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# Rotation of the Earth's plasmasphere at different radial distances

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**Abstract**

We have studied the rotation of the plasmasphere using a large plasmaspheric notch observed by the Extreme Ultraviolet (EUV) instrument onboard the IMAGE spacecraft on 2001/173. The time scale is more than 20 h. On the magnetic equatorial plane the notch extends over more than 1.5 Re in radial distance. By analyzing the brightness for four annuluses at different average values of $L$ from 2.0 to 3.25 over time, we determine the rotation rate of the plasmasphere at different radial distances. The analysis reveals that, with the increase of $L$, the rotation rate of the plasmasphere tends to strongly decrease on the dusk side and slightly increase on the dawn side.
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*Keywords:* Plasmasphere; Notch; Rotation rate

## 1. Introduction

The sub-corotation was first observed in the magnesphere of Jupiter (Hill, 1979, 1980). EUV plasmaspheric images from the IMAGE satellite (Burch, 2000; Sandel et al., 2000), provide the possibility to analyze the rotation of the Earth's plasmasphere.

From the EUV images, a variety of plasmaspheric structures have been found (Carpenter et al., 2002; Sandel et al., 2003). One of the largest density structures is the notches, which are characterized by deep density cavities inside the outer plasmasphere. Through tracking a number of notches, Sandel et al. (2003) confirmed that the plasmaspheric departure from corotation with the Earth for the first time. For studying the rotation rate of the plasmasphere, a corotation factor $\xi$ was defined as the ratio of the observed angular rate to the one of Earth's rotation. So, if perfect corotation (or $\xi = 1$) is assumed, the plasma should move 1 h eastward in magnetic local time (MLT) over 1 h of universal time (UT). And they finally found that the corotation factor of plasmasphere in the region from 2 to 4 Re was most frequently from 0.85 to 0.90. Later, Burch et al. (2004) hypothesized that the observed plasmasphere corotation lag was caused by the ionospheric disturbance dynamo. Furthermore, through the study of 18 notches, Gallagher et al. (2005) found most of the cases were observed to corotate lag with the values of $\xi$ between 0.85 and 0.97, except for one case of $\xi = 1$. Besides, the corotation factor $\xi$ can be found by dividing the change in the MLT location of a plasmaspheric feature by the UT elapsed between two EUV snapshots, using a mean-removed cross-correlation of brightness profiles from the plasmaspheric EUV images for different times (Galvan et al., 2008). All those results of the plasmaspheric departure from corotation were reviewed by Darrouzet et al. (2009). Recently, Galvan et al. (2010) calculated the corotation factor of the plasmasphere centered at $L = 2.5$ and $L = 3.5$, and found the rotation rates near dusk were generally lower than those at dawn.

In this paper, we expect that the rotation rate varies with different positions within the plasmasphere, and analyze the variation of the rotation of the plasmasphere for different L-shells and MLT by tracking the position of a large notch.

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## 2. Data selection and analysis

The EUV instrument onboard the IMAGE spacecraft is sensitive to 30.4 nm sunlight resonantly scattered by $He^{+}$ ions in the plasmasphere, which observed a large notch with a radial scale more than 1.5 Re in radial distance on 2001/173, and this notch persisted for more than 20 h. Therefore, the notch can be used to study the plasmaspheric rotation for different L-shells and MLT.

Due to the 14.2 h orbit of IMAGE, these data are within two IMAGE spacecraft orbits, and there is a gap between the two orbits when the satellite is within or near the plasmasphere. Hence the time intervals of the two data sets are 02:15–09:25 UT and 16:23–23:13 UT with a time resolution of 10 min. Within these two time intervals, eight images are selected and displayed in Fig. 1. The background of these images has been subtracted, and they have been mapped to the geomagnetic equatorial plane (Roelof and Skinner, 2000; Goldstein et al., 2003; Dent et al., 2003). Based on the fact that the plasmaspheric density falls off rapidly with increasing $L$ and the assumption of dipole coordinates, each pixel in an EUV image can be mapped to the equator along the dipole field line corresponding to the minimum-$L$ touched by its field of view.

