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ABSTRACT

The temporal development of the latitudinal position of the 600 km midlatitude electron density trough at dawn and dusk during the period 25-27 May 1967, which encompassed a large magnetic storm, was measured by the RF capacitive probe on the polar orbiting Ariel 3 satellite. The substorm-related changes in the L coordinate of the trough minimum and the point of most rapid change of

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density gradient on the low latitude side of the trough are similar. Oscillations of the trough position at dusk are in phase with substorm activity whereas movement of the trough at dawn is only apparent with the onset of the large storm. Near dusk there is evidence of structure in the form of a tail-like extension of the plasmasphere at the peak of the storm. Detailed model calculations assuming a spatially invariant equatorial convection E field which varies in step with the K_p index reproduces much of the observed behavior, particularly at dusk, and shows that more than one plasmapause-type transition may be identifiable in the trough region.

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TEMPORAL VARIATIONS IN THE DAWN AND DUSK MIDLATITUDE TROUGH POSITION-MODELED AND MEASURED (ARIEL 3)

INTRODUCTION

Measurements of the electron density by the RF probe on the satellite Ariel 3 (Tulunay and Sayers, 1971; Tulunay and Hughes, 1973) have revealed the feature which is widely known as the midlatitude trough (c.f. Muldrew, 1965). The behavior of this electron density trough can provide useful information about magnetosphere dynamics since its existence is dependent upon magnetospherically induced motions – the trough being the near-earth signature of the plasmapause (Thomas and Andrews, 1968; Rycroft, 1970). Hence an understanding of the variations in the measured trough location in the light of models depicting the dynamics of the plasmapause would be useful.

Tulunay and Hughes (1973) observed and explained in general terms some of the features of the storm-induced changes in the dawn and dusk trough locations as observed by Ariel 3. The work to be presented here is basically a continuation of that study using detailed model calculations to interpret the trough observations during the period May 23-27, 1967.

EXPERIMENT

The Ariel 3 satellite was launched on May 5, 1967 into a near polar orbit inclined 80° to the earth's equatorial plane. It s orbital period was 96 minutes with its altitude ranging from 500 to 600 kilometers. During the large magnetic storm which occurred in May 1967 the orbital plane lay near dawn and dusk as the satellite crossed the equator at local times near 0500 and 1700. The details of the RF electron density probe experiment has been described by Wager (1968) and Sayers et al. (1969). The spatial resolution of the experiment is 1.7° in latitude over the midlatitude region.

METHOD OF ANALYSIS

The examination of the electron density trough on consecutive orbits throughout the period May 23-27, 1967 should reflect the time history of the magnetosphere convection activity. However, since the satellite did not traverse the plasmasphere exactly in a radial direction, longitudinal density variations may obscure the position of the trough. To minimize this error each profile was compared with a quiet time profile obtained at similar universal times during the period of May 21-23, 1967 (an orbit shifts less than 2° in longitude per day). The identification of the midlatitude trough was made from the data in the region of invariant latitudes between 30 and 70 degrees. Due to the difficulty of positively identifying a trough below 600 km in the summer hemisphere on these dawn-dusk passes, most of the data used is from the winter hemisphere (southern hemisphere) with only occasional references to observations in the north.

It has yet to be conclusively established which point, if any, in the region of the electron density trough corresponds to the plasmapause. Statistical studies (Rycroft, 1970) indicate that on the average the trough minimum (MP) correlates well with the field line on which the equatorial plasmapause is found. Another possible location of the plasmapause is a point on the low latitude side of the trough where the electron density decreases abruptly with increasing latitude analogous to the abrupt density change across the plasmapause at high altitudes. For example Tulunay and Hughes (1973) select the point on the low latitude boundary of the trough at which the latitudinal density gradient change is a maximum (this point will be denoted LLP). Because of the uncertainty which can exist in defining a single plasmapause location at a fixed local time, both the MP and the LLP as measured by Ariel 3 (see Figure 1) will be considered in this paper. Under realistic conditions multiple plasmapause-like transitions can occur at a fixed local time (c.f. Chen and Wolf, 1972) and hence the possibility exists that both the LLP and the MP are signatures of abrupt plasmapause-like changes.

TROUGH MEASUREMENTS

The experimentally observed trough locations in L coordinates and the corresponding K_p variations for the period May 23-27, 1967 are plotted in Figure 2. A large magnetic storm began on May 25 following two smaller substorms on the previous two days. Both the measured LLP and MP tended to vary in step with one another, indicating that either point is a general indicator of how the trough position changes with time. The difference between the LLP and MP is not constant, but rather decreases during the peak of the magnetic storm.

The dusk trough locations show the most pronounced changes with time as the L coordinate decreases with the onset of substorm activity, only to increase again following the substorms. The dawn trough locations, on the other hand, show no clear variation with respect to the small storms, although the dawn trough does precipitously decrease to lower L coordinates with the onset of the large storm.

Another interesting feature of the electron density measurements is the appearance of narrow regions of enhanced density poleward of the trough during the large storm (see Figure 3). These appear to be similar to the observed patches of light ions observed outside the main plasmasphere near midnight by Taylor et al. (1971). The latter observations were interpreted as plasmatail-like extensions of the plasmasphere.

