The quiet and disturbed plasmasphere

by

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Abstract

The plasmasphere and its outer surface, the plasmapause, 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.

The ionosphere of the Earth extends deeply into the magnetosphere. In the F-region and above (i.e. in the exosphere), the distribution of the 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 (Te + Ti)/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 3×10^8 ions and electrons per cm^2 and per second. Empty flux tubes at low latitude and mid-latitude are refilled in less than a week with new plasma pouring out of the terrestrial atmosphere . This means that the ionization density in plasmaspheric flux tubes at $L < 5$ reaches saturation level - corresponding to diffusive and hydrostatic equilibrium - in less than 6-7 days.

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 cm^{-3}) to less than 10 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 "plasmapause" by D.L. Carpenter (Ref. 2) who discovered it from VLF whistler observations. The sharp density gradient forming at the plasmapause surface has been observed with many different satellites since (Refs. 7, 9, 10, 11). Actually, the plasmapause density "knee" had first been observed in 1960 by Gringauz with ion traps (Refs. 15, 16).

At a recently formed plasmapause the equatorial density decreases very abruptly by two orders of magnitudes from 300-500 cm^{-3} to less than 10 cm^{-3}, over an equatorial distance of 0.15 R_E. These density gradients separate partly empty magnetospheric flux tubes just outside the plasmapause 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 plasmapause 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 tendancy to fill 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 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 plasmapause 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 preceeding hours (Ref. 4). 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 plasmapause 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) (Refs. 11, 13, 14). 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 (Ref. 6), as well as in the post-midnight sector (Ref. 19). This is shown in fig.5. For $K_p > 2$, the occurence frequency of detached plasma elements has 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 plasmapause is not always clearly identifiable. There are, however, in the topside ionosphere, different features which are related to the equatorial plasmapause. These lower altitude features are :(i) the mid-latitude electron density trough which was discovered by Muldrew (Ref. 22), (ii) the Light Ion Trough (LIT), first named by Taylor et al. (Ref. 23), (iii) the plasmapause associated temperature enhancement (Ref. 1), and also (iv) Stable Auroral Red arcs (SAR) (Ref. 17) which are observed in the vicinity of the footprints of plasmapause 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 plasmapause magnetic field lines. Furthermore, the LIT does not exhibit well developed dawn-dusk nor noon-midnight asymmetries like the equatorial plasmapause.

It must also be mentioned that significant polar wind like upward ionization flow is not only observed outside the plasmapause surface, but also in the intermediate region inside the plasmasphere (Refs. 7, 24). In this outermost portion of the plasmasphere the electron temperature is usually much higher than the corresponding ionospheric temperatures (Ref. 18).

The upward ionization flow is predominantly composed of suprathermal H^+ ions with 10% He^+ ions of an energy ranging between 1 and 2 eV (Ref. 8). Finally it is worthwhile to point out that beyond the outer edge of the plasmapause the upward ion flux contains generally more suprathermal O^+ ions (Ref. 18). 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 at 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 (Ref. 20, 21). Multiple step equatorial density profile (see fig.6) (Ref. 12) can be formed by a series of such plasmasphere peeling off processes occuring in sequence, at larger and larger radial distances (Ref. 21).

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

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) (after ref.3).

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 (after ref.5).

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. (after ref.11).

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 (after ref.19).

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 plasmapause and the new one is shown by an additional "step" in the equatorial plasma density distribution.