In the center of Fig. 1, the two heavy black arcs mark the MLT location of the notch, corresponding to the dusk and dawn sector, respectively. The curved arrow represents the notch moving direction. The two spaces on the day and night side correspond to the times when the IMAGE satellite is near or within the plasmasphere, so the notch's position on the day and night side could not been observed. The eight different positions of the notch are displayed with ①, ②, ③, ④, ⑤, ⑥, ⑦ and ⑧, connecting with lines to its corresponding images. These eight images are arranged counterclockwise. The first four images in the upper part of the figure correspond to UT = 02:46, 04:49, 06:52 and 08:54 with the notch on the dusk side. The others in the lower part of the figure are the notch on the dawn side, and corresponding to UT = 16:44, 18:47, 20:49 and 22:52, respectively. In each image, the direction of the sun is to the right, where the white radial line is the center of the Earth's shadow at MLT = 0 (or midnight), and the black circle is the Earth. Two white circles, with radii equal to 2.0 Re and 3.5 Re in each image, are the boundaries of the image data that we will analyze, and correspond to the scale of the notch.

The appearance of the plasmaspheric departure from corotation is roughly estimated. The minimum value of the average brightness between 2.0 Re and 3.5 Re excluding the Earth's shadow, is taken to be the center of the notch, which is noted with an arrow in each image. The dotted radial line tracks the Earth's rotation, coinciding