In order to interpret these measured characteristics of the dawn and dusk trough variations, detailed model calculations will be presented.

MODEL DEVELOPMENT

Before considering the details of the measured dawn-dusk trough variations, the general evolution of the plasmapause in the equatorial plane expected during the May storm will be explored. The temporal development of the plasmasphere boundary is determined using the method employed by Grebowsky (1970) and Chen and Wolf (1972). The earth's magnetic field is assumed dipolar and the electric field driving the equatorial magnetosphere tail wind is chosen as spatially invariant and directed from dawn to dusk. The magnitude of the electric field is varied in step with K_p so that the corresponding steady state dawn plasmapause L coordinate is identical to that predicted by Binsak's (1967) statistical relation $L = 6\ (1 - 0.1\ K_p)$. The boundary development was determined beginning at 1500 GMT on May 25 at which time it is assumed the plasmapause was in the steady state configuration. The assumption of a steady state initially will be relaxed in later calculations but for the present it is a convenient approximation for depicting the complexities which will be induced in the plasmasphere boundary by fluctuating magnetic activity.

The model evolution of the plasmapause is plotted in Figure 4. The radial coordinate in the polar plots corresponds to the L coordinate, the scale of which is suppressed for clarity since only the qualitative aspects of the figure are of significance. Due to the onset of the small substorm on May 23 the plasmasphere expands in the noon-dusk sector forming a long tail like appendage. This tail (of the type observed by Taylor et al., 1971) then tends to thin and its cusp corotates with the earth during the relatively quiet period after the substorm. With the onset of the second substorm on the 24th, another extension of the plasmasphere is produced in the noon-dusk quadrant while the cusp of the tail produced earlier continues to rotate with the earth resulting in a thin filament of plasma outside the main inner plasmasphere boundary. With the onset of the large storm on the 25th of May, the tail-like structures resulting from the smaller preceding substorms are wiped out due to the immensity of the storm. However a constantly thining filament of plasma may still be detectable near, but outside, the inner plasmasphere boundary. After the large storm subsides the severely eroded plasmasphere with its elongated plasmatail will tend to corotate with the earth as ionospherically produced plasma fills up the depleted flux tubes to form a plasmapause at higher L coordinates. During the large storm the model predicts plasmapause L coordinates less than 1.0. Although unrealistic, the model computations were not abandoned since the tail structure and the general behavior of the plasmapause configuration is not affected by this result. It does however lead to two questions which have yet to be resolved: 1. Can Binsack's relation between the plasmapause position and K_p, which was obtained at moderate K_p values, be used at the high K_p's as was done in these calculations? and 2. During a large storm does the magnetosphere tail wind penetrate to near the surface of the earth where chemical effects must be considered explicitly in determining the dynamics of the plasmapause?

The model computation depicted in Figure 1 shows that density measurements at dusk in the region of the plasmasphere boundary should be characterized by extremely variable structure due to the generation and movement of the plasmasphere tails. At dawn the tails may still be observable but due to their thinness are probably not within the resolution of the experiment. Before comparing the Ariel measurements of trough position with the model predictions, a detailed calculation of the expected plasmasphere boundary evolution at dawn and dusk will be made using a different approach – one which eliminates the assumption of a steady state plasmapause configuration at some point in time and which takes into account the partial filling of magnetic flux tubes by ionospherically produced plasma.

NEW METHOD

To obtain a better indication of the expected electron density variations at dawn and dusk, the magnetic flux tubes and their frozen-in plasma (drifting according to $\vec{v} = \vec{E} \times \vec{B}/B^2$ where E is related to K_p as in the previous section) are traced backwards in time from the universal time of interest. Since the flux tubes are depleted of plasma when they open to interplanetary space and are effectively filled with plasma when they are closed, the density in a closed flux tube at a specified time will depend roughly upon the total time the flux tube has been closed and on the dayside of the earth where solar ionization produces the plasma. By computing this time at all L coordinates at dawn and at dusk during the May storm period a general idea can be obtained as to where plasmapause-type transitions are to be expected.

In determining the closure time of the flux tubes under consideration the earth's magnetic field is again assumed dipolar with field lines corresponding to L coordinates greater than 10 assumed to be open. The computed times for the dawn and dusk periods traversed by Ariel are plotted in Figure 5b and Figure 6b respectively. For simplicity, only broad ranges of closure time are considered with the indicated times labeling the number of days the flux tubes were closed and yet traversed the dayside of the earth – i.e. 1 day correspond to 12 hours spent in daylight.

Field lines that have been closed for more than five days are considered filled to the high densities characteristic of the inner plasma-sphere (for a discussion of the filling-up times see the review by Carpenter and Park, 1973). Since flux tubes which are closed for only a short period of time are partially depleted, a plasmapause-type transition is to be expected when the closure time changes abruptly from 5 days or more to less than two days or even from 2 days to 0 days. Hence multiple plasmasphere boundaries are readily produced from changing magnetic activity conditions.

