Plasmaspheric filament: an isolated magnetic flux tube filled with dense plasmas

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[1] The Telescope of Extreme Ultraviolet (TEX) onboard Japan’s lunar orbiter KAGUYA provided the first sequential images of the Earth’s plasmasphere from the “side” (meridian) view. The TEX instrument obtained the global distribution of the terrestrial helium ions (He+) by detecting resonantly scattered emission at 30.4 nm. One of the most striking features of the plasmasphere found by TEX is an arc-shaped structure of enhanced brightness, which we call a “plasmaspheric filament”. In the TEX image on 2 June 2008, the filament structure was clearly aligned to the dipole magnetic field line of L = 3.7 at 7.3 magnetic local time. Our analysis suggests that the filament represents an isolated flux tube filled with four times higher He+ density than its neighbors. We found four events of plasmaspheric filament in the images obtained between March and June 2008, and in all four events, the geomagnetic activity was quite low. The plasmaspheric filament in the TEX image is the first evidence that a “finger” structure seen in the IMAGE-EUV image is the projection of an isolated flux tube. Citation: Murakami, G., I. Yoshikawa, K. Yoshioka, A. Yamazaki, M. Kagitani, M. Taguchi, M. Kikuchi, S. Kameda, and M. Nakamura (2013), Plasmaspheric filament: an isolated magnetic flux tube filled with dense plasmas, Geophys. Res. Lett., 40, 250–254, doi:10.1002/grl.50124.

1. Introduction

[2] The Earth’s plasmasphere is a torus-shaped region filled with cold plasmas in the inner magnetosphere [e.g., Lemaire and Gringauz, 1998; Darrouzet et al., 2009a]. Helium ions (He+) are the second major components in the plasmasphere and resonantly scatter the solar extreme ultraviolet (EUV) emission at 30.4 nm (He-II). Detecting this emission leads us to the global imaging of the plasmasphere. Meier et al. [1998] performed the proof-of-concept observations using the EUV instrument onboard the STP 72-1 satellite and gave us inside-out views of the plasmasphere. The first plasmaspheric imaging was carried out by a small EUV scanner onboard the Planet-B (Nozomi) spacecraft [Nakamura et al., 2000; Yoshikawa et al., 2000a, 2003]. It has encouraged us to build global images of the terrestrial plasma distribution, that is, plasmasphere, polar wind, and plasma sheet [Yoshikawa et al., 2000b, 2001].

[3] Recent advances in satellite-based imaging techniques have made it possible to routinely obtain full global images of the plasmasphere. The EUV imager onboard the IMAGE satellite [Sandel et al., 2000] produced consecutive images of the Earth’s plasmasphere from the “top” (equatorial) perspective by detecting He-II emission [Sandel et al., 2001; Burch et al., 2001]. The IMAGE mission provided new evidence of the dynamic and spatially structured nature of the plasmasphere. For example, the plasmapause inward motion in response to the solar wind electrical field has been investigated in several studies [e.g., Goldstein et al., 2003a; Spasojević et al., 2003; Murakami et al., 2007] and they found that it requires 10–30 min to propagate from the magnetopause to the inner magnetosphere. Furthermore, the IMAGE mission identified not only conventional pictures of the plasmasphere (plasmapause [Goldstein et al., 2003b], plume [Darrouzet et al., 2006; Spasojević et al., 2004], and duskside bulge [Moldwin et al., 2003]) but also novel structures, for example, depleted regions that are called “notches” [Sandel et al., 2003; Gallagher et al., 2005] and a sharp azimuthal gradient in He+ density called “shoulders” [Goldstein et al., 2002] (for more details, see the review article by Darrouzet et al. [2009b]).