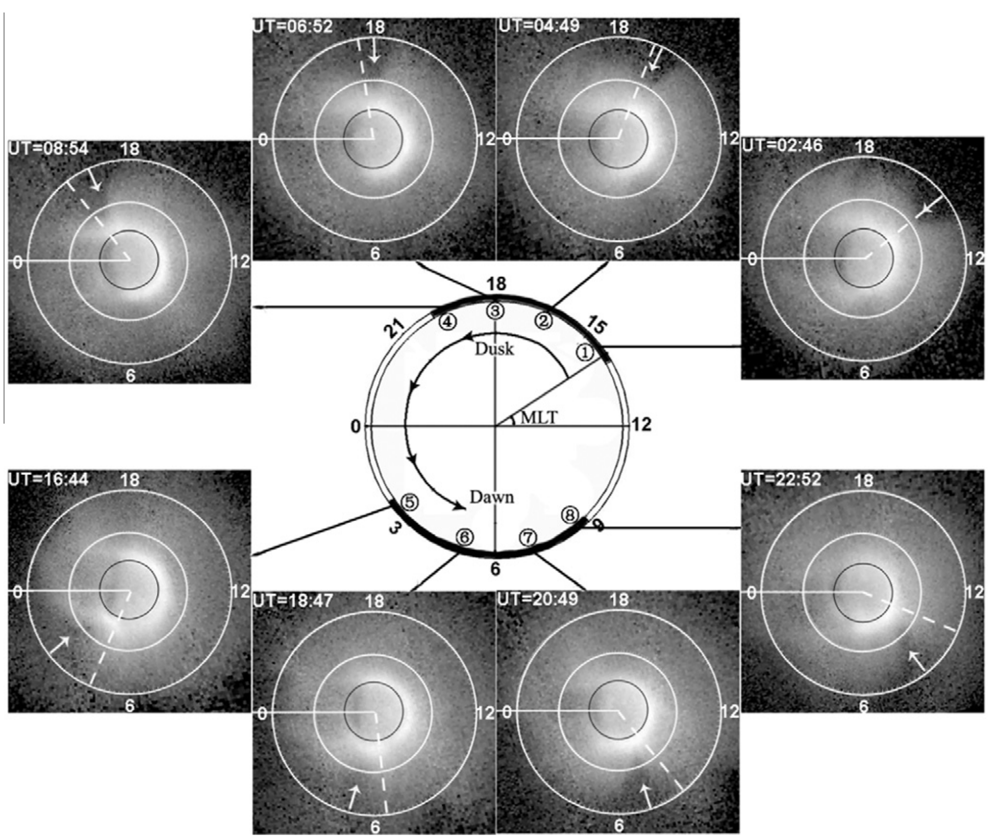


Fig. 1. A sequence of eight plasmasphere EUV images displayed counterclockwise. Each image is mapped to the geomagnetic equatorial plane with the inner and outer white circles corresponding to 2.0 Re and 3.5 Re, respectively. The black circle shows the position of Earth. The center of the notch is marked with an arrow and the radial dotted line tracks the rotation of the Earth. In the center of the Figure, the two heavy black arcs mark the MLT location of the notch and the curved arrow represents the notch moving direction.

with the arrow in the first panel. If perfect corotation is assumed, the dotted radial line should coincide with the arrow in the subsequent panels. However, the center of the notch is trailing behind the dotted line. That is the rotation of the plasmasphere lags significantly behind the Earth's.

To estimate the rotation of the plasmasphere for different radial distances, we divide this large notch into four annuluses for different radial distance $L_n$, where $n$ is the number of annulus. In our calculation the width of each annulus is taken to be 0.5 Re. To enlarge the number of the pixels in each annulus, the annuluses are allowed to overlap each other, and the overlap between each neighbor annulus is 0.25 Re. Since the plasmaspheric density falls off rapidly with $L$, we calculate the corotation factors using only four annuluses at average radial distances of $L_1 = 2.25$, $L_2 = 2.50$, $L_3 = 2.75$ and $L_4 = 3.0$, respectively. For the annulus $L_1$, the inner and outer boundaries correspond to 2.0 Re and 2.5 Re. And for other annuluses $L_2$, $L_3$ and $L_4$, the inner and outer boundaries correspond to 2.25 Re and 2.75 Re; 2.50 Re and 3.0 Re; 2.75 Re and 3.25 Re. The center of the notch for $L_n$ is taken to be the minimum point of the average brightness between the inner and outer boundaries.

The average brightness of the plasmasphere EUV image at $L_1 = 2.25$ for different UT is shown in Fig. 2a. The horizontal axis is MLT, and the vertical axis is the average brightness between 2.0 Re and 2.5 Re in units of photon counts for 128 pixels. The center of the notch is at MLT ≈ 14.5 when UT = 02:46. The upper curves in Fig. 2a, displayed with dashed lines, correspond to UT = 02:46, 04:49, 06:52 and 08:54. The lower curves displayed with solid lines, correspond to UT = 16:44, 18:47, 20:49, and 22:52. The dashed lines are the notch in the dusk region while the solid lines are the dawn region.

The average brightness of the plasmasphere EUV image for different annuluses of $L_2 = 2.50$, $L_3 = 2.75$ and $L_4 = 3.0$ are similar with the case of annulus $L_1 = 2.25$, and they are displayed in Fig. 2b. From Fig. 2, we can find that when $L$ increases, the brightness of the notch becomes weaker and its MLT-width broadens, but it remains clearly discernible. When $L_4 = 3.0$, the width of the notch occupies almost a region of 6 MLT. So for studying the movement of the position (or MLT) of the notch for different time (UT) and avoiding the influence of other structures, we only need to consider the brightness vs. MLT within a scale of 6 MLT. These regions are shown as the rectangular shaded region in Fig. 2.