This new method of computing the temporal development of the plasmasphere boundary can produce features not seen in the development of the previous section. For example, the plasmatail evident at dusk in Figure 6b near 1500 GMT on May 24 is not seen in Figure 4, although it would have been produced in the earlier computation if the initial steady state configuration had been selected much further back in time. However all of the qualitative variations predicted in Figure 3 also result in the computations leading to Figures 5b and 6b.

INTERPRETATION OF MEASUREMENTS

DAWN

At dawn (Figure 5) the model predicts an average temporal decrease in the L position of the outer plasmasphere boundary during the two days preceding the large storm which convects the boundary to L values near 1. Thin patches of enhanced plasma density corresponding to the plasmatail development previously described in Figure 4 always delineate the outer boundary. The cusps of the most pronounced tails are predicted to occur at dawn one or two days following the subsidence of enhanced magnetic activity – a delay of two days corresponds to a tail which has encircled the plasmasphere once. The largest tail development is expected to follow the large storm on May 26.

The measured L position of the trough, as noted by either MP or LLP, does not show the boundary oscillations predicted by the model before the large storm, but the measured LLP position is on the average in excellent agreement with the computed boundary. At the onset of the large storm the measured trough positions depart significantly from the model as the model predicts the movement of the plasmasphere boundary to $L = 1$. How close the dawn boundary approaches $L = 1$ during the large storm is obscured by the appearance of large scale oscillations in the electron density along the satellite orbit making a positive trough identification at dawn difficult when K_p approaches its highest values.

DUSK

The measured locations of the dusk electron density trough show more noticeable temporal variations than the corresponding dawn measurements. These variations are also evident in the model calculation at 1800 MLT (Figure 6). The model predicts oscillations in the outer plasmasphere boundary (defined by the outermost plasmatail) with an enhancement of K_p associated with a movement of the dusk boundary to smaller L coordinates and the onset of magnetic quieting associated with an expansion of the plasmasphere to higher L values-similar to the predicted behavior at dawn (Figure 5). The dusk variation can be interpreted approximately as the motion of the plasmasphere bulge towards the dayside of the earth with increasing K_p and a tendency of the bulge to be positioned near dusk during steady magnetic activity. Again thin filamentary plasmatails are predicted in the outer plasmasphere with the most prominent tail being produced by the large storm which drives the innermost plasmapause to L values near 1.

The difficulty in uniquely defining a single plasmapause boundary is readily seen. In the outer plasmasphere near 1800 GMT on May 23, according to the dusk computations, the plasma density should drop precipitously with increasing L near L = 5 as the dayside closure time changes abruptly from more than 5 days to the order of 3 days. Near L = 6 a sharp spikelike plasmatail density enhancement is expected beyond which the density should drop to its minimum value as the closed flux tubes at the higher L coordinates have spent no time on the dayside of the earth. Since the electron density probe on Ariel 3 is unable to resolve spatial features of extent much less than 1° of latitude, the outer plasmatail enhancement is probably undetectable, but a plasmapause transition corresponding to a change in dayside closure times from 3 days to 0 days near L = 6 should still be evident. Comparing the measured trough positions with the model boundaries on May 23 and the beginning of the 24th it is seen that the MP is apparently in good agreement with the predicted outer boundary and the LLP corresponds to the inner boundary.

To carry this comparison further consider the computed closure times near 1800 GMT on May 24. Again a thin plasmatail is expected defining an outer plasmasphere boundary, but now the closure times of the flux tubes between the outer boundary and the inner boundary near L = 5 are less than two days. Hence the plasma density in this region is expected to be small compared to the densities at the same L values a day earlier. Due to the large flux tube volumes at high L coordinates, such relatively short closure times might imply a relatively small replenishment of the plasma within the flux tube. If this were the case and the plasmatail is too thin to be detected, only the innermost plasmasphere boundary may be prominent in the measurements. Indeed, if the MP is compared with the model in this region, it compares favorably with the inner boundary.

At the onset of the large storm the model predicts a sharpening of the outer plasmasphere boundary as the boundary moves preciptously to small L coordinates. After the storm a new plasmatail is expected, the cusp of which passes 1800 MLT near 1100 GMT on May 26. The measured locations of the trough, again, vary in step with the computed outermost boundary during and after this storm. This new plasmatail may have been thick enough to be observed experimentally since the Ariel 3 measurements at dusk on May 26 (Figure 3) reveal enhanced patches of electron density poleward of the low latitude plasmasphere. The observed patches however are detected at the peak of the storm-almost 10 hours before the model predicts their occurence at dusk. Whether this implies that the observed structure is something other than a tail-like extension of the plasmasphere or whether the simple magnetosphere convection model is inadequate remains to be ascertained.

CONCLUSIONS

The comparison of the dawn and dusk 500-600 kilometer electron density trough locations during May 23-26, 1967 has shown that the assumption of a convection electric field varying in step with K_p produces theoretical temporal plasmapause variations in good agreement with the measurements. The agreement at dawn is not as striking as at dusk, although a statistical comparison of the dawn trough position with K_p shows that the measured position correlates best (in an inverse sense) with the K_p index 3-6 hours preceding the measurement, in agreement with the model (both the model and measured dusk position correlate best with the K_p at the observation time).

