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Contributed Paper

Influence of Plasma in the Vicinity of Io on Brightness and Angular Extension of Io's Magnetic Footprint

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ABSTRACT

In Jupiter's auroral region, a spot-like emission feature, called the auroral magnetic footprint, is the result of a magnetic disturbance near the extended atmosphere of Io. The magnetic footprint is direct evidence of the interaction between the atmosphere of slow-orbiting Io and the rapidly-corotating magnetic field and magnetospheric plasma of Jupiter. The result of the magnetic disturbance is that a significant amount of current is carried from the interaction region towards Jupiter's ionosphere. Accordingly the precipitating electrons result in the auroral emission. Far ultraviolet (FUV) images of Jupiter's auroral region were used to study this phenomenon. In 2007, using the Advanced Camera for Surveys (ACS) instrument on the Hubble Space Telescope (HST), the observation of Io's magnetic footprint provided the opportunity for a detailed study of the correlation between the spot's brightness and its angular size. With a strong correlation (>0.7) between the brightness and the angular size, these two physical properties were clearly related during March and June, 2007, several weeks after major volcanic eruptions on Io were observed. These results suggest a connection between the plasma supply from Io, due to the volcanic activities on Io and the satellite's auroral magnetic footprint morphology.

Keywords: Jupiter, Io, planets and satellites: aurorae

1. INTRODUCTION

The electrodynamic interaction between Jupiter's magnetospheric plasma and Io's atmospheric particles takes place in the vicinity of Io (see review by Kivelson et al., 2004) [1]. The interaction corresponds to the fast corotation velocity of the magnetospheric plasma (74 km/s) and the much slower particles in Io's extended atmosphere, which move within the inertial frame of Io's orbit velocity (17 km/s). The differential velocity causes the collision between the magnetospheric plasma and the moon's atmosphere. As a result, the Alfvenic disturbance is created at the upstream of the interaction region and travels along Jupiter's magnetic field lines, escaping from the satellite towards Jupiter's ionosphere. The newly ionized charged particles in the interaction region near Io are picked up and accelerated. In this process, some of the electrons are accelerated along the magnetic field and into Jupiter's atmosphere. These precipitating electrons excite atmospheric H_2 molecules and release the energy in the Lyman and Werner bands [2]. The emission, which is directly connected to the interaction region, is called the Main Alfven Wing spot (MAW). On the other hand, the reflection of the Alfvèn wave in Jupiter's plasma torus could cause the secondary spot called the Reflected Alfvèn wing spot (RAW). During the acceleration of electrons towards Jupiter's ionosphere, the reflection of electrons towards the auroral region in the opposite hemisphere could create the Trans-hemispheric Electron Beam spot (TEB). The last feature is tail emission, which connects to the location downstream from interaction region at Io [3-5]. The MAW spot will be referred to as *Io's magnetic footprint* emission, which is the main focus in this study, as shown in Figure 1. In Figure 1, at Io's system III longitude of 135.6 degrees, where there is minimal effect of reflected Alfven wave toward Jupiter's northern hemisphere, the magnetic footprint appears as one emission spot. The appearance of multiple spots of Io's magnetic footprint strongly corresponds to Io's location in plasma torus [6].

