Final Report

Magnetospheric Plasma Controls over Jupiter's Auroral Emissions

By Suwicha Wannawichian

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Final Report

Project Title

Magnetospheric Plasma Controls over Jupiter's Auroral Emissions

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Abstract

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Project Title **: Magnetospheric Plasma Controls over Jupiter's Auroral Emissions**

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Abstract:

Being the biggest planet in our solar system, Jupiter provides vast information of star-planet and planet-satellite electro-magnetic interactions. One of major evidences of those interactions is the auroral emission on Jupiter. Ultraviolet imaging via 25MAMA (Multi Anode Micro channel Array) and Advanced Camera for Surveys (ACS) onboard Hubble Space Telescope reveals systematic and short time variations of auroral features on Jupiter. Auroral variation's controlling factors, which are solar wind condition and volcanic activities on Io, will be investigated in detail. The solar wind conditions will be obtained from both direct observations and modeling. On the other hand, the density and variation of magnetospheric plasma will be acquired via in situ observations and Earth-base observations. This study, which covers ten-year observations of auroral features, will reveal the connection between the physical conditions of magnetospheric plasma and Jupiter's auroral emission. The result could provide the explanation for the nature of electro-magnetic interaction between the Sun and Jupiter, as well as, Jupiter and its satellites. The main expected application of this work is the ability to understand the other solar system, which leads to the extension of this research field.

Keywords : Jupiter, Magnetosphere, aurora

Executive summary

The relation between variations of Jupiter's auroral zone is analyzed in comparison with solar wind condition as well as the change of plasma contribution to Jupiter's magnetosphere due to the volcanic eruption on Io. From previous work, suggested controlling factors to the electromagnetic interactions between the Sun and Jupiter should be the dynamic pressure of solar wind. ***We discovered the unstable behavior of the spot emissions, whose positions appear to be fix in System III longitude. The latitudes and longitudes are found to slightly varied within 3 degrees for each day. The recurrent of bright spots, connected to the distances beyond magnetospheric boundary, suggests the connection with day side reconnection. However, in this work, the direct connection between Jupiter polar emission and solar wind dynamic pressure cannot be strongly confirmed. More polar brightening events are analyzed based on recent observations of Hubble Space Telescope (HST).***

As for the electromagnetic interactions inside Jupiter's magnetosphere, the significant evidence of the interaction is magnetic footprint of Jupiter's satellites. Short term variation of magnetic footprint brightness is numerically analyzed and under investigation for the direct connection to the volcanic eruption on Io. ***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.*** For long term variation of the magnetic footprint, the angular sizes of the footprint show somewhat correlation with the brightness. Some differences are discovered and under discussion for theoretical explanation. Two decades of data base for Io magnetic footprint, according to available data from HST, could be one of the key explanation for the long term variation of connection between auroral magnetic footprint and plasma environment hear Io.

Finally, magnetic field model was employed to map the location of auroral features in Jupiter's auroral region. The model shows various origins of auroral particles, from which are either inside or outside Jupiter's magnetosphere***. Based on the prediction by the model, lead angle and Io's footprint brightness has a positive relation to each other. On the other hand, correlation coefficients between footprint brightness and magnetic field strength show disagreement of correlation coefficient between both hemispheres. One explanation***

could be the negative relationship between magnetic field strength and the number of precipitating auroral particles. It is clear that, while magnetic field strength and magnetic field configuration can play a controlling role in the footprint brightness This information could provide significant explanation for nature of magnetospheric plasma controls over Jupiter's auroral emissions.

Objective

The work will investigate the relation between Jupiter's auroral emission and magnetospheric properties, mainly solar wind independence and magnetospheric plasma density. The study of Jupiter's auroral variations will lead to the understanding of controlling factors to the electromagnetic interactions between the Sun and Jupiter, as well as, the electro-magnetic interactions inside Jupiter's magnetosphere. In order to connect the ionospheric phenomena with the origin of auroral particles in magnetosphere, as known as, M-I coupling, VIPAL magnetic field model is chosen to simulate Jupiter's magnetic field. The model will be used to investigate the influence of magnetospheric plasma density and magnetic field configuration on the auroral emission at the foot of satellite's magnetic footprint. The result will reveal the connection between electro-magnetic interaction at the satellite and the auroral production in ionosphere, via magnetic field line. This study will be based on direct observations of Jupiter auroral emissions, which were imaged by Hubble Space Telescope (HST) and solar wind observations. The output is expected to be employed for further investigation based on theoretical and computation approaches.