The good agreement between the trough variations as predicted by the model and the observed variations whether measured by the trough minimum density point or a point on its low latitude side indicates that locators such as MP or LLP are valid indicators for studying the general trough (plasmapause) motion, although it is uncertain yet whether each or both of these parameters always denote the same plasmapause feature. Any attempt to define the location of only a single plasmapause point along a satellite pass can easily cause confusion when multiple plasmapause-like boundaries exist – a condition which may be the rule rather than the exception. However the selection of only one point is often necessary, due to a lack of sufficient spatial resolution in most density experiments to identify all of the abrupt density changes at midlatitude near the earth.

Since Ariel 3 traversed altitudes at which the ambient plasma is predominately heavy ions and yet a net loss of light ions accounts for the existence of the plasmapause, chemical reactions play a very important role in determining the details of the measured trough. Further study is needed to determine whether such reactions can produce significant differences between features of the trough and expected plasmapause structure. This could be particularly important for intense storms in which the magnetosphere plasma convection in the equatorial plane penetrates close to the earth with such intensity that a direct interaction between this solar wind-induced flow and chemical production and loss properties dominates the physics of the trough at low latitudes – a situation analogous to that proposed for Mars by Bauer and Hartle (1973).

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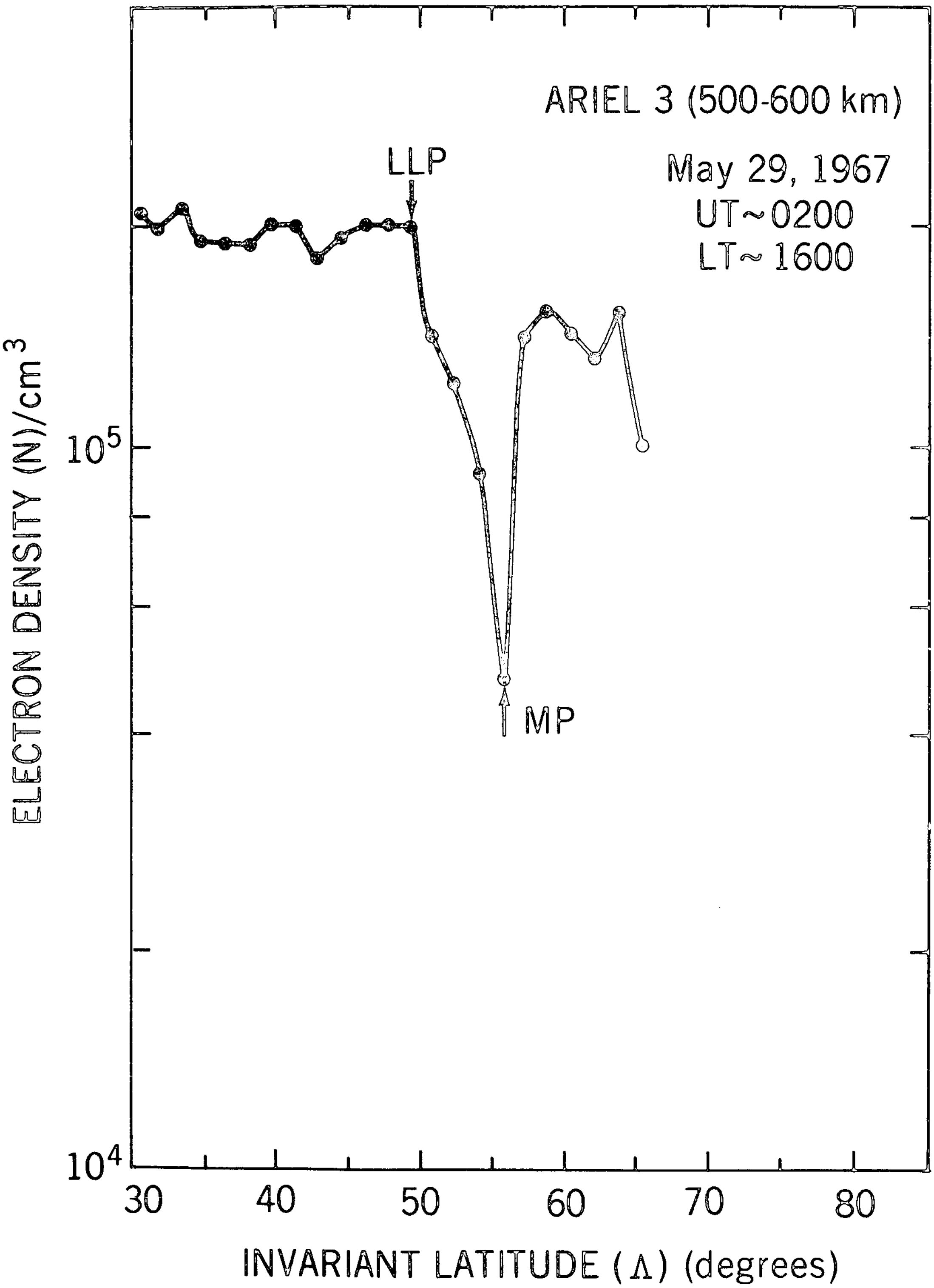

Figure 1. An example of an electron density trough with its position locators MP (minimum point) and LLP (low latitude point) indicated.