[4] One of the most striking and puzzling features seen in the EUV image is a radial structure of enhanced brightness called a “finger” [Sandel et al., 2001]. Sandel et al. [2001] interpreted these structures as isolated flux tubes that have been filled to higher densities than neighboring tubes. Such flux tubes viewed from a position at high magnetic latitude would appear projected into the magnetic equator plane, leading to the observed finger-like appearance. Although the EUV imager observed fingers many times, they have not been completely understood due to the limited perspective of the EUV imager, that, only from high magnetic latitude.

emissions of oxygen ions at 83.4 nm (O-II) and He\textsuperscript{+} at 30.4 nm (He-II) [Yoshikawa et al., 2008]. The view afforded by the KAGUYA orbit enables us to examine the global distribution of the plasmasphere from the “side” (meridian) perspective. Obana et al. [2010] investigated the plasmapause location using the TEX images and the ground-based geomagnetic data and found good agreement between them. Furthermore, the TEX instrument also succeeded in identifying the corotation and the erosion of the plasmasphere in quiet and disturbed periods, respectively [Murakami et al., 2010; Yoshikawa et al., 2010]. These results confirmed that the TEX instrument successfully obtained the spatial distribution and temporal variation of the plasmasphere from the meridian perspective.

In this letter, we report new observations of a striking feature in the plasmasphere, an isolated flux tube filled up to higher density than neighboring tubes. The TEX instrument first identified this feature from the meridian perspective.

2. Instrumentation and Observation

The KAGUYA spacecraft was launched in September 2007, and the TEX instrument had observed the Earth’s plasmasphere from a lunar orbit during March–June 2008. It was the first time to obtain sequential images of the global plasmasphere from the meridian perspective. The TEX instrument has a field of view (FOV) of 8.3° × 8.3°, which corresponds to 8.7 \( R_E \times 8.7 \, R_E \) at the Earth’s position. The FOV is divided into two parts by the band-pass filter: one is for He-II and the other is for O-II. Because the O\textsuperscript{+} distribution is out of focus of this study, we use only the He-II images (the results of the O-II images will be published in a separate article). The plasmasphere is optically thin for the He-II radiation, so the measured brightness is directly proportional to the He\textsuperscript{+} column density along the line of sight through the plasmasphere. The KAGUYA spacecraft orbits around the Moon with an orbital period of 2 h. Because of some geometrical conditions required to turn on the instrument, TEX has an observation window during 20–30 min every 2 h [Murakami et al., 2010]. The maximum spatial and temporal resolutions are 0.07 \( R_E \) and 1 min, respectively.

3. Results and Discussion

On 1–2 June 2008, the geomagnetic activity was quite low, and no geomagnetic storm had been identified since May 23. Figure 1 shows the geomagnetic conditions (Kp and Dst) and interplanetary magnetic field (IMF) Z-component (in GSM coordinates) on 1–2 June 2008. The Kp was 1 during the TEX observation described below (09:21–09:39 UT on 2 June 2008), and the maximum Kp was 3– during the previous 24 h. ACE measured no abrupt southward turning of the IMF, which can cause major disturbances in the plasmasphere (e.g., erosion and plume formation).

Figure 2a presents a snapshot of the He\textsuperscript{+} plasmasphere obtained by the TEX instrument on 2 June 2008. To improve the signal-to-noise ratio of the image, (1) we accumulated all images obtained in the same revolution (09:21–09:39 UT) and (2) we increased the spatial resolution to 0.14 \( R_E \) using 2 × 2 pixel binning. During this period, the TEX instrument gazed down the Earth from the Moon (23.5° off from the magnetic equator) and the North Pole is presented as a cross-mark in the image. The two gray circles are put in order to mask the artificial circular ghosts, as described in detail by Yoshikawa et al. [2010].

We discovered a striking feature of the plasmasphere in the image obtained by the TEX instrument on 2 June 2008. In Figure 2a, an arc-shaped structure of enhanced brightness is clearly identified as indicated by the red dashed lines. Here we call this structure a plasmaspheric “filament.” We searched the magnetic field line that is most closely aligned to the filament structure. We calculated the average counts along every magnetic field line (at the magnetic latitude between ±20°) and defined the one that has the maximum enhancement of the counts as the best-fitted line to the filament structure. For example, Figure 2b shows the average counts of the pixels along each dipole magnetic field line (\( L = 2.5–4.5 \)) at 7.3 magnetic local time (MLT) in Figure 2a. A clear peak can be identified at \( L = 3.7 \) in Figure 2b. The increase of the average count at the peak (\( L = 3.7 \)) comparing to the backgrounds (e.g., \( L = 3.4 \) and \( L = 3.9 \)) is larger than the statistical errors of ±0.05 count/ min/bin. In this way, we found the best-fitted line to the filament structure, and it is shown as a black curve in Figure 2a. The shape of this structure seems to be consistent with this dipole magnetic field line. Our result suggests that the filament represents an isolated flux tube filled up to higher density than the neighboring tubes. The TEX instrument first succeeded in identifying the isolated flux tube in the plasmasphere by imaging from the meridian perspective.