Research methodology

HST Observations Data Analysis: Far-ultraviolet (FUV) imaging of auroral emissions

The analysis of Jupiter auroral emission will be based on Ultraviolet images of Jupiter auroral emission during 1997-2007, which were taken by two instruments: 25MAMA (Multi Anode Micro channel Array) and Advanced Camera for Surveys (ACS) on broad Hubble Space Telescope (HST). Pipeline routine was developed at Boston University [Nichols et al., 2009; Wannawichian et al., 2010]. All 242 images response to the brightness spanning over the wavelengths 115-170 nm, which is the majority of energy emitted from Jupiter auroral region. The analysis of auroral features and brightness will be taken place at the Department of Physics and Materials science, Chiang Mai University via the Interactive Data Language (IDL) software properly licensed to the Astronomical Laboratory. The external controlling factor, i.e., solar wind condition, will be acquired from web-based data bases, e.g. MSWim simulation at Michigan University (Zieger and Hansen, 2008) and observational data based from http://www.srl.caltech.edu/.

Variation of brightness and size of Io's magnetic footprint is studied based on FUV images of Jupiter's auroral region, taken by by Advanced Camera for Surveys (ACS) instrument on Hubble Space Telescope (HST). Specifically, the brightness and size of Main Alfvèn Wing spot was investigated. The size of magnetic footprint corresponds to the angular size of Full Width at Half Maximum (FWHM) of the main emission spot. The brightness of the footprint is in in kilo-Rayleighs (1 kR = 10^9 photon $cm^{-2}s^{-1}$ into 4π steradians).

Modeling: VIPAL magnetic field model is chosen to simulate Jupiter's magnetic field model (Hess et al., 2011). VIPAL was constructed based on observations by Pioneer and Voyager spacecrafts. This model appears to have a lot of benefits. For example, it can be used to analyze auroral emission in Jupiter's ionosphere. This model also has the best prediction of contact positions between ionosphere and magnetic field lines that cross Io, called Io's footprint. VIPAL also gives better magnetic field strength prediction than previous models. In order to predict footprint positions in both north and south hemispheres, we traced along the magnetic field lines beginning from Io orbital position to the footprint locations in ionosphere.

Result

1. The study of Jupiter's aurora: bright spot variation in active region

A bright spot, an ambiguous feature in Jupiter's polar aurora is chosen to study in this work. Jupiter's northern aurora images were taken during May-June 2007 by the Advanced Camera for Surveys (ACS), an instrument onboard the Hubble Space Telescope (HST). We investigate for the variations in brightness, location, and size of bright spots during this campaign. Their mapped positions in magnetosphere were analyzed using Jupiter Ionosphere/Magnetosphere Online Mapping Tool based on flux equivalent calculation by VIP4, VIPAL, and GAM internal magnetic field models (Vogt et al., 2011 and 2015). Here we present the results which eight bright spots were detected, including its morphology evolution and variations.

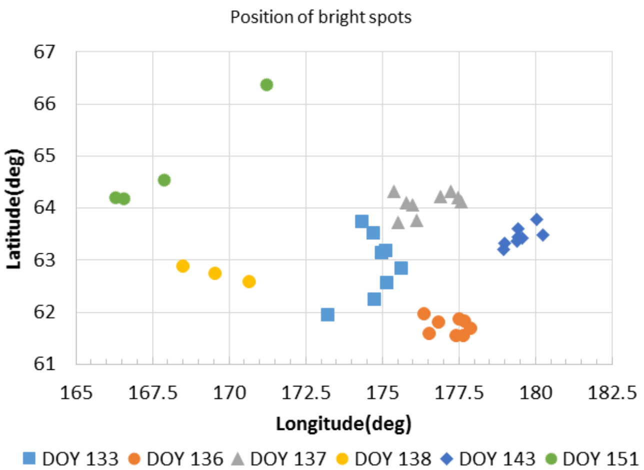
We clearly detected eight bright spots from Jupiter's aurora images data set. The position of bright spots peak along System III longitude in Jupiter's ionosphere and mapped position in magnetospheric region are summarized in Table 1.1. For convenience, the bright spots were labeled by letter a to h. The result shows that the latitude position of bright spots are slightly vary between 61- 66 degrees, while the longitude are found varying within 10 degrees. The positions in magnetosphere of bright spot are found to map to radial distance more than 70 Jovian radii with local time near noon except bright h whose local time is at 18 hr. Moreover, some bright spots are found to correspond to region beyond dayside magnetopause which usually consider to relate with the open-close field lines region.

In detail analysis, we analyze for consecutive Jupiter's aurora images before and after the images the appear bright spot in order to study the variation in location and size of bright spots, as shown in Figure 1.1 Each day shows a slight variation for both latitude and longitude positions. Bright spot g seems to appear differently from others, at latitude higher than 66°. However, it is the first image of that day so we cannot know the position of bright spot earlier that time and cannot confirm that spot originate different from bright spot h. From figure 1, all data that can determine the position in magnetospheric region are found to locate at radial distance range from 70-100 RJ, except for bright spot h which locate at larger distance and different time. Therefore, bright spot might be related to another process differ from other bright spots.

Table 1.1 Bright spot characteristics and positions in magnetosphere based on Jupiter Ionosphere/magnetosphere online mapping tool.