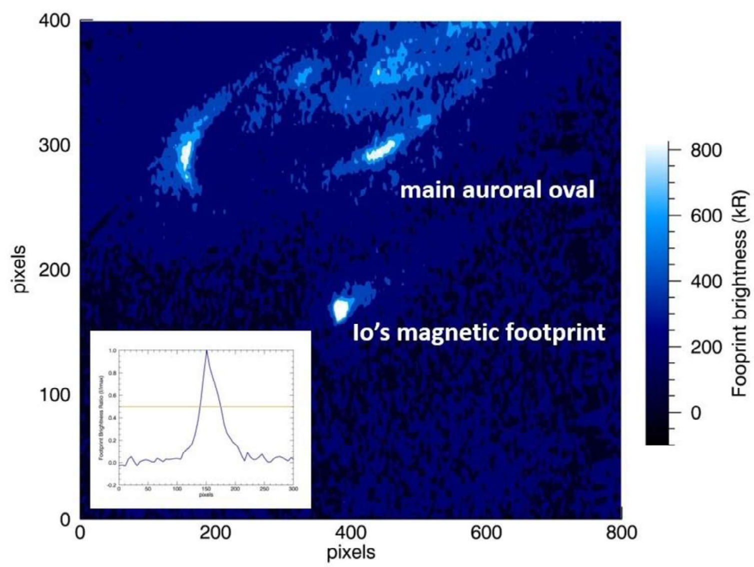

Figure 1. This FUV image of Jupiter's northern auroral region was taken in March 2, 2007 at universal time 07:12:29 by an ACS instrument onboard the HST. Io's magnetic footprint is clearly seen at a lower latitude from the main oval emission. The image was taken when Io was located at a system III longitude of 135.6 degrees. The left inset image is the magnified version of brightness distribution of Io's magnetic footprint. The displayed pixel size appears twice the actual size of the image. Along with the peak emission of Io's magnetic footprint, the angular extension of the footprint was analyzed as an equivalent scale to the full width at half maximum (FWHM) of the emission. In this work, the FWHM cuts were made according to the size of major axis of the MAW footprint emission, while we considered the footprint extending along an elliptical path.

Io's magnetic footprint is evidence of the strong electrodynamics interaction between Jupiter's magnetic field and the satellite's extended atmosphere. The neutral atmospheric particles mostly originate from the atomic and molecular components of SO_2 ejected from the active volcanoes of Io. These neutral particles become ionized via collisional and charge exchange processes with the magnetospheric plasma as well as through photoionization due to the solar radiation in Io's upper atmosphere [7].

The interaction is thought to take place far from Io's surface, at ~ 1.5 Io radii (R_{Io}) [8, 9]. With the conservation of magnetic flux, the interaction region of Io can be mapped to the size of Io's magnetic footprint of ~100 km. This scale length is approximately equivalent to 1-2 pixels detectable by FUV imaging instruments onboard the Hubble Space Telescope (HST). An earlier study of Jupiter's far ultraviolet (FUV) imaging by the Faint Object Camera onboard HST was presented by Prange et al. (1996) [10]. The size of Io's magnetic footprint was found to be approximately 5° at half-maximum elongation in longitude. With FUV auroral imaging by HST Wild Planetary Camera 2 (WFPC2), Clarke et al. (1996) [11] found that, while the magnetic flux mapped to Io's diameter projecting to distance of 200 km at Jupiter's ionosphere, the full width at half maximum of the footprint was in fact between 1000-2000 km. The more detail study of the main spot's size, by Space Telescope Imaging Spectrograph (STIS) and Advanced Camera for Surveys (ACS) instruments on HST, revealed that the footprint's size varies between approximately 400 - 8000 km, or 1-14° on the planet, which is suggested to depend on the size of interaction region at Io [12]. Moreover this detail study of Io's magnetic footprint in three dimensions showed complex variation trends of the footprint's width and length. A previous study [13] revealed a study of the angular sizes of Io's magnetic footprints, when the satellite was at different locations in Jupiter's magnetosphere. During the 1997-1999 observation era of HST, the footprint's angular sizes appeared to be most extended when Io was near the center of the plasma torus (approximately 110° system III longitude).

With approximately a 10° tilt between the magnetic axis and rotation axis, the central density of Jupiter magnetospheric plasma, or plasma torus, inclined ~7° from the orbital plane of Io, which is illustrated in Figure 2. As a result, the brightness of Io's magnetic footprint was found to be tightly connected to the location of Io [14]. Previously, with WFPC2 instrument onboard HST, the systematic variation in system III longitude of Io's footprint emission was presented [15]. Brightness distribution, peak emission, and the appearance of multiple spots were found to connect with Io's system III longitude and latitude from the plasma torus plane [6]. In addition, based on STIS/HST observations during 1997-2001, the systematic variation of Io's magnetic footprint brightness was found to strongly connect with Io's location in System III longitude, which is an indication of Io's position in the plasma torus [16]. The confirmation of this systematic variation was presented by the longitudinal modulation of Io's auroral footprint brightness based on ten-year observation of HST [17]. Along with the location of Io in the plasma torus, the study of Io's magnetic footprint from 1997 to 2009 showed that the magnetic field asymmetry influences the variation of Io's magnetic footprint brightness as well [18].