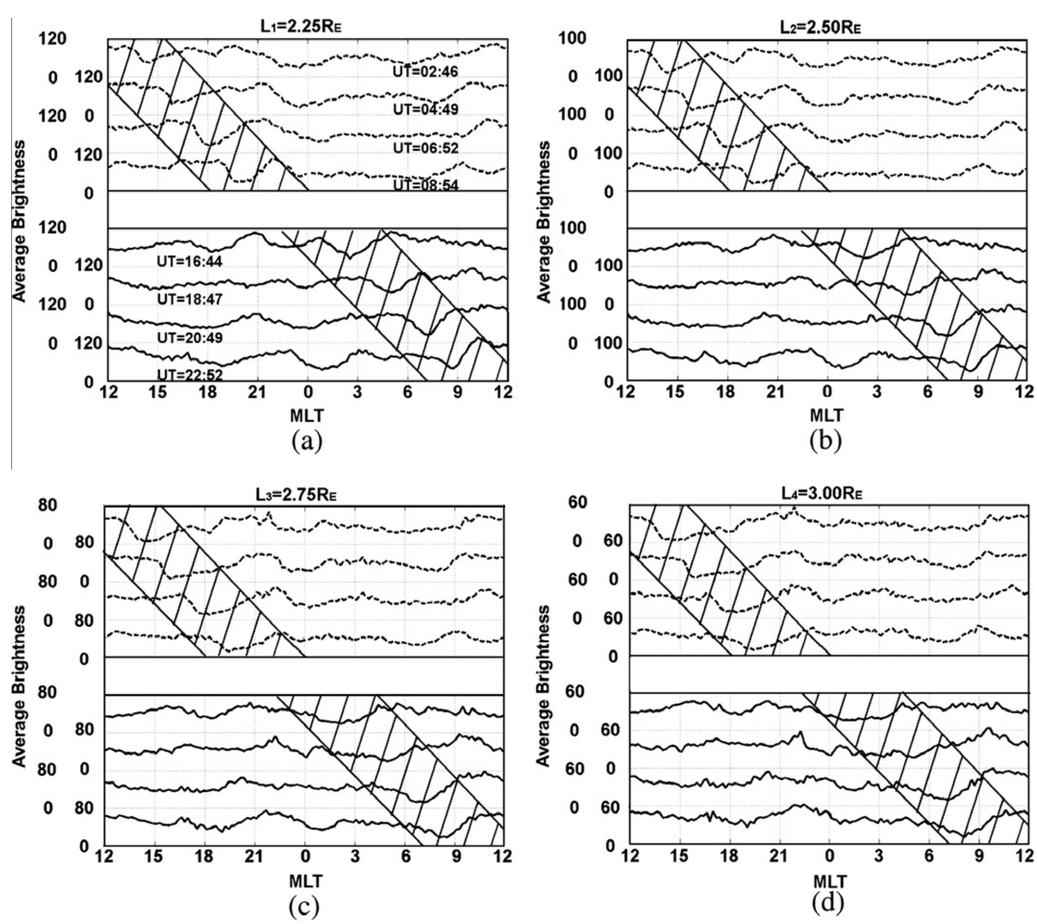


Fig. 2. The average brightness of EUV image within different annuluses vs. MLT. In each panel, the dashed and solid lines correspond to two different IMAGE spacecraft orbits. These four panels are similar but the value of the brightness becomes weaker and MLT-width of the notch broadens with the increase of $L$. The notch's width for different annuluses is in a region of 6 MLT, which is shown as the rectangular shaded region.

## 3. Results

For studying the rotation of the plasma in each annulus, we used the method of ΔMLT/ΔUT to calculate the corotation factor $\xi$, where the ΔMLT is the change in the MLT location of the notch, and the ΔUT is the real time (or UT) elapsed between two EUV snapshots.

The uncertainty of the corotation factor has been considered during the data processing by Galvan et al. (2008). Because the annulus in each image is divided into 128 pixels, each being 11.25 min (=24 h/128) wide in MLT, the uncertainty of the corotation factor for each pair of images is 11.25 min/ΔUT. Hence the uncertainty will become smaller for larger time differences between a pair of images. So if we expect the uncertainty of the corotation factor not to exceed 0.05, every pair of images within an orbit should be separated by at least 3.75 h (=11.25 min/0.05).

For example, we can get a corotation factor of $0.81 \pm 0.04$ for the annulus of $L_1 = 2.25$ from the two EUV images taken at 02:46 and 07:53, where 0.04 is the uncertainty. If the seven consecutive hourly EUV images during the period from 02:46 to 08:54 are considered and every image is cross-correlated with every other image as long as they are separated by more than 3.75 h, we can get six different corotation factors with their individual uncertainty. The final corotation factor is $0.82 \pm 0.02$, which is the mean of the six individual ones, where the uncertainty of 0.02 is the standard deviation of the weighted mean. We can find the uncertainty of the corotation factor becomes smaller when the number of the EUV images increases.