Bright spot	UT (DOY)	CMLS (deg)	Latitude (deg)	Longitude (deg)	Position in magnetosphere		
					Model	Radial distance (R_J)	Local Time (Hr)
a	133.708	163.46	63.13±0.84	175.01±1.77		B	B
b	133.724	177.74	61.94±0.88	173.26±1.46	VIP4	85.516	10.836
c	136.648	202.78	61.67±0.74	177.91±2.18	VIP4	74.236	11.698
					VIPAL	89.675	11.849
d	137.854	171.98	64.32±0.91	177.25±1.53		B	B
e	138.724	210.08	62.87±0.88	168.53±2.47	VIP4	91.429	14.534
f	143.635	164.51	63.33±0.79	178.98±1.27		B	B
g	151.487	159.90	66.35±1.44	171.27±1.05		B	B
h	151.510	180.01	64.18±0.74	166.34±1.46	GAM	145.128	18.836

Note: The position in magnetosphere obtained from the Jupiter Ionosphere/Magnetosphere Online Mapping Tool are based on VIP4, GAM, and VIPAL magnetic field models. **B** refers to mapped location beyond 150 Jovian radii or beyond the dayside magnetopause. Occasionally, bright spot can be mapped to position in magnetosphere by some models while others give prediction to **B**. In this case, we showed only predictions that are not **B**.



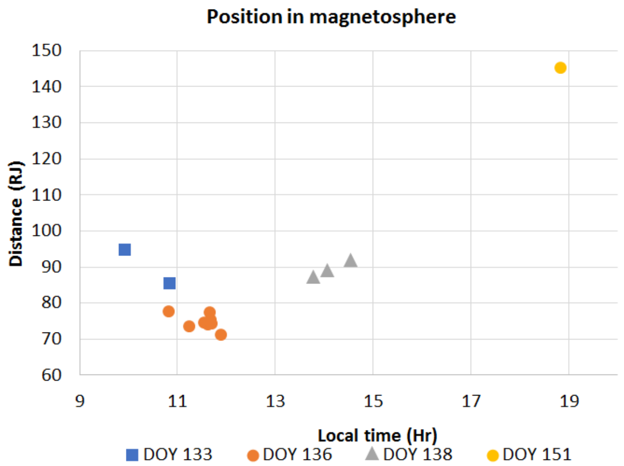


Figure 1.1 (left) shows the bright spot's latitudes and longitudes according to System III from each day of year. In addition, the position in magnetosphere and its local time were plotted as shown in the right figure.

Furthermore, we plotted stimulated solar wind dynamic pressure at Jupiter versus time using data from MsWim. The graph shown in Figure 1.2 is for the interval between May 11, 2007 and June 12, 2007. We found that there are some increasing of dynamic pressure both earlier and later than the time that we found bright spots. This corresponds to Clarke et al. (2009) who suggested that the arrival times of solar wind propagated to Jupiter of MsWim model had some uncertainty. Nevertheless, by further investigation, we found bright spot occurred at the time of no significant solar wind dynamic pressure. This phenomenon could be related to other dynamics. In addition, more events of bright emission spots should be investigated

