Cause of plasmasphere corotation lag

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1. Introduction

It is hypothesized that the recently observed plasmasphere corotation lag is caused by a corresponding corotation lag in the upper ionosphere. Rotation rates of long-lived plasmaspheric notches are compared to ionospheric drifts observed on DMSP spacecraft in the same longitude sectors. Good agreement between the two observations is found, and the cause of the corotation lag is identified as the ionospheric disturbance dynamo. The observed corotation lag will have to be accounted for in future magnetospheric convection models, which until now have assumed strict plasmasphere corotation.


2. Observations

Figure 1 shows a sequence of plasmasphere images obtained on April 6–8, 2001 by the EUV instrument.
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relative to the 96

the ordinate correspond to eastward drift, which is defined

during the respective ten-hour periods. Positive values of

data are plotted in Figure 2 with the six-hour MLT sectors

longitudes bounds the location of the notch throughout its

the DMSP spacecraft F12, F13 and F15 were compiled for

of plasmaspheric notch features follows the overall plasma-

significantly behind corotation over the 55-hour period

which is marked with a yellow arrow, is clearly seen to lag

line moves with the rotation of the Earth, while the notch,

a plasmaspheric density notch. In subsequent panels the red

Goldstein et al.

Dent et al.

Figure 1. EUV images in 30.4-nm light plotted in L-MLT on April 6–8, 2001. Each frame of EUV data is an

extension of the drift data averages to higher latitudes

Heelis and Coley

[9] Each panel in Figure 2 covers a ten-hour time

period beginning with the first observation of the plasma-

density notch early on April 6, 2001. In each panel, high

and variable values of east-west drift associated with the

auroral oval are clearly seen at latitudes above 50°—60°.

At low and midlatitudes, the drifts are generally within

100 m/s of the corotation velocity, which is denoted by

the 0-line in Figure 2; but since the corotation velocity at

the DMSP altitude of ~850 km and at 45° magnetic

latitude is only ~325 m/s, the variations are quite

significant. As shown by the color-coded MLT sectors,

there are significant dependencies on MLT and latitude,

and these features of the data in Figure 2 are consistent

with those published by Heelis and Coley [1992]. For

example, a supercorotation at midnight for magnetic

latitudes near 25° and a subcorotation at all MLTs remote

from noon at midlatitudes are clearly seen in Figure 2 as

well as in Figure 3 of Heelis and Coley [1992].

[8] Each panel in Figure 2 is color coded. Also shown in each panel are the Kp values

during the respective ten-hour periods. Positive values of the ordinate correspond to eastward drift, which is defined

relative to the 96° orbital plane of DMSP so that only drift

meter data, and not RPA data, are used. The rationale for

this restriction is the same as that used by Heelis and Coley

[1992]. The drift meter data are obtained with higher time

resolution, are affected to a lesser degree than the RPA data

by sources of error such as spacecraft potential variations,

and for the midlatitude region occupied by the outer

plasmasphere are very close to representing geographic or

magnetic east-west flow velocities.

[5] In order to test the hypothesis that the corotation lag of plasmaspheric notch features follows the overall plasma-

density and ionosphere rotation rate, drift-meter data from the

DMSP spacecraft F12, F13 and F15 were compiled for

the magnetic longitude sector 100°–180°. This range of

longitudes bounds the location of the notch throughout its

period of observation beginning on April 6, 2001. These

data are plotted in Figure 2 with the six-hour MLT sectors

color coded. Also shown in each panel are the Kp values

during the respective ten-hour periods. Positive values of the ordinate correspond to eastward drift, which is defined

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[Sandel et al., 2000] on the IMAGE satellite. In each panel is

an EUV image that has been mapped to the magnetic equator

in L and magnetic local time (MLT) [see Roelof and Skinner,

2000; Goldstein et al., 2003b; Dent et al., 2003].

For the line of sight corresponding to the center of each pixel, the mapping procedure identifies the dipole field line of minimum L value touched by the line of sight and assigns the brightness of the pixel to the [L, MLT] coordinates of that field line. This procedure is based on the fact that the plasmaspheric density falls off rapidly with L (∼L −4) and is most accurate where sharp edges occur in the density profile (e.g., at the plasmaopause). The color scale intensity is proportional to the log of the line-of-sight integrated He + column abundance. In the center of each image, which is a view from above the north pole, the apparent size and location of the Earth are indicated by the black and white circle. The Sun is to the right in each panel, and a faint shadow extends antisunward from the Earth on the nightside. The plasmasphere is the greenish-to-white haze of 30.4-nm light that surrounds the Earth; close to the Earth the emissions are dominated by airglow from neutral helium and O 7.

[6] In each panel of Figure 1 a red line is drawn radially outward from the Earth, and in the first panel the line bisects a plasmaspheric density notch. In subsequent panels the red line moves with the rotation of the Earth, while the notch, which is marked with a yellow arrow, is clearly seen to lag significantly behind corotation over the 55-hour period covered by the five panels.