We approximately estimated the He\textsuperscript{+} density in the filament flux tube and its neighboring tubes at \( L = 3.7 \) using the methods employed by Yoshikawa et al. [2000b] and Gallagher et al. [2005]. The measured brightness is directly proportional to the He\textsuperscript{+} column density along the line of sight because the plasmasphere is optically thin for the He-
II radiation. Observed TEX instrument counts are converted to column density using the following equation derived from the laboratory and in-orbit calibrations (details will be published in a separate article):

$$N = a \times 1.0 \times 10^{20}/F_{30.4}. \tag{1}$$

where $N$ is the He$^+$ column density (cm$^{-2}$), $a$ is the EUV signal in count/min/bin (for 2 x 2 pixel binning), and $F_{30.4}$ is the solar flux at 30.4 nm (photons/cm$^2$/s). The solar 30.4 nm flux was $3.03 \times 10^9$ photons/cm$^2$/s on 2 June 2008, as measured by the SEE instrument [Woods et al., 2005] onboard the TIMED satellite. Column density can be converted to average density by dividing by an estimate of the distance along the line of sight that contributes most to the image intensity at each location in the FOV [Gallagher et al., 2005].

[12] In the event on 2 June 2008 shown in Figure 2, the average 30.4 nm intensity of the plasmasphere at $L = 3.7$ was 0.5 count/min/bin. This value corresponds to the He$^+$ column density of $1.7 \times 10^{10}$ ions/cm$^2$ according to Equation (1) and the $F_{30.4}$ value shown above. The calculated column length through the L-shell of 3.7 along the line-of-sight of TEX was 1.1 x 10$^9$ cm. Thus, the average He$^+$ density in the plasmasphere at $L = 3.7$ was estimated to be 15 ions/cm$^3$. This value is consistent with past in situ measurements of the plasmasphere [e.g., Carpenter and Anderson, 1992], considering the low He$^+$/H$^+$ density ratio of ~0.05 for the minimum solar activity [Craven et al., 1997]. On the other hand, the 30.4 nm intensity along the filament was higher than its neighboring bins by 0.25 count/min/bin, and then the He$^+$ column density along the filament was higher by $8.3 \times 10^9$ ions/cm$^2$ according to Equation (1). If we assume the outer shape of the filament as the cylinder whose diameter is ~2 bins (equal to 0.28 $R_E$), the column length through the filament was estimated to be $2.0 \times 10^9$ cm. Therefore, the difference in the He$^+$ density between the filament flux tube and its neighboring tubes (15 ions/cm$^3$) at $L = 3.7$ was 42 ions/cm$^3$. This means that the filament flux tube has four times higher He$^+$ density ($42 + 15 = 57$ ions/cm$^3$) than its neighbors.

[13] We found four events of the plasmaspheric filament in all the TEX data (March–June 2008). Figure 3 shows the filament event observed on 8 May 2008. In this case, two filament tubes are identified, and only the magnetic field line fitted to the brighter one is shown for simplicity. Table 1

**Figure 2.** (a) An accumulation of EUV images obtained by the TEX instrument onboard KAGUYA on 2 June 2008. The Earth is located near the upper edge of the image. The dashed arc and the dot on the Earth represent the geomagnetic equator and the subsolar point, respectively. The dipole magnetic field lines ($L = 2.5, 3.0, 3.7,\text{ and } 4.0$) at 7.3 MLT are also shown. The line of $L = 3.7$ (black solid curve) seems to be along the structure of enhanced brightness, the “plasmaspheric filament,” indicated by the red dashed lines. (b) Average count along each dipole magnetic field line at MLT 7.3 in the image of (a). The counts of the pixels along each dipole magnetic field line (at magnetic latitudes between ±20°) were averaged. Error bar gives the standard deviation of accumulated counts along each magnetic field line.