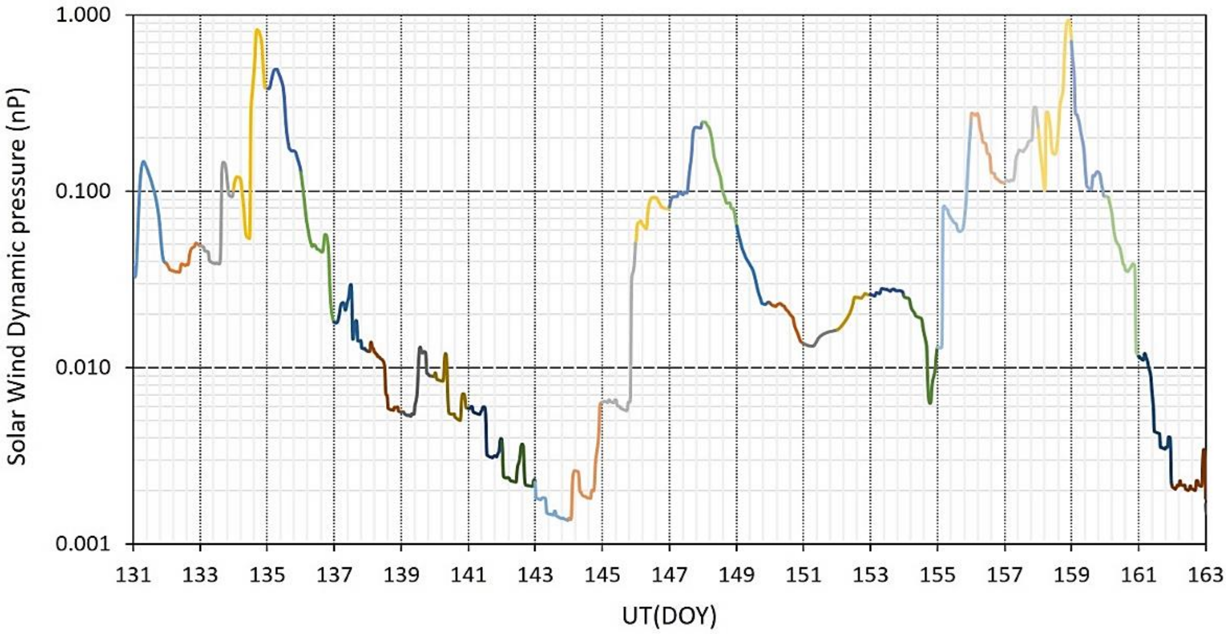


Figure 1.2 A plot of stimulated solar wind dynamic pressure propagation to Jupiter from May 11, 2007 to June 12, 2007. Data was obtained from MsWim model. Each color represents consecutive days in observation.

In discussion for bright spots evolution, figure 1.3. shows example of bright spots' evolution a on DOY 133. The emissions are found to start from unclear shape and large area (i), then develop to a spot form ((ii) and (iii)) with increasing in brightness, follows by the dropping in brightness ((iv) and (v)) and finally disappear.

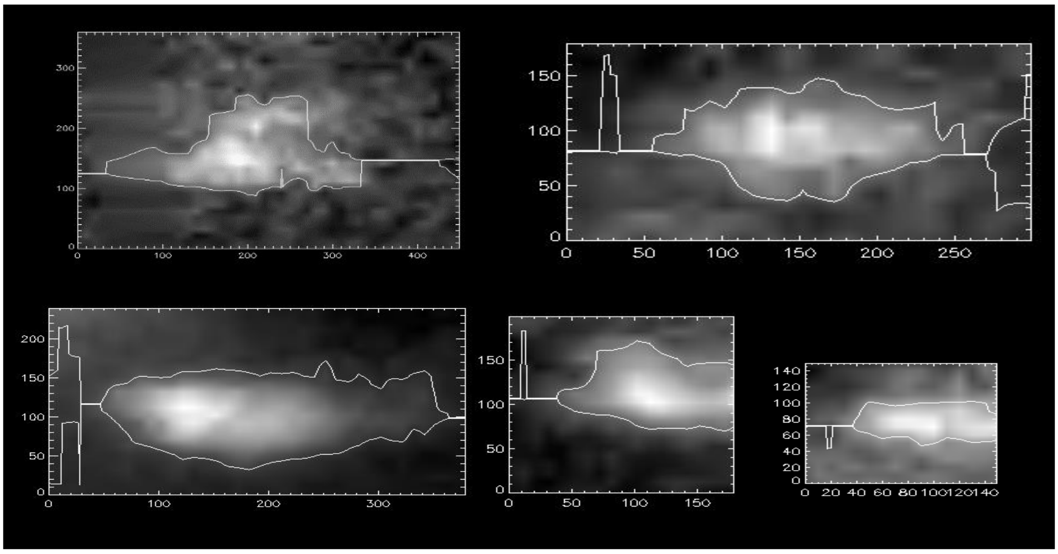


Figure 1.3 A bright spots' evolution on DOY 133

The positions of auroral particles' origins causing the bright spots, based on magnetic field mapping, in magnetosphere for these images are found to be at distances beyond dayside magnetopause. The changing of other properties, which are location, brightness, and approximately sizes are summarized and shown in table 1.2. The total brightness based on elliptical fit are found to be order of 10^4 kR and brighten up to ~10^5 kR for bright spot a or label (iii) in the table. The horizontal and vertical distance along Jupiter's surface based on elliptical fit appear to vary in order of thousands kilometers.

Table 1.2 Bright spot's location, brightness, and approximately size. The expected origin of auroral particles causing the bright spot in magnetosphere is identified based on magnetic field

Bright spot evolution	UT (DOY)	CMLS (deg)	Latitude (deg)	Longitude (deg)	Brightness (10^4 kR)	Size	
						Horizontal(km)	Vertical(km)
(i)	133.705	150.64	63.72±1.12	174.37±1.46	2.14±0.36	4426.80±272.09	4374.02±268.84
(ii)	133.706	162.05	63.51±0.72	174.73±1.01	1.13±0.20	3048.56±195.15	2637.40±168.83
(iii)	133.708	163.46	63.13±0.85	175.01±1.77	11.05±1.41	5324.80±200.50	2977.92±112.13
(iv)	133.710	164.87	62.23±0.62	174.76±0.96	2.14±0.48	2973.04±240.90	1963.62±159.11
(v)	133.711	166.28	62.56±0.34	175.79±0.76	0.50±0.12	2314.43±272.45	1139.352±134.12

This work was presented in an international conference:

Haewsantati. K., S. Wannawichian, J. T. Clarke, J. D. Nichols, Auroral bright spot in Jupiter's active region in corresponding to solar wind dynamic, Journal of Physics: Conference Series, 901(1), 012013, 2017

Consequently, after the discussion with experts in the field, the analyzed data should include the recent observations of Hubble Space Telescope, until 2017. Data reduction and analysis of the new format, time-tag data, are needed to be proceeded. In term of solar wind propagation model, we have discussed with Dr. Chihiro Tao, from National Astronomical Observatory of Japan - NAOJ (Tao, 2019 private communication), who will provide us a more detail simulated solar wind data, exactly corresponding to our data.