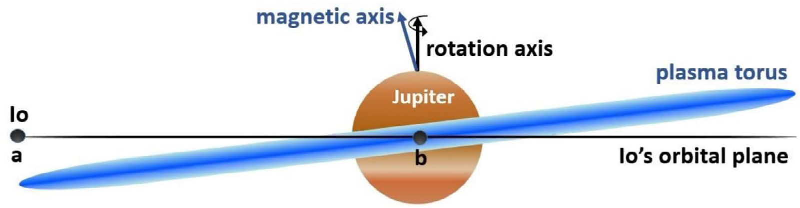

Figure 2. Under the influence of the tilted magnetic axis at approximately 10° from the rotation axis [13], Io experiences a dramatic change of plasma density in the vicinity of the satellite. During the course of orbiting Jupiter, Io is periodically located far from the center of the plasma torus (a), especially when Io is located at approximately 20° and 190° System III longitude. On the other hand, Io can also be embedded in the center of the plasma torus (b), when located at approximately 110° and 270° System III longitude [14]. The above sketch is not to actual scale.

In this study, the variation of angular extension from another observation era by the HST in 2007 is presented. In addition, a direct comparison between the angular size and the brightness of Io's magnetic footprint will reveal the influence of satellite location in the plasma torus on electrodynamic interactions at Io.

2. OBSERVATION AND DATA ANALYSIS

During the observational campaign of the Hubble Space Telescope (HST) in 2007, FUV images of Jupiter's auroral region were taken. All images were reduced under the pipeline routine developed at Boston University [14]. HST's two instruments; the Advanced Camera for Surveys (ACS) and the Solar Blind Channel (SBC), were employed for imaging with two filters: 115LP and 125LP. Filter 115LP is sensitive to wavelengths greater than 115 nm, while 125LP is sensitive to wave lengths greater than 125 nm up to approximately 170 nm. These two filters require different factors for converting count/sec to brightness in kilo-Rayleighs (1 kR = $10^9/4$ p photons cm^{-2} sr^{-1} s^{-1}). The conversion factors were originally generated by a synthetic UV spectrum of auroral emission from H_2 and Lya emission [19]. These different conversion factors for two filters were calculated to compensate for the different wavelength sensitivities of different filters. In our calculation, we consider the newly calculated variation of the conversion factor corresponding to the atmospheric absorption measured by the color ratio [2, 18]. In the data reduction process, the image size was scaled corresponding to Jupiter's distance at 4.2 AU from Earth with the pixel size of 0.025 arc second. The brightness variation of each MAW spot was analyzed for its Full Width at Half Maximum (FWHM) to obtain the angular size, as seen in Figure 1. In addition to the previous study of the connection between the angular size of Io's magnetic footprint and the satellite's longitude, the peak emission of the footprint is taken into consideration. From all data observed in 2007, the footprints were chosen based on their distances to the limb, corresponding to Serio and Clarke (2008) and Wannawichian et al. (2010) [14, 16]. This limit provides footprints that are far from the limb, more than 2100 km, with no significant geometric distortions.

3. Results and Discussion

Angular extensions of the Io magnetic footprint from several observations by the Hubble Space Telescope in 2007 show a temporal variation as a function of observing time. From the results in Figure 3, there are strong variations in the angular size of Io's magnetic footprint. Several peaks appear to be noticeable; for example, when Io was near 80 and 295 degrees longitude. It must be noted that there is another peak near 0 degrees as well, which is not completely related to the magnetic footprint brightness, as shown in Figure 4. The variation of angular size appears to be under the influence of Io's system III longitude.

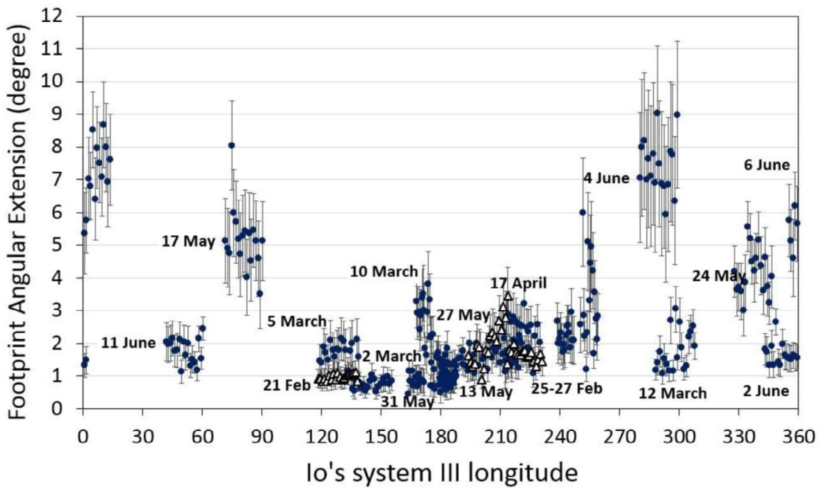

Figure 3. The angular sizes of Io's magnetic footprint from several observations by HST during 2007 campaign. The angular size was obtained by an analysis of Full Width at Half Maximum (FWHM) of each MAW spot, as seen in Figure 1. For clarification, the data on February 21, 23, and 26 were plotted with triangular symbols.