Figures

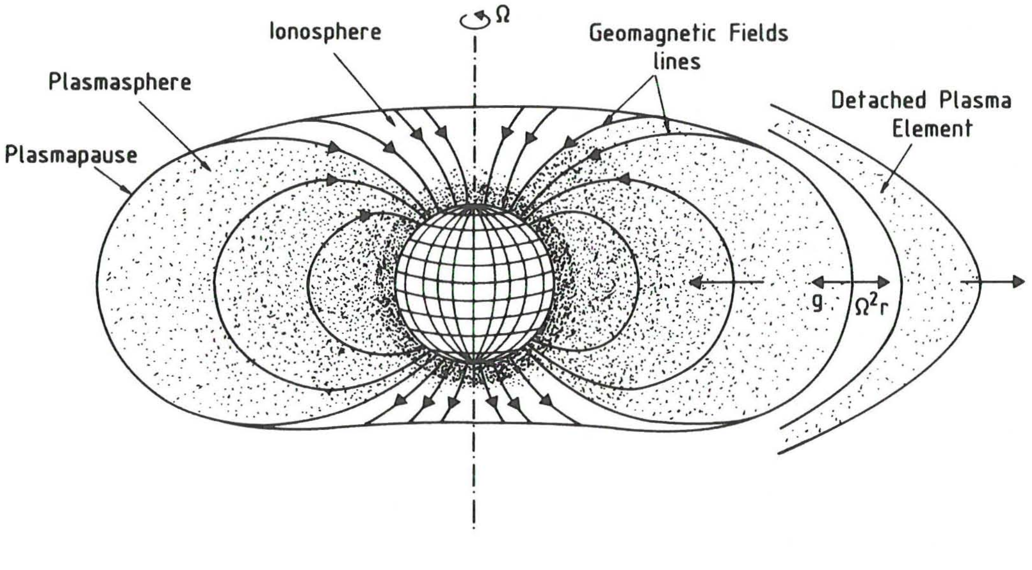

Fig.1

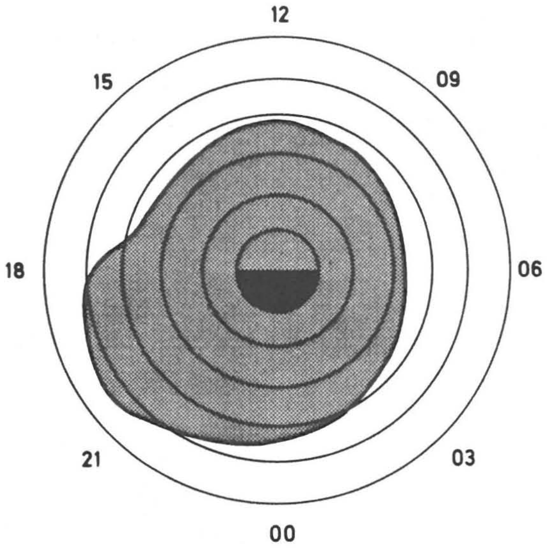
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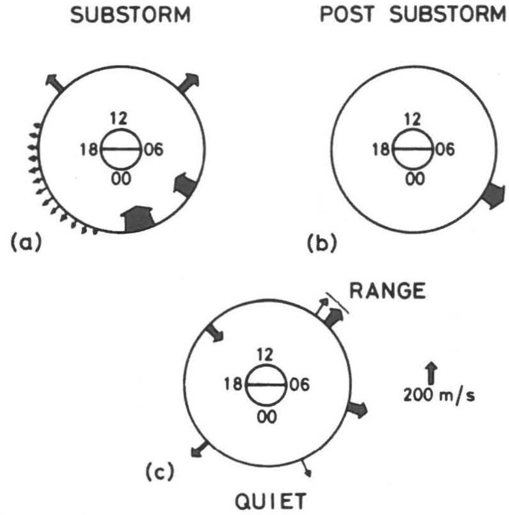
Fig.2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(c)
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Fig.3

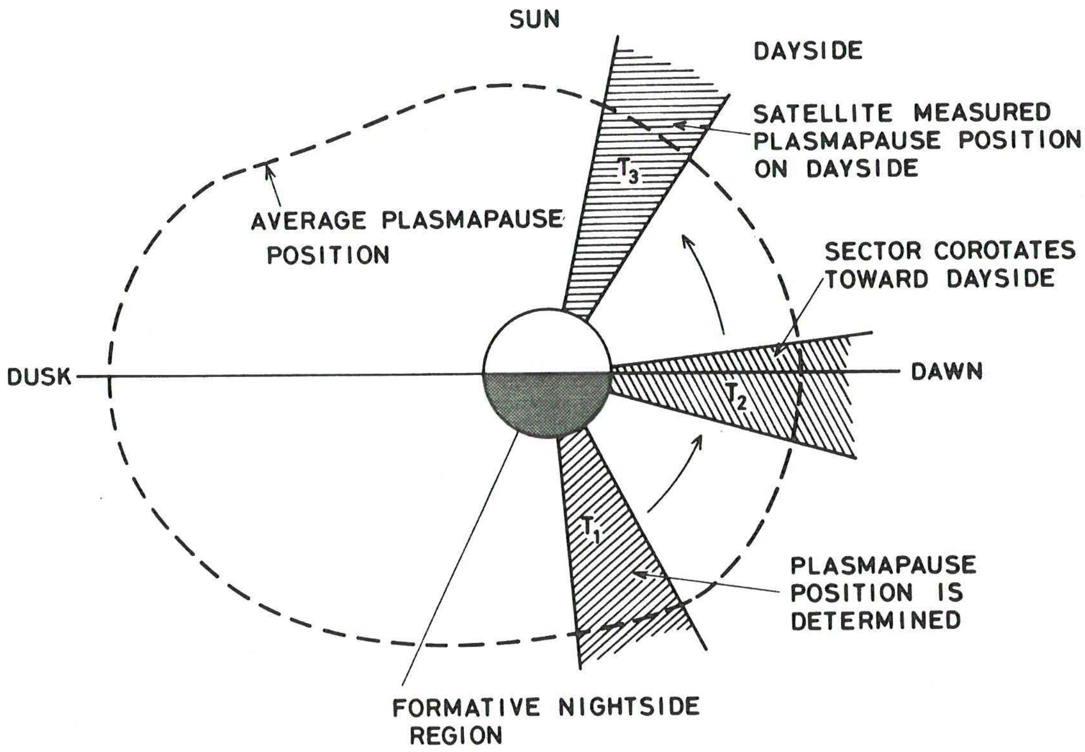
SUN
DAYSIDE
SATELLITE MEASURED PLASMAPAUSE POSITION ON DAYSIDE
AVERAGE PLASMAPAUSE POSITION
T_3
SECTOR COROTATES TOWARD DAYSIDE
DUSK
DAWN
T_2
T_1
PLASMAPAUSE POSITION IS DETERMINED
FORMATIVE NIGHTSIDE REGION