We have a plan to expand the data base to cover nearly two decades. The results are expected to be presented in TRF-OHEC Annual Congress 2020 (นักวิจัยรุ่นใหม่พบเมธีวิจัยอาวุโส สกว พ.ศ. 2563).

2. Angular Extension of Io Magnetic Footprint in Corresponding to Io’s Longitudinal Variation

Corresponding to difference between plasma corotating velocity and satellite’s orbital velocity, the electrodynamic interaction between Jupiter’s magnetospheric plasma and Io’s atmospheric particles takes place in the vicinity of Io. The interaction causes Alfvènic disturbance and results in picked up charge particles along the magnetic field line from interaction region toward Jupiter Ionosphere [Kivelson et al., 2004]. Precipitating electrons cause the auroral emission at the foot of magnetic flux tube, as Satellite’s magnetic footprint. Io’s magnetic footprint is the most prominent emission.

With the conservation of magnetic flux, the size of interaction region at Io, 1.5 Io radii, should be corresponding to the emission size of ~100 km. In this study FUV images of Jupiter’s auroral region, which were taken in 2007 by Advanced Camera for Surveys (ACS) instrument on Hubble Space Telescope (HST), were used to analyze the variation of Io’s magnetic footprint emission (Wannawichian et al., 2019), as shown in Figure 2.1.

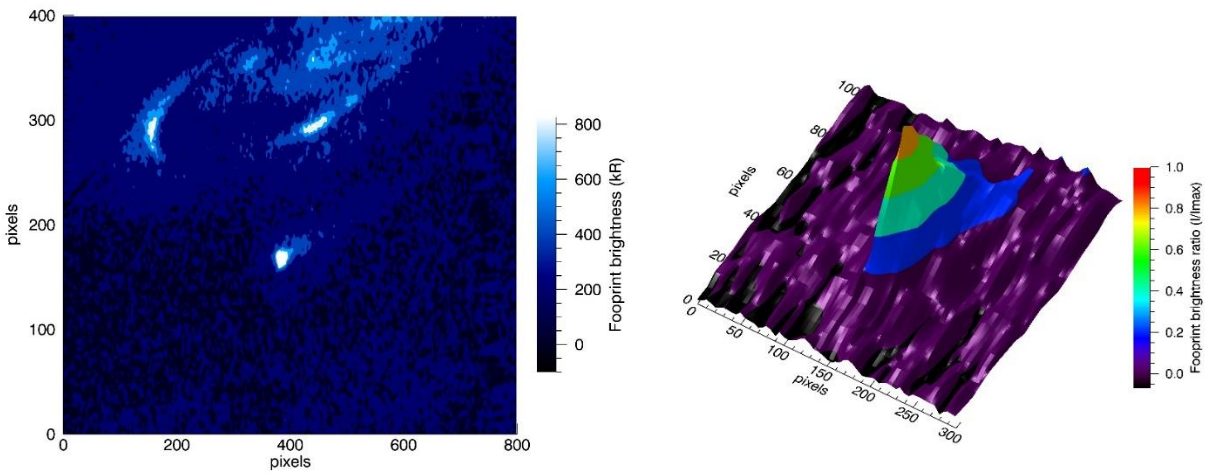


Figure 2.1 Along with the peak emission of Io’s magnetic footprint (left image taken on March 2, 2007), angular extension of the footprint was analyzed as equivalent scale to the full width at half maximum (FWHM) of the emission.

For the analysis of Io’s angular size, the mapping on Jupiter surface includes following calculation. Where $\boldsymbol{r} = \sqrt{\boldsymbol{x}^2 + \boldsymbol{y}^2}$, ellpsoid equation for coordinate is

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1.$$

In case of Jupiter, we can write

$$\frac{x^2}{a^2} + \frac{y^2}{a^2} + \frac{z^2}{c^2} = 1$$

Where $\boldsymbol{a} = \mathbf{71,492\ km}$ and $\boldsymbol{c} = \mathbf{66,854\ km}$. Above equation can be written as

$$r^2 = \frac{a^2c^2}{c^2\sin\phi^2 + a^2\cos\phi^2}$$

Where $\boldsymbol{\theta}$ is longitude and $\boldsymbol{\phi}$ is co-latitude. From angular extension $\boldsymbol{\alpha}$, physical extension is $\boldsymbol{\alpha \cdot r\sin\phi}$ km.