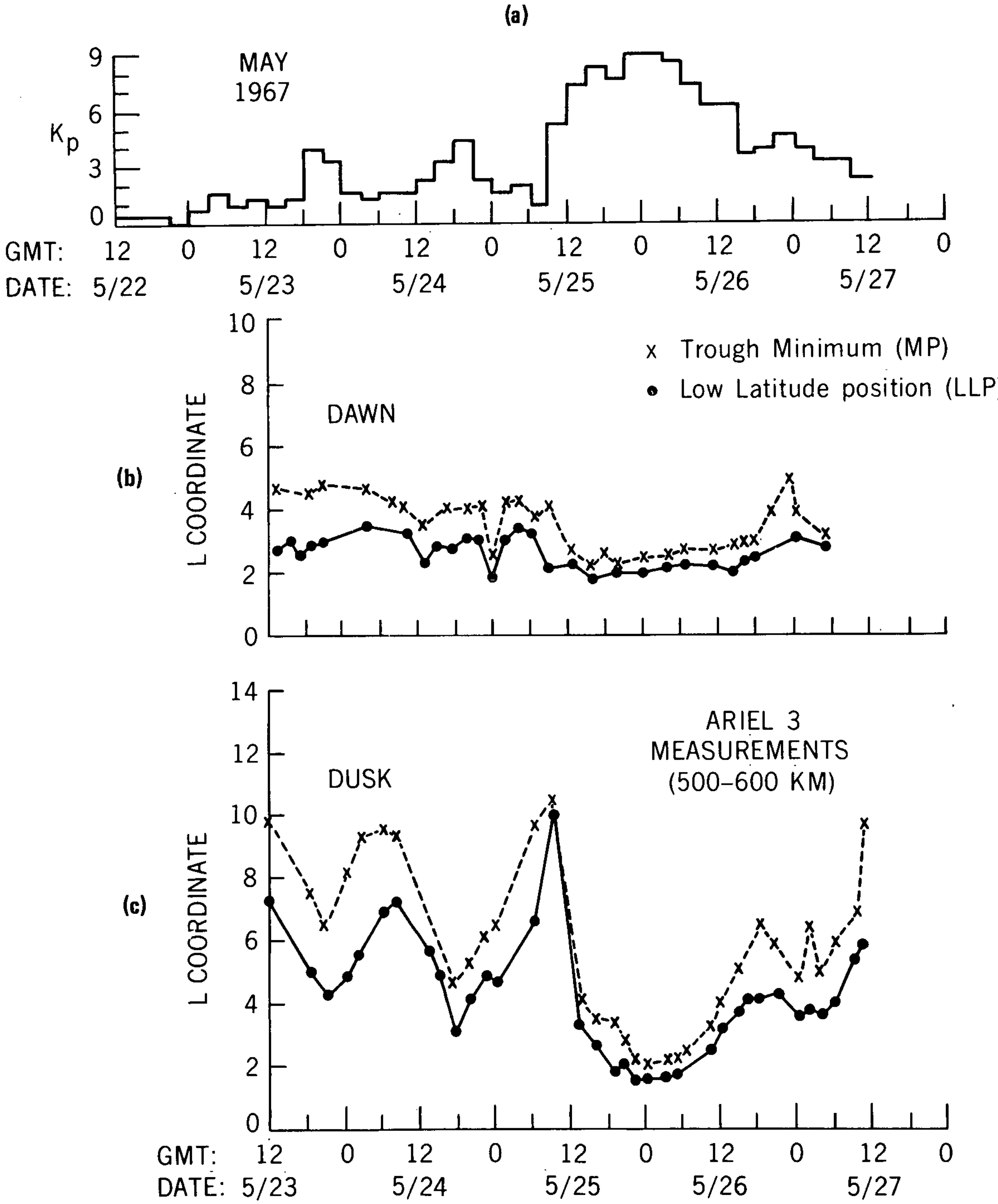

Figure 2. (a) Magnetic K_p index variation for the period of interest. (b) Measured Ariel 3 electron density trough locations at dawn. (c) Measured electron density trough position at dusk.