[7] In order to test the hypothesis that the corotation lag of plasmaspheric notch features follows the overall plasmasphere and ionosphere rotation rate, drift-meter data from the DMSP spacecraft F12, F13 and F15 were compiled for the magnetic longitude sector 100°–180°. This range of longitudes bounds the location of the notch throughout its period of observation beginning on April 6, 2001. These data are plotted in Figure 2 with the six-hour MLT sectors color coded. Also shown in each panel are the Kp values during the respective ten-hour periods. Positive values of the ordinate correspond to eastward drift, which is defined relative to the 96° orbital plane of DMSP so that only drift meter data, and not RPA data, are used. The rationale for this restriction is the same as that used by Heelis and Coley [1992]. The drift meter data are obtained with higher time resolution, are affected to a lesser degree than the RPA data by sources of error such as spacecraft potential variations, and for the midlatitude region occupied by the outer plasmasphere are very close to representing geographic or magnetic east-west flow velocities.
Figure 7c of Sandel et al. [2003], we find a consistent overall value of 90 ± 1% of corotation.

3. Discussion and Conclusions

[11] The data shown in Figures 1–3 show clearly that the outer plasmasphere, as traced by a density notch feature, rotates at a rate significantly slower (∼10%) than corotation, as first noted by Sandel et al. [2003]. Analysis of DMSP data for the same spatial and temporal locations occupied by the notch show that the departures from corotation observed in the midlatitude upper ionosphere are fully capable of predicting the plasmaspheric corotation lag when the MHD approximation is assumed to hold for the region above 850 km altitude. Thus, while the observed corotation lag should not be surprising, it is considerably at odds with the usual assumption of strict corotation that has been used in all magnetospheric convection models that have been in use for at least the past three decades.

[12] The cause of the corotation lag at midlatitudes is most likely the ionospheric disturbance dynamo as described by Blanc and Richmond [1980]. In its simplest terms, this phenomenon involves the input of energy to the auroral ionosphere by particle precipitation and joule heating. This heat input produces equatorward winds that carry gas into the midlatitude region where the rotational velocity of the Earth is increasing. Conservation of angular momentum within this gas (or equivalently the Coriolis force), which originated at higher latitudes, causes it to lag behind the Earth’s rotation. This lag at latitudes just below the auroral oval is clearly seen in the DMSP data of Figure 2.

[13] The most obvious result of a slower plasmasphere rotation rate in magnetospheric convection models is that the boundary between open and closed convection paths will move closer to the Earth. In addition, the details of the convection patterns throughout the inner magnetosphere will be affected since at every point the corotation electric

Figure 2. Drift-meter data from the DMSP 12, 13 and 15 satellites for six ten-hour periods during the observation of the plasmaspheric notch shown in Figure 1. Each plot is a composite of data from all three satellites whenever they were between geomagnetic longitudes of 100° and 180°, which defines the longitude sector containing the notch throughout its period of observation. Noon (09–15 UT), midnight (21–03 UT), dawn (03–09 UT) and dusk (15–21 UT) data are color coded. Kp values for the ten-hour period are listed at the top of each plot.

Figure 3. Plot in MLT and UT of position of the plasmaspheric notch from its first observation at 03:05 UT on April 6, 2001 until 12:03 UT on April 8, 2001 (red data points); the locations predicted by corotation (blue line), and the locations predicted by the DMSP data in Figure 2 within the geomagnetic latitude interval 40°–45° (green data points).
field and any externally imposed electric fields are added to produce a total electric field. 

[14] One can estimate the effects of the corotation lag by considering the analytical Volland-Stern electric potential model ($\Phi = \Phi_C/L + \Phi_M L^2 \sin(\varphi)$) [Volland, 1973; Stern, 1975] where $\Phi_C$ and $\Phi_M$ are the corotation potential and the magnetospheric convection potential, respectively, and $\varphi$ is an azimuthal angle measured counterclockwise from midnight. The location of the last closed equipotential (LCE) in the equatorial dusk meridian ($\varphi = 270^\circ$), where both the corotation electric field and the magnetospheric electric field are aligned radially) can be obtained by setting $E$ (the sum of the corotation electric field, $E_C$, and the magnetospheric electric field, $E_M$) equal to zero, i.e.,

$$E_{(\varphi=270^\circ)} = -\Phi_C/L + \Phi_M L^2 = -\Phi_C L^{-2} + 2\Phi_M L = 0,$$

$$L^2 = \Phi_C/(2\Phi_M).$$

Thus, for a given value of the magnetospheric potential, the L-value of the dusk-meridian LCE in the equatorial plane varies as the cube root of the corotation potential. Maynard and Chen [1975] have derived a specific $K_p$ dependence of $\Phi_M$, which can be used to show, for example, that for $K_p = 4$ the equatorial dusk meridian LCE will lie at $L = 5.2$ for strict corotation but at $L = 4.9$ for a 15% corotation lag applied uniformly throughout the plasmasphere.

[15] It is interesting to note that, although the Hill [1979] model does not apply to Earth, there is a point of commonality in the physical mechanisms at work. In both cases, the corotation lag results from the Coriolis force acting on plasma that is being transported “outward” (away from the spin axis). At Jupiter, the outward plasma transport occurs in the equatorial plane and results from the centrifugal instability of the Iogenic plasma. At Earth, the “outward” plasma transport occurs in the ionosphere and results from the disturbance dynamo effect. (T. W. Hill, personal communication, 2003).

[16] Since the observed corotation lag is significant, it is important that future convection electric-field models treat this phenomenon accurately either by incorporating empirical ionospheric data or by including a realistic model of midlatitude ionospheric convection that reflects the systematic variations with latitude and local time (as illustrated in Figure 2 and previously presented by Heeils and Coley [1992]) that are known to occur. In fact, the latitude dependence shown in Figure 2 suggests that the plasmaspheric rotation speed varies significantly with radial distance.

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References


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