Angular extensions of the Io magnetic footprint from several observations by the Hubble Space Telescope during 1997-2007 (we decided to use larger data base than originally plan for statistical efficiency) show a temporal variation as a function of observing time. From the results below, 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° 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 below. The variation of angular size appears to be under the influence of Io's system III longitude, as shown in figure 2.2 and 2.3.

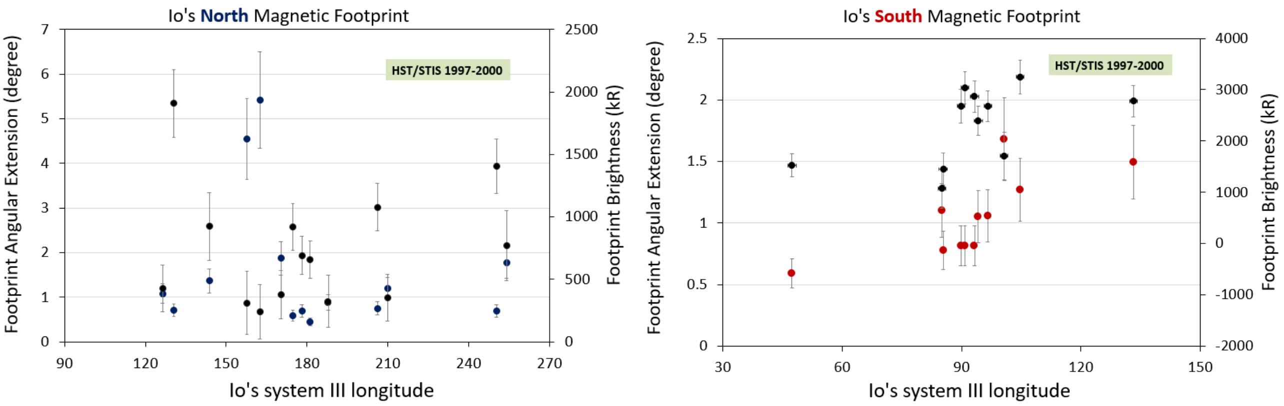


Figure 2.2 The angular sizes of Io's magnetic footprint (blue dots for northern footprints, red dots for southern footprints) from several observations by HST during 1997-2000 campaign, are compared with the magnetic footprint brightness (black dots). The unit of brightness is in kilorayleighs (1 kR = 10^9 photon cm^{-2}s^{-1} into 4π steradians).

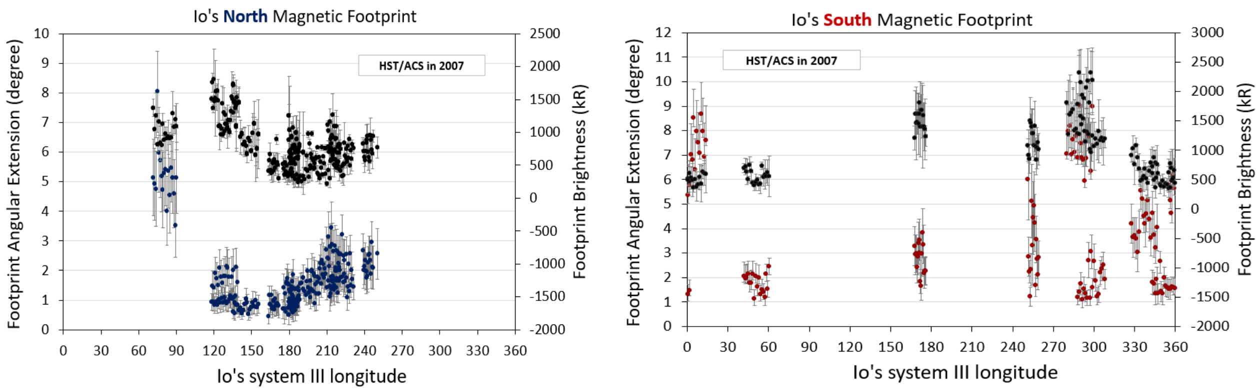


Figure 2.3 The angular sizes of Io's magnetic footprint (blue dots for northern footprints, red dots for southern footprints) from several observations by HST during the 2007 campaign, are compared with the magnetic footprint brightness (black dots). The unit of brightness is in kilorayleighs (1 kR = 10^9 photon $cm^{-2}s^{-1}$ into 4π steradians).

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 [Spencer et al., 2007]. 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). 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 [Wannawichian et al., 2010], as shown in Figure 2.4.

During several HST observations in 2007, 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 above. As shown in Table 2.1, 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. This result implies some connection with the volcanic eruptions on Io, which were reported to be strong during February and May 2007 [Spencer et al., 2007]. It has been suggested that a strong mass loading from Io's volcanoes can weaken the field aligned-current, which is connected to the auroral emission in Jupiter's ionosphere [Clarke et al., 2002]. 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.