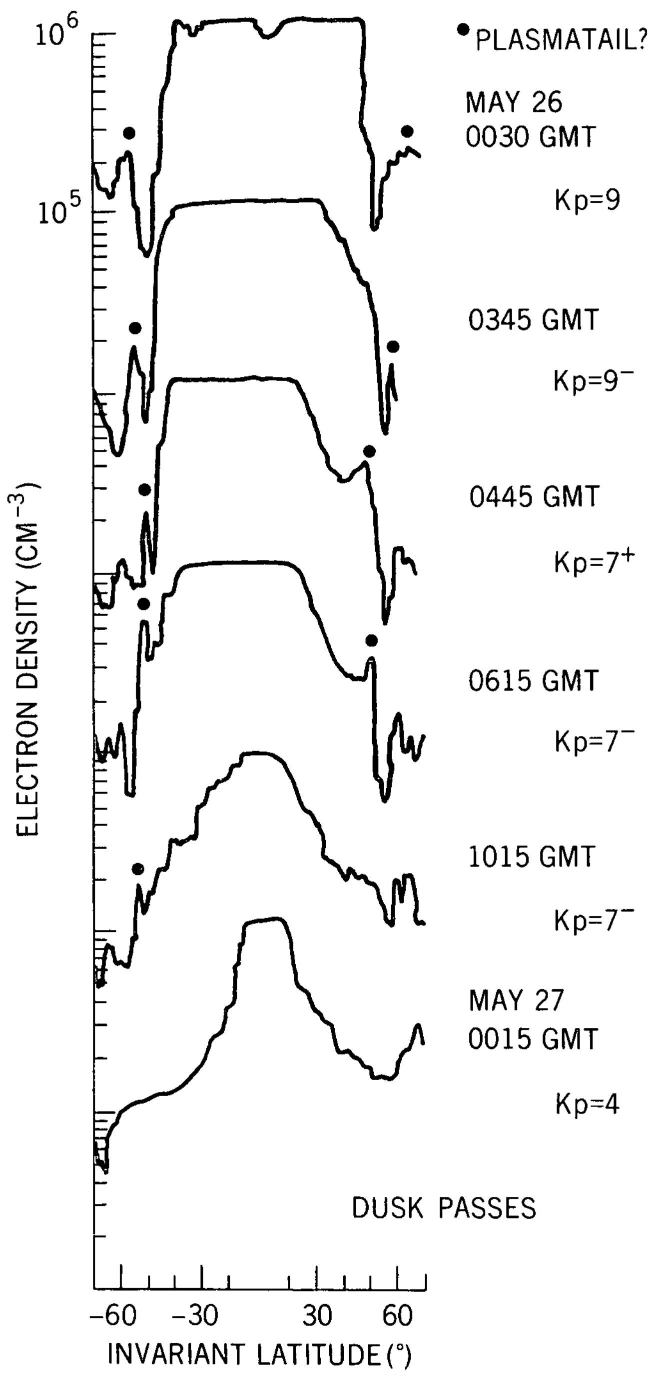

Figure 3. Density variations on successive Ariel 3 orbits at the peak of the May 1967 storm reveal enhanced plasma density peaks (see asterisks) poleward of the main plasmasphere. The indicated universal times characterize the starting times of the data records.