Fig. 4

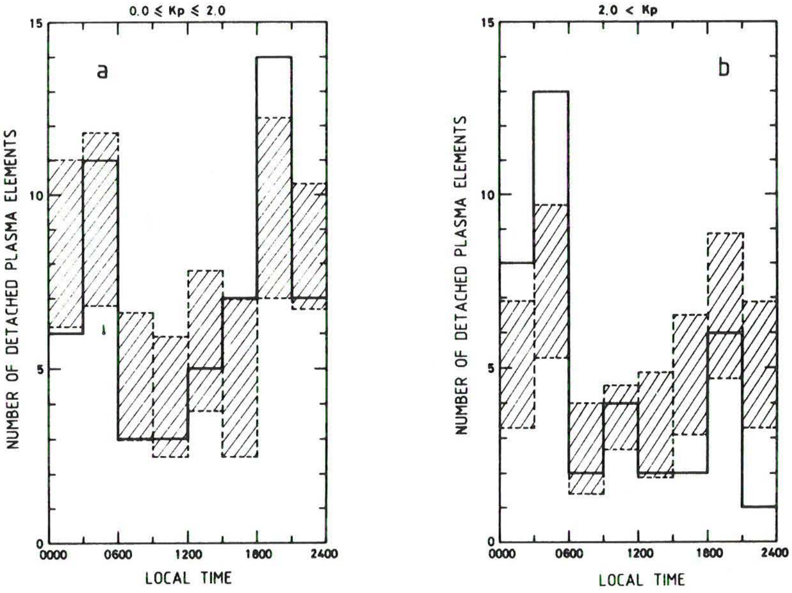
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Fig.5

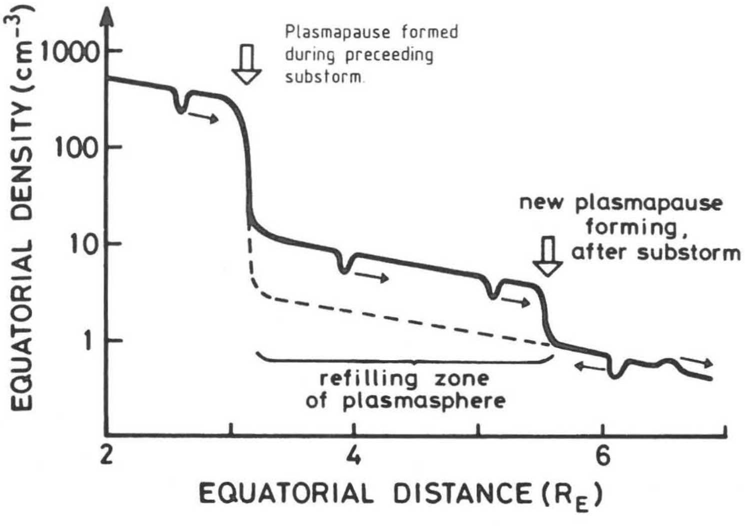

Fig.6

DISCUSSION

L.Bossy,BE

Could you comment about the ELECTRIC FIELD MODEL used?

Author's Reply

The Electric Field Model which I have used in some of the simulations of the formation and deformations of the plasmasphere is the E3H Electric Field model with a scale factor "f" changing with Kp. But any other electric field model can be used as well. Indeed the theory of plasmosphere peeling and the physical mechanism which is behind (i.e. plasma interchange motion) is independent of the particular model which is used. Except, of course, for the position of the ZRF (Zero Radial Force) surface. whether the Electric field model has one or ten stagnation points (which are mathematical singularities) does not really matter. Except that these singularities make numerical integration sometimes more difficult and time consuming.

E.R.Schmerling,US

Dr.Lemaire has presented a comprehensive morphology of the plasmasphere based on the plasma density. Can he provide some idea of the plasma temperatures in these regions?

Author's Reply

The plasma temperature is gradually increasing when one gets closer to the plasmapause from the inside. Plasma temperatures are 10000K-100000K in the plasmapause region. In the depleted regions, outside the dense plasmasphere, even higher electron temperatures are formed as a result of the relatively higher concentration of magnetospheric (hot) particles.
The effect of run-zero temperature differences between the inside and outside of plasma density irregularities has been addressed in a recent monograph by Lemaire (1985, Aeronomica Aeta A#296) and will be presented at a future meeting in France.