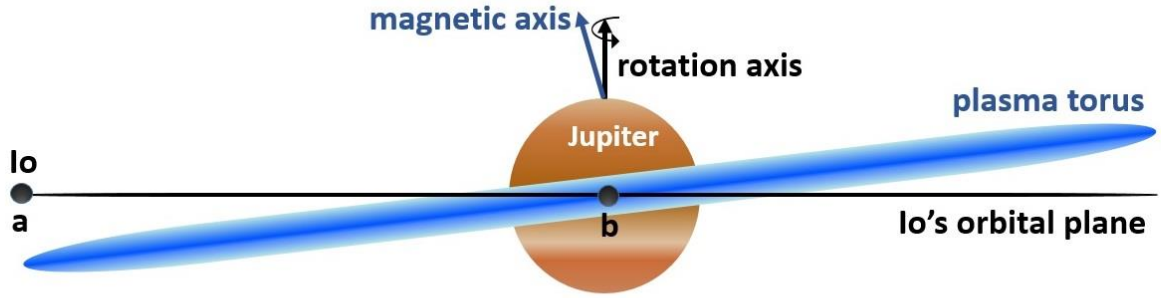


Figure 2.4 Under the influence of the tilted magnetic axis at approximately 10° from the rotation axis [Wannawichian et al., 2016], Io experiences a dramatic change of plasma density in the vicinity of the satellite. During the course of orbiting Jupiter, Io is periodically located far from the center 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 [Wannawichian et al., 2010]. The above sketch is not to actual scale [Wannawichian et al, 2019].

Table 2.1 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 (degree)	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

Taking into account the complex configuration of Jupiter's magnetic field, Io's northern and southern magnetic footprints were found to vary differently [Bonfond et al., 2009, 2010]. As shown in Figure 2.5, 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.

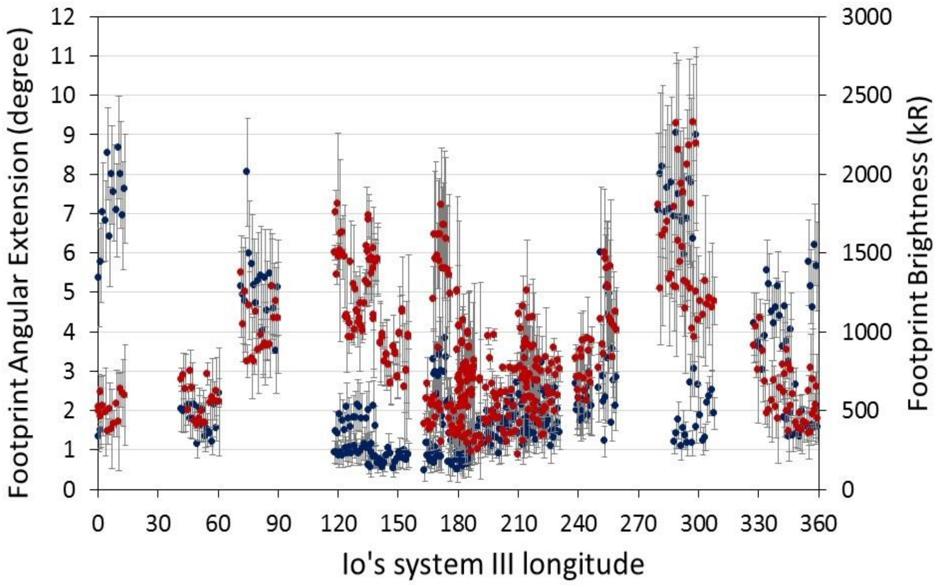


Figure 2.5 The angular sizes of Io's magnetic footprint (blue dots) from several observations by HST during the 2007 campaign, as shown in Figure 3, are compared with the magnetic footprint brightness (red dots). The unit of brightness is in kilorayleighs.

Previous numerical studies, using magnetohydrodynamics (MHD) model proposed that the Alfvén wave and corotational lag relate to conditions in Io's plasma wake [Bonfond et al., 2013]. 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 the Main Alfvèn Wing spot (MAW) and the Trans-hemispheric Electron Beam spot (TEB) 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.

Output: ***Wannawichian, S., A. Laphirattanakul, Influence of plasma in the vicinity of Io on Brightness and Angular Extension of Io's Magnetic Footprint, Chiang Mai J. Sci., 2019, 46(2), 408-416***

This study was recently presented in an international conference:

Wannawichian S., J. T. Clarke, J. D. Nichols, Brightening Behavior of Io's Magnetic Footprint, Presentation at The Conference on Magnetospheres of the Outer Planets 2019, June 3 – 7, 2019, Tohoku University, Sendai, Japan

According to suggestions from experts in the field, the data base should cover two decades of Hubble Space Telescope observations. Data reduction and analysis of the new format, time-tag data, are needed to be proceeded. Moreover, the improvement of analytical criteria of the footprint's structure and position was recommended by our research collaborators. Therefore, the additional procedure is required in order to conclude our analysis. The results are expected to be presented in TRF-OHEC Annual Congress 2020 (นักวิจัยรุ่นใหม่พบเมธีวิจัยอาวุโส สกว พ.ศ. 2563).

