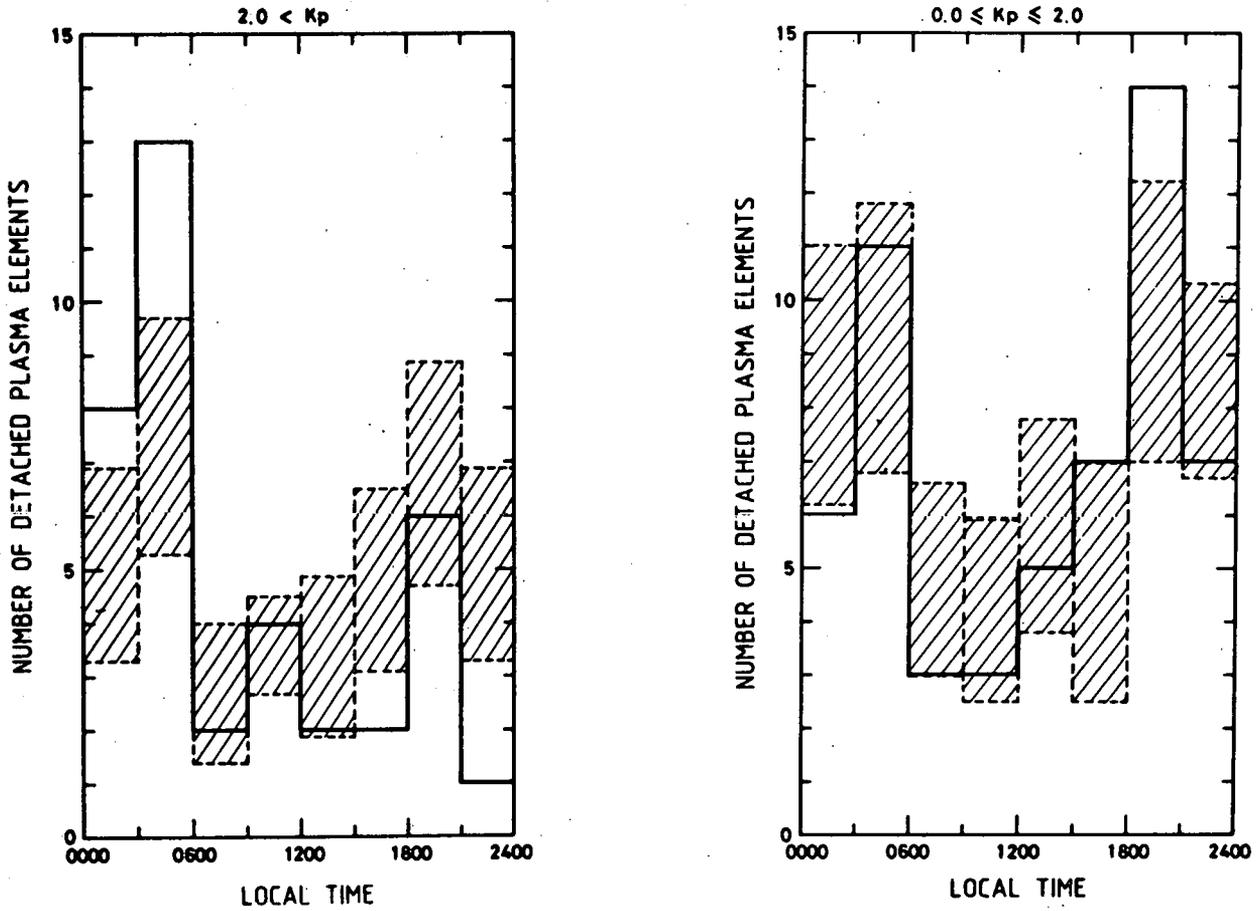


Fig.5: Histograms of the number of detached plasma elements observed in different local time sectors for  $K_p < 2$  and for  $K_p > 2$ . The shaded areas correspond to the confidence range  $m_i \pm \sigma_i$  around the expected mean values which are proportional to the number of satellite trajectories in each of these local time sectors. Note that the number of detached plasma elements observed in the dusk local time sector is significantly larger than the corresponding mean expected value when  $K_p < 2$ . Under disturbed conditions ( $K_p > 2$ ) a large excess of detached elements is observed in the post-midnight sector where the plasmasphere is peeled off by plasma interchange motion (Kowalkowski and Lemaire, 1979).

indeed a statistically significant peak between 03 and 06 hours LT. The existence of this peak confirms that the plasmasphere is peeled off in the post-midnight sector where magnetospheric convection velocities are maximum.