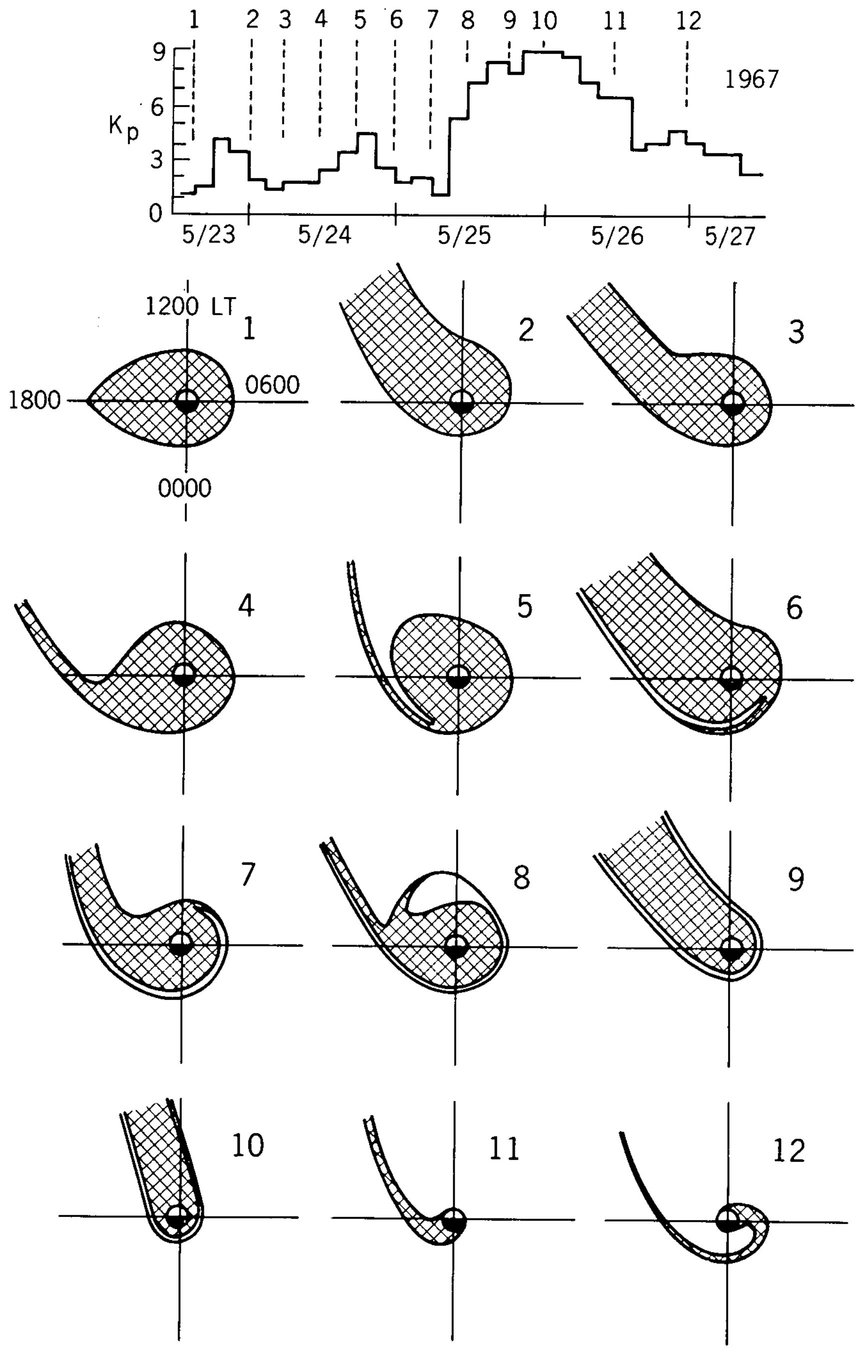

Figure 4. Computed equatorial temporal evolution of the plasmasphere boundary (assumed to be in a steady state configuration initially) is referenced to the K_p variation. The convection electric field in the equatorial plane, assumed spatially invariant, is varied in step with K_p. The radial coordinate in the polar plot is dipole L and the azimuthal coordinate is magnetic local time.