**Figure 3.** An accumulation of EUV images of the plasmaspheric filament obtained by the TEX instrument on 8 May 2008, shown in the same format as Figure 2a. Two filament tubes can be identified. The dipole magnetic field lines at 8.0 MLT are also shown, and the line of $L = 3.4$ (black solid curve) seems to be along the brighter filament structure.

**Table 1.** Event List of the Plasmaspheric Filament Showing the Date, UT, Maximum and Average Kp Values During the 24 h Preceding Each Event, L-value, and MLT

<table>
<thead>
<tr>
<th>Date</th>
<th>UT</th>
<th>Max (Average) Kp</th>
<th>L-value</th>
<th>MLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Previous 24 h</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 April 2008</td>
<td>18:10–18:32</td>
<td>2.7 (1.3)</td>
<td>3.5</td>
<td>15.7</td>
</tr>
<tr>
<td>8 May 2008</td>
<td>06:54–07:12</td>
<td>2 (1.2)</td>
<td>3.4</td>
<td>8.0</td>
</tr>
<tr>
<td>26 May 2008</td>
<td>02:32–02:46</td>
<td>1.7 (1.3)</td>
<td>3.5</td>
<td>21.0</td>
</tr>
<tr>
<td>2 June 2008</td>
<td>09:21–09:39</td>
<td>2.7 (1.6)</td>
<td>3.7</td>
<td>7.3</td>
</tr>
</tbody>
</table>
and their surrounding conditions in the ionosphere and the observed by IMAGE-EUV. Our research indicates that the [2001]. However, the origin of plasmaspheric structure may cause the localized density enhancements in the plasmasphere through the magnetic field line. Another possibility is that the filament flux tubes result from disorganized convection electric fields. Such a highly structured convection field might very well stir up the outer plasmasphere and cause isolated flux tubes to be peeled away from the rest of the outer plasmasphere [e.g., Wilson et al., 1992], such ionospheric structure may cause the localized density enhancements in the plasmasphere magnetic field line. [15] One possible source of the filaments is localized density structures in the ionosphere. In recent years, localized plasma density enhancements in the ionosphere (called “plasma blobs”) have been observed by in situ and ground-based observations [e.g., Yokoyama et al., 2007; Pimenta et al., 2007; Park et al., 2008]. Because the refining rate of the plasmasphere is dependent on the plasma density at the ionosphere [e.g., Wilson et al., 1992], such ionospheric structure may cause the localized density enhancements in the plasmasphere through the magnetic field line. [16] The TEX instrument onboard the KAGUYA spacecraft obtained the first sequential EUV images of the Earth’s plasmasphere from the meridian perspective in March–June 2008. We reported new observations of a striking feature named “plasmaspheric filament”, which is an isolated magnetic flux tube filled with four times denser plasmas than their neighbors. Only the TEX instrument can observe this structure from its unique perspective. We identified four events of the plasmaspheric filament during quiet periods. This result is consistent with the recent studies of finger structures observed by IMAGE-EUV. Our research indicates that the finger structures represent the projection of isolated flux tubes onto the magnetic equator plane, as suggested by Sandel et al. [2001]. However, the origin of plasmaspheric filaments is still an open issue. Further investigations of filaments or fingers and their surrounding conditions in the ionosphere and the inner magnetosphere are necessary to solve this issue.

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4. Summary

The TEX instrument onboard the KAGUYA spacecraft obtained the first sequential EUV images of the Earth’s plasmasphere from the meridian perspective in March–June 2008. We reported new observations of a striking feature named “plasmaspheric filament”, which is an isolated magnetic flux tube filled with four times denser plasmas than their neighbors. Only the TEX instrument can observe this structure from its unique perspective. We identified four events of the plasmaspheric filament during quiet periods. This result is consistent with the recent studies of finger structures observed by IMAGE-EUV. Our research indicates that the finger structures represent the projection of isolated flux tubes onto the magnetic equator plane, as suggested by Sandel et al. [2001]. However, the origin of plasmaspheric filaments is still an open issue. Further investigations of filaments or fingers and their surrounding conditions in the ionosphere and the inner magnetosphere are necessary to solve this issue.

References