3. Analysis of Io's magnetic footprint features using VIPAL magnetic field model

Currents from the interaction between plasma and satellites follow the magnetic field lines and fall into the Jovian ionosphere. These currents collide with Jupiter atmospheric particles, which emit auroral emission. One of the most intense aurora emission comes from the interaction between Io, one of Galilean satellite, and magnetosphere. In order to predict Io footprint positions in both north and south hemispheres, we traced along the magnetic field lines beginning from Io orbital position to the footprint locations in ionosphere via Jovian magnetic field model. Model of magnetosphere is used to determine magnetic field strength and the direction of magnetic field lines around magnetized object. There are many models of Jupiter's magnetosphere. Each model varies depending on the method and constraints used to construct.

VIPAL magnetic field model is chosen to simulate Jupiter's magnetic field model (Hess et al., 2011). VIPAL was constructed based on observations by Pioneer and Voyager spacecrafts. This model appears to have a lot of benefits. For example, it can be used to analyze auroral emission in Jupiter's ionosphere. This model also has the best prediction of contact positions between ionosphere and magnetic field lines that cross Io, called Io's footprint. VIPAL also gives better magnetic field strength prediction than previous models. In order to predict footprint positions in both north and south hemispheres, we traced along the magnetic field lines beginning from Io orbital position to the footprint locations in ionosphere, as shown by figure 3.1.

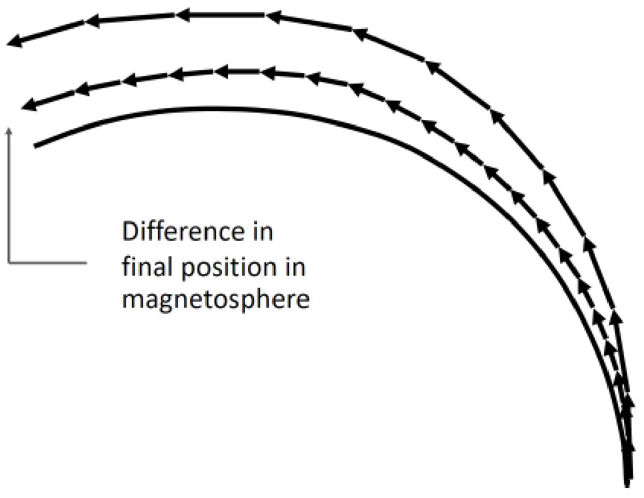


Figure 3.1 Diagram of Magnetic field tracing technique

There are many factors to be considered, for example, the shape of Jupiter, Io's orbit inclination and eccentricity, to get the best prediction of footprint position as possible. These positions are expected to have the emission of auroral features. One of the most important of this features are their brightness. Previous studies found that this brightness has a strong relation with Io longitude and relates to the latitude of Io in the torus. Therefore, in order to make better physical interpretation, the relation between Io footprint brightness and magnetic field strength is presented in Table 3.1.

Table 3.1 Comparison between magnetic field strength and footprint brightness of six footprints in north and south hemispheres (Sukollapun and Wannawichian, 2016).

North			**South**		
Io Longitude (degree)	Magnetic Field Strength (gauss)	Brightness (kR)*	Io Longitude (degree)	Magnetic field strength (gauss)	Brightness (kR)*
89.12	13.77	376.96	89.11	6.38	547.27
118.31	16.116	359.96	115.65	7.41	1162.37
133.16	16.65	343.88	133.19	8.10	902.62

*1 kR = 10^9 photon cm^{-2}s^{-1} into 4π steradians

At the same Io longitude, magnetic field strength is different in both north and south hemispheres. In addition, their trend does not correlate with each other across 360° Io's longitude. While, the observed magnetic footprint brightness has two peak brightness around 110° and 270°, however, there is discontinuity around 110°. The relation between magnetic field strength and footprint brightness should be further investigated, while other factors are well controlled.

The effect from Io torus can be defined as equatorial lead angle as shown in Figure 3.2. Equatorial lead angle in this research is the different of two Io longitudes, both correspond to the exact same footprint but with and without Io torus. Because Io position is inconsistent along the torus, the lead angle for each Io's longitude will also be varied according to the changing in magnetic field bending in the torus. The lead angle in VIPAL magnetic field model is described as $\boldsymbol{\alpha_{\mathrm{mod}} = \lambda_{Io} - \lambda_{mfl}}$, where $\boldsymbol{\alpha_{\mathrm{mod}}}$ is the lead angle of modeled footprint location. $\boldsymbol{\lambda_{Io}}$ is longitude of actual Io and $\boldsymbol{\lambda_{mfl}}$ is the longitude of Io corresponding to the mapping magnetic field line (Hess et al., 2011). Equatorial lead angle should behave like