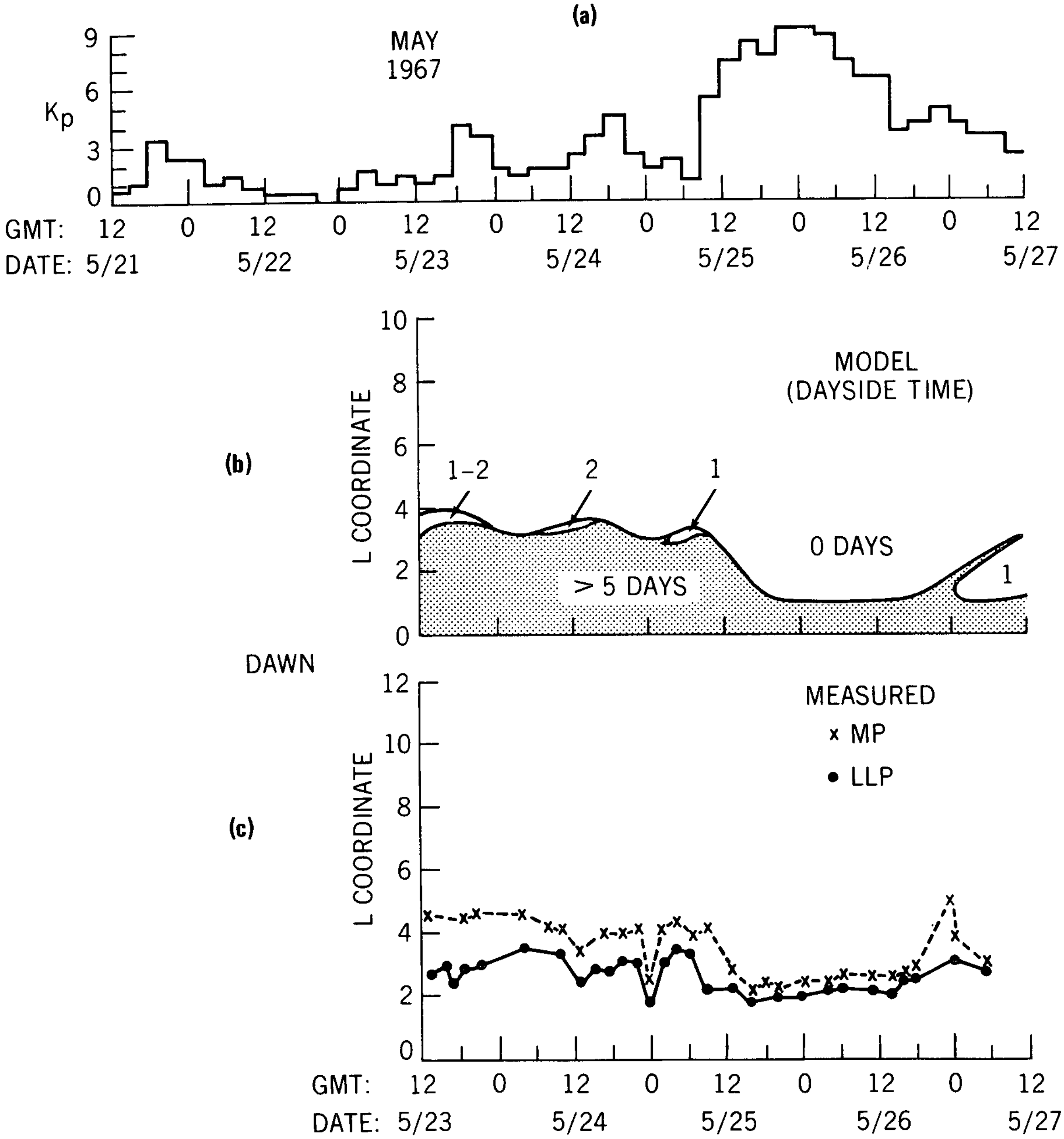

Figure 5. (a) Variation of K_p near the measurement times. (b) Computed plasmasphere boundary results at 0600 MLT are plotted. The times indicated correspond to the number of days a magnetic flux tube has been closed and on the dayside of the earth. The ambient plasma density will be proportional to this time. (c) The Ariel 3 measured trough locations at dawn.

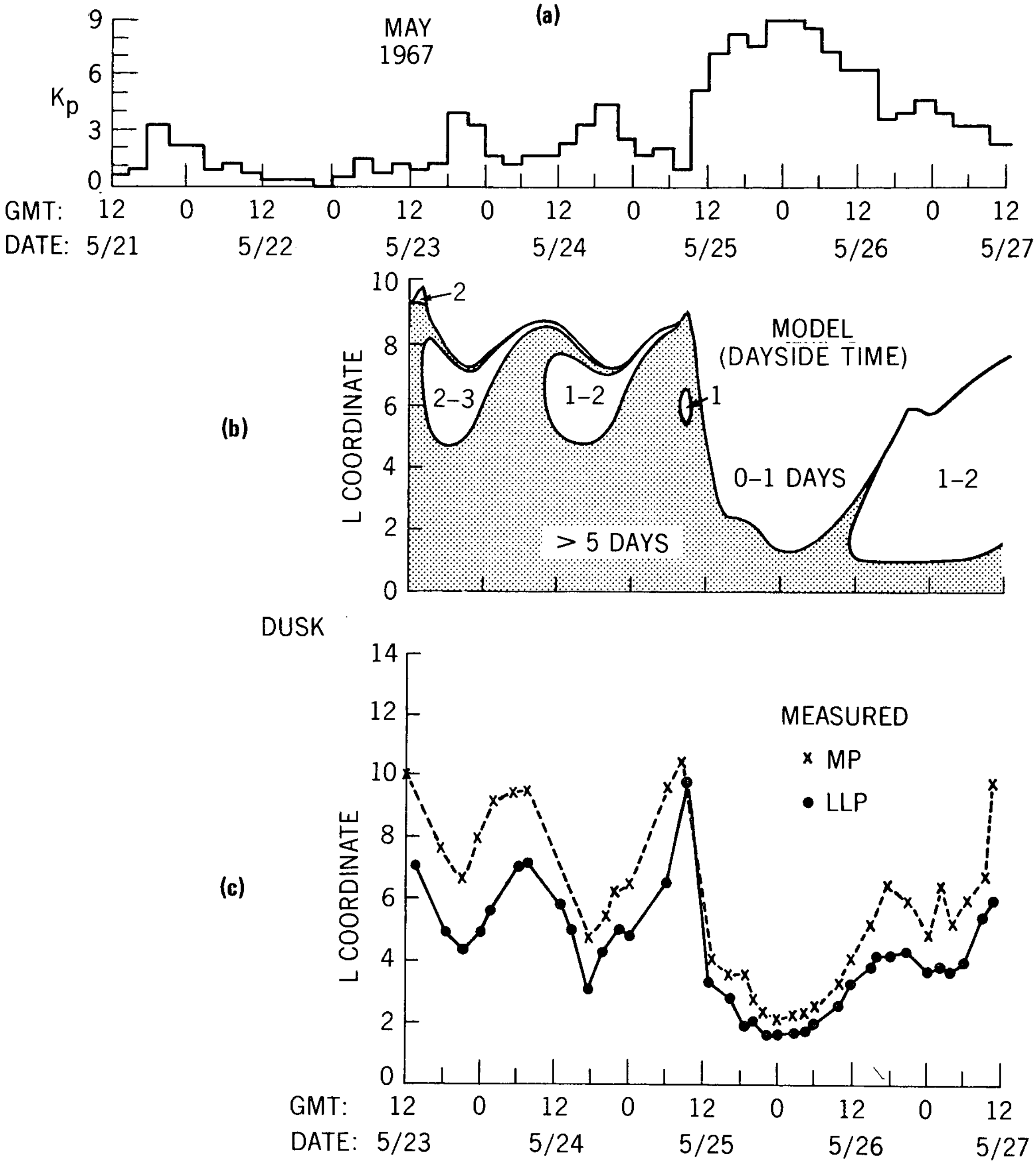

Figure 6. (a) Variation of K_p assumed responsible for the observations. (b) Computed plasmasphere boundary evolution at 1800 MLT is plotted. Multiple plasmapause – like transitions are apparent as abrupt changes in the dayside closure time with increasing L. Each such transition is also characterized by a thin plasmatail density enhancement. (c) Ariel 3 measurements of the electron density trough location compare favorably with the model.

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