In our work, the consecutive 10-min EUV images during each single orbit are considered, which results in a very small uncertainty ($\leqslant 0.003$) of final corotation factors. As adopting the first two figures after the decimal point, the uncertainty of the corotation factor can be negligible.

Our results of the corotation factor for different annuluses, corresponding to $L_1 = 2.25$, $L_2 = 2.50$, $L_3 = 2.75$ and $L_4 = 3.0$, in the dawn and dusk region are shown in Fig. 3, which reveals that the plasmasphere corotation rate is different at different place. The detailed characteristics of the plasmasphere corotation are as follows: When $L$ increases from 2.25 to 3.0, $\xi$ decreases from 0.88 to 0.72 on the dusk side but increases from 0.96 to 1.05 on the dawn side. $\xi$ is larger than 1 once $L \geqslant 2.75$. This means that the plasmasphere corotates a little bit faster than the Earth's rotation. As $L$ increases from 2.25 to 3.0, a larger decrease of 0.16 on the dusk side and a smaller increase of 0.09 on the dawn side were found.

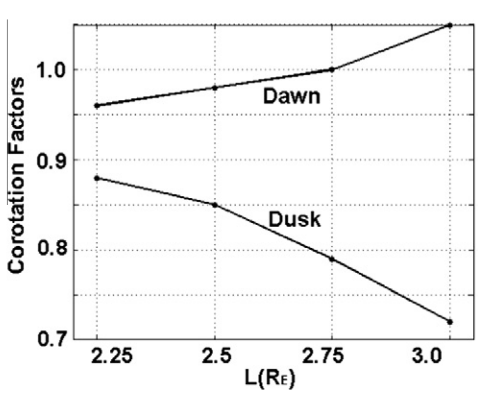


Fig. 3. The corotation factors for four annuluses corresponding to different radial distances in the plasmasphere on 2001/173, in the dusk and dawn regions.

Moreover, on the same annulus, the speed is higher in the dawn region than it in the dusk region. The difference of the rotation speeds on the same annulus is more obvious when $L$ increases. When $L = 2.25$, the difference of $\xi$ between the lowest and the largest is 0.08, while the difference increases to 0.33 at $L = 3.0$. That is the differences between $\xi$ in the dawn and dusk sector become smaller as $L$ decreases, and we expect that they will nearly coincide with each other in the region where $L$ is nearly equal to 1.

## 4. Conclusion and discussion

The rotation of the Earth's plasmasphere at different radial distances has been studied by using a notch in the plasmaspheric EUV image data, observed by the IMAGE spacecraft on 2001/173. The notch is large, so that we can divide it into four annuluses with different radii $L$. The time span of the data is more than 20 h, which includes two satellite orbits, where the position of the notch is on the dawn and dusk side, respectively.

Our analytical results show that the rotation rate of the plasmasphere varies with the magnetic local time and the distance from the Earth's center in the equatorial plane. With the increase of $L$, the corotation factor in the dawn sector increased from 0.96 to 1.05. This indicates that the rotation rate of the plasmasphere can be larger than that of the Earth. In the dusk region, the corotation factor drops from 0.88 to 0.72. Thus, it is easily seen that the rotation speed in the dusk region remains smaller than the one in dawn region. Besides, a larger decrease on the dusk side and a smaller increase on the dawn side are found when $L$ increases. Moreover, the difference of corotation factors on the dawn and dusk side becomes smaller with the decrease of $L$, which leads us to expect that there will be a possibility that these two corotation factors will merge to each other in the region near the Earth.

A further investigation on the particle dynamics of the plasmasphere and the analysis of the EUV image data are in progress to study the details of the plasmaspheric rotation phenomena.

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