At altitudes below 3000 km the signature of the plasmopause is not always clearly identifiable. There are, however, in the topside ionosphere, different features which are related to the equatorial plasmopause. These lower altitude features are : (i) the mid-latitude electron density trough which was discovered by Muldrew (1965) ; the Light Ion Trough (LIT), first named by Taylor et al. (1969) ; (iii) the plasmopause associated temperature enhancement (Brace and Theis, 1974), and also (iv) Stable Auroral Red arcs (SAR) (Hoch, 1973) which are observed in the vicinity of the footprints of plasmopause field lines. A series of satellite observations have confirmed that the Light Ion Trough in the topside ionosphere is consistently located at about one L-value smaller than the equatorial plasmopause magnetic field lines. Furthermore, the LIT does not exhibit well developed dawn-dusk nor noon-midnight asymmetries like the equatorial plasmopause.

It must also be mentioned that significant polar wind like upward ionization flow is not only observed outside the plasmopause surface, but also in the intermediate region inside the plasmasphere (Chappell et al., 1980 ; Titheridge, 1976). In this outermost portion of the plasmasphere the electron temperature is usually much higher than the corresponding ionospheric temperatures (Horwitz and Chappell, 1979).

The upward ionization flow is predominantly composed of suprathermal  $H^+$  ions with 10%  $He^+$  ions of an energy ranging between 1 and 2 eV (Chappell et al., 1982). Finally it is worthwhile to point out that beyond the outer edge of the plasmopause the upward ion flux contains generally more suprathermal  $O^+$  ions (Horwitz and Chappell, 1979). From the large amount of observations collected since 1963 when this new magnetospheric frontier was discovered, it has become evident that the

plasmasphere is a highly structured and variable body of corotating cold plasma.

Steady state models for the magnetospheric electric field and for the plasmasphere have often been used to describe the formation of this boundary. These stationary models have, however, only a limited usefulness in describing the proper physical processes involved in the formation of the equatorial plasma density knee. Time dependent electric field models had eventually to be introduced to simulate in a more realistic way the dynamical motion and deformations of the plasmasphere as well as of its outer edge during periods of variable geomagnetic conditions.

Finally, it should be emphasized that the whole plasmasphere is magnetically and electrically coupled (connected) to the low and mid-latitude ionosphere. As a result of the finite value of the transverse Pedersen conductivity in the ionosphere, plasma interchange motion driven by various forces can develop only a finite velocity. The electric resistivity in the lower ionosphere limits the plasma interchange velocity to a maximum value. It is with this maximum velocity that blocks of plasma are detached from the plasmasphere in the post-midnight local time sector at the onset of each new substorm when the azimuthal convection velocity is suddenly enhanced. As a consequence of this detachment a new plasma density gradient is formed in the inner magnetosphere along the Zero Radial Force (ZRF) surface where the gravitational force is balanced by the enhanced centrifugal force (Lemaire, 1975, 1985). Multiple steps equatorial density distributions (see fig.6) (Corcuff et al., 1972) can be formed by a series of such plasmasphere peeling off processes occurring in sequence, at larger and larger radial distances (Lemaire, 1985).