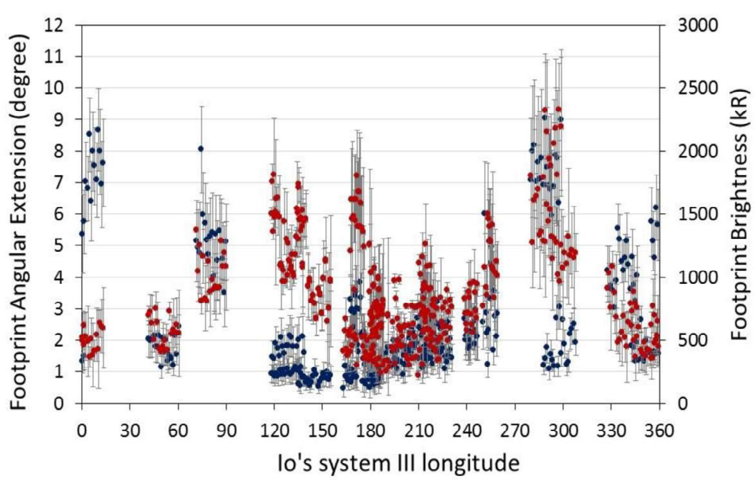

Figure 4. The angular sizes of Io's magnetic footprint (blue dots) from several observations by HST during the 2007 campaign, as shown in Figure 3, are compared with the magnetic footprint brightness (red dots). The unit of brightness is in kilorayleighs (1 kR = 10^9 photon $cm^{-2}s^{-1}$ into 4π steradians [25]).

There are several possibilities for the controlling factors of Io's angular size. The first factor could be the volcanic eruptions on Io. In February and March 2007, during the New Horizon's spacecraft Jupiter flyby, several eruptions of volcanoes on Io were detected [20]. The next factor could be variation in the plasma torus. Temporal and longitudinal variation of the plasma torus was observed in Cassini UVIS observations by Steffl et al. (2008) [21]. Another explanation for the variation could be Io's locations. The location of Io in Jupiter's magnetosphere appears to be strongly correlated with the brightness of the satellite's magnetic footprint [14].

Previously, Wannawichian et al. (2010) [14] showed that the footprint brightness varies in the form of a general sinusoidal trend, which corresponds to the location of Io in Jupiter's magnetosphere. Accordingly, the comparison of brightness and angular size as a function of Io's system III longitude is shown in Figure 4. Overall, the Pearson correlation between the brightness and the angular size of Io's magnetic footprint was found to be 0.730. This correlation implies a positive relationship between the magnetic footprint brightness and its angular size. It is noticeable that the relationships between these two properties of the magnetic footprint vary in different months during HST's 2007 campaign. We conclude, therefore, that the correlations between the brightness and angular size of Io's magnetic footprint varies between the different observations, as shown in Table 1. The correlations between footprint brightness and angular size appear to be strongest during the observations in March and June 2007. This result implies some connection with the volcanic eruptions on Io, which were reported to be strong during February and May 2007 [20, 22]. It has been suggested that a strong mass loading from

Table 1. Correlation between the brightness and angular size of Io's magnetic footprint based on different observations.

Observation Months in 2007	Correlation between the brightness and angular size	Ranges of Io's System III longitude (°)	Correlation between the brightness and angular size
February	0.816	0-30	0.930
March	0.893	31-100	0.949
April	0.838	101-160	0.918
May	0.723	161-270	0.883
June	0.878	271-360	0.845

Io's volcanoes can weaken the field aligned-current, which is connected to the auroral emission in Jupiter's ionosphere [22]. As a result, after the strong eruptive events, throughout February and at the end of May 2007, the relaxation of mass loading led to the increase of precipitating particles into Jupiter's auroral region. Consequently, the better correlations between the auroral magnetic footprint brightness and angular size was detected. It is significant to note that, from previous studies by Bonfond et al. (2009; 2010) [4, 12], the inter-spot distances vary strongly with Io's system III longitude.

The spot brightness and size should be carefully accounted for when the inter-spot distances are very small, since the merging between MAW and TEP spots is possible. During our analysis of the MAW emission, occasionally the TEP spots appeared near the main emission. Therefore the detail analysis of spot-by-spot evolution to clarify the general trend in this work should be further studied. In addition, the similar feature of spot multiplicity was also found for the case of Ganymede auroral footprint [18]. Moreover the influence of Io's volcanism over Jupiter's radio emission, corresponding to expansion of the main auroral oval, as well as the Ganymede footprint, appears to vary with system III longitude [22, 23]. Therefore longitudinal and time variations, based on volcanic activities on Io, should be taken into account. Taking into account the complex configuration of Jupiter's magnetic field, Io's northern and southern magnetic footprints were found to vary differently [4, 12]. As shown in Figure 5, the angular extensions of northern and southern magnetic footprints clearly show different trends. The variation of surface magnetic field as well as the magnetic anomaly in northern hemisphere could play a major role in the brightness and the angular extension of the footprint. Previous numerical studies, using magnetohydrodynamics (MHD) model proposed that the Alfven wave and corotational lag relate to conditions in Io's plasma wake [24]. The match between the calculated downstream current distribution, corresponding to corrotational lag of up to 500 seconds, and Io's brightest footprint spot, MAW, suggested the inter-spot angle between MAW and TEP to be 7° or smaller. This is the same range as our analyzed extension angle. The corotational motion of downstream flux tube could play an important role in controlling the inter-spot distance and correspondingly interfering with the MAW extension angle.

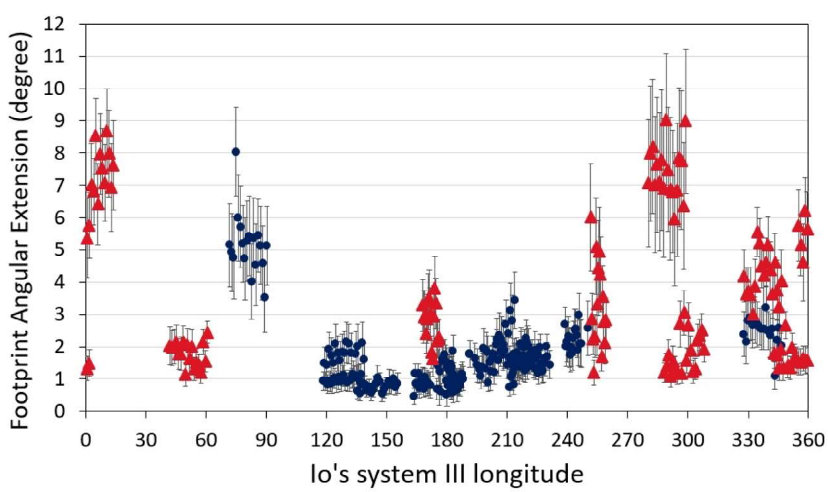

Figure 5. The angular sizes of Io's northern magnetic footprint (blue dots) from several observations by HST during the 2007 campaign, as shown in Figure 4, are compared with the angular size of southern magnetic footprint (triangular symbols).

4. Conclusions

During several HST observations, Io's auroral magnetic footprint emissions appeared to be highly variable in terms of brightness and angular size. Two clear peaks near 80 and 295 degrees longitude are as expected and related to Io's locations in the plasma torus as shown in Figure 2. A strong correlation (> 0.7) was found between the brightness and angular size, with the best correlations found for the observations performed in March and June 2007. The results suggest a connection between the morphology of Io's magnetic footprint and the volcanic activities on Io. Previous works [4, 12, 22, 23] showed possible interferences due to the TEP and tail emission in the MAW emission, along with longitudinal variation of the influence of Io's volcanic activity. These effects should be carefully taken into consideration in future studies. The detail analysis of temporal variations should be further investigated.

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References

[1] Kivelson M.G., Bagenal F., Kurth W.S., Neubauer F.M., Paranicas C. and Saur J., Magnetospheric Interactions with Satellites, in Bagenal F., Dowling T. and McKinnon W., eds., *Jupiter The Planet, Satellites and Magnetosphere*, Cambridge Univ. Press, Cambridge, UK, 2004: 513-536.

[2] Gustin J., Bonfond B., Grodent D. and Gerard J.C., *J. Geophys. Res.*, 2012; **117**: A07316, DOI 10.1029/2012JA017607.

[3] Clarke J.T., Grodent D., Cowley S.W.H., Bunce E.J., Zarka P., Connerney J.E.P. and Satoh T., Jupiter's Aurora, in Bagenal F., Dowling T. and McKinnon W., eds., *Jupiter The Planet, Satellites and Magnetosphere*, Cambridge Univ. Press, Cambridge, UK, 2004: 639-670.