The time has come where coordinated measurement campaigns are most desirable to obtain multi-point plasmasphere observations. The detailed shape of the plasmopause at a given instant of time as well of the

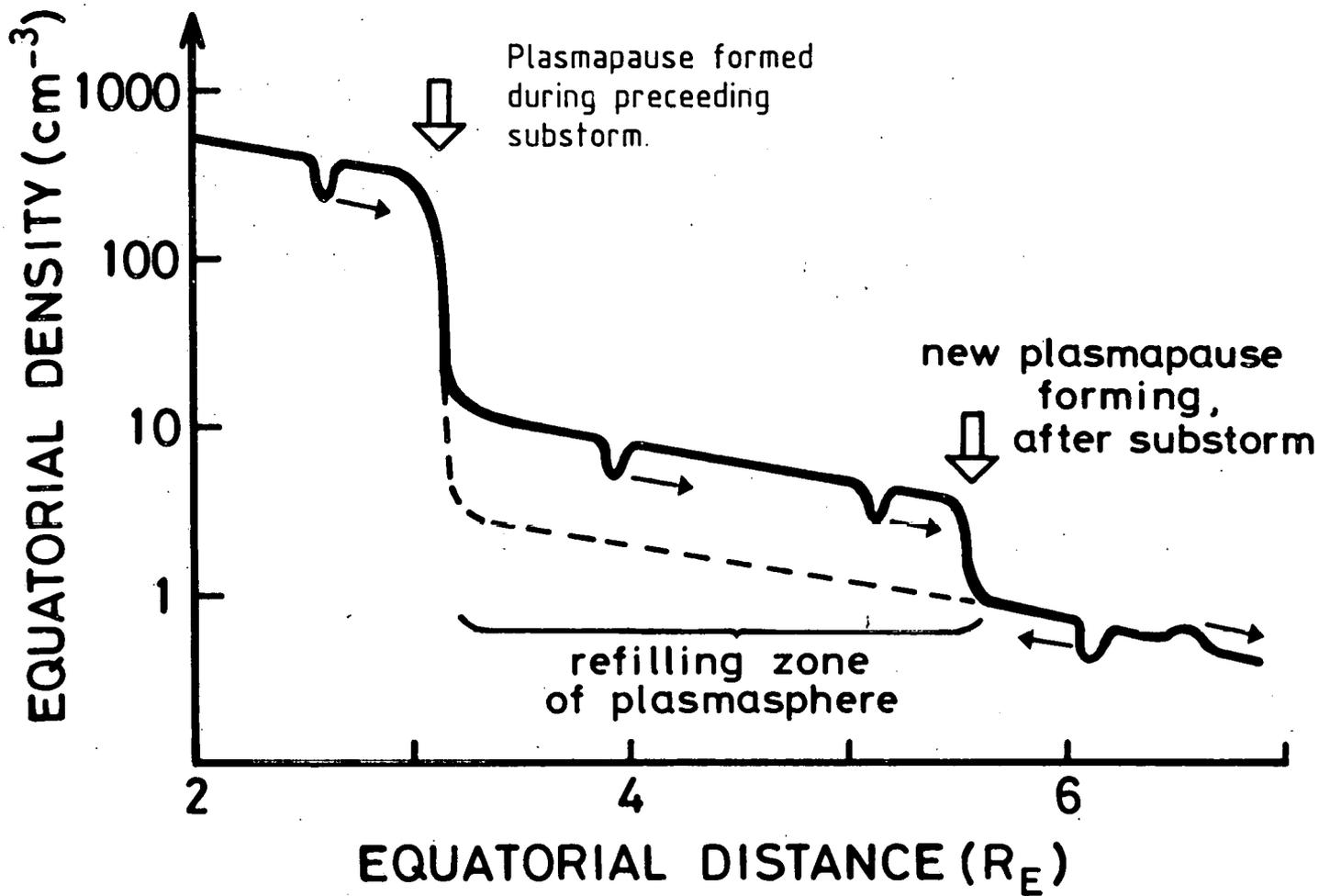


Fig.6: Illustration of the formation of "multiple plasmapauses" after an extended period of high geomagnetic activity. The gradual refilling of the depleted region between the old position of the plasmopause and the new one is shown by an additional "step" in the equatorial plasma density distribution.

dynamical deformations of the plasmaspheric whistler medium can only be obtained from such a coordinated effort. The experimental results from such a multidisciplinary survey would also be able to answer a number of controversial questions and theories.

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