[4] Bonfond B., Grodent D., Gerard J.C., Radioti A., Dols V., Delamere P.A. and Clarke J.T., *J. Geophys. Res.*, 2009; **114**: A07224, DOI 10.1029/2009JA014312.

[5] Bonfond B., Grodent D., Gerard J.C., Radioti A., Saur J. and Jacobsen S., *Geophys. Res. Lett.*, 2008; **35**: L05107, DOI 10.1029/2007GL032418.

[6] Gerard J.C., Saglam A., Grodent D. and Clarke J.T., *J. Geophys. Res.*, 2006; **111**: A04202, DOI 10.1029/2005JA011327.

[7] Smyth W.H. and Marconi M.L., *Icarus*, 2005; **176**: 138-154.

[8] Grodent D., *Space Sci. Rev.*, 2015; **187**: 23-50.

[9] Hill T.W. and Pontius D.H., *J. Geophys. Res.*, 1998; **103**: 19879-19886.

[10] Prange R., Rego D., Southwood D., Zarka P., Miller S. and Ip W., *Nature*, 1996; **379**: 323-325.

[11] Clarke J.T., Ballester G.E., Trauger J., Evans R., Connerney J.E.P., Stapelfeldt K., Crisp D., Feldman P.D., Burrows J., Casertano S., Gallagher III J.S., Griffiths R.E., Hester J., Hoessesl J.G., Holtzman J.A., Krist J.E., Meadows V., Mould J.R., Scowen P.A., Watson A.M. and Westphal J.A., *Science*, 1996; **274**: 404-409.

[12] Bonfond B., *J. Geophys. Res.*, 2010; **115**: A09217, DOI 10.1029/2010JA015475.

[13] Wannawichian S., Clarke J.T. and Nichols J.D., *Chiang Mai J. Sci.*, 2016; **43**: 870-875.

[14] Wannawichian S., Clarke J.T. and Nichols J.D., *J. Geophys. Res.*, 2010; **115**: A02206, DOI 10.1029/2009JA014456.

[15] Clarke J.T., Ballester G., Trauger J., Ajello J., Pryor W., Tobiska K., Connerney J.E.P., Gladstone G.R., Waite Jr.J.H., Jaffel L.B. and Gerard J.C., *J. Geophys. Res.*, 1998; **103**: 20217-20236.

[16] Serio A.W. and Clarke J.T., *Icarus*, 2008; **197**: 368-374.

[17] Wannawichian S., Clarke J.T., Bagenal F., Smyth W.H., Peterson C.A. and Nichols J.D., *J. Geophys. Res.*, 2013; **118**: 3336-3345.

[18] Bonfond B., Hess S., Gerard J.C., Grodent D., Radioti A., Chantry V., Saur J., Jacobsen S. and Clarke J.T., *Planet. Space Sci.*, 2013; **88**: 64-75.

[19] Gerard J.C., Gustin J., Grodent D., Delamere P. and Clarke J.T., *J. Geophys. Res.*, 2002; **107**: 1-30.

[20] Spencer J.R., Stern S.A., Cheng A.F., Weaver H.A., Reuter D.C., Retherford K., Lunsford A., Moore J.M., Abramov O., Lopes R.M.C., Perry J.E., Kamp L., Showalter M., Jessup K.L., Marchis F., Schenk P.M. and Dumas C., *Science*, 2007; **318**: 240-243.

[21] Steffl A.J., Delamere P.A. and Bagenal F., *Icarus*, 2008; **194**: 153-165.

[22] Clarke J.T., Ajello J., Ballester G., Jaffel L.B., Connerney J., Gerard G.C., Gladstone G.R., Grodent D., Pryor W., Trauger J. and Waite J.H., *Nature*, 2002; **415**: 997-1000.

[23] Yoneda M., Tsuchiya F., Misawa H., Bonfond B., Tao C., Kagitani M. and Okano S., *Geophys. Res. Lett.*, 2013; **40**: 671-675.

[24] Bonfond B.S., Hess F., Bagenal J.C., Gerard D., Grodent A., Radioti J., Gustin and Clarke J.T., *Geophys. Res. Lett.*, 2013; **40**: 4977-4981.

[25] Chen C.X., *J. Geophys. Res.*, 2007; **112**: A03204, DOI 10.1029/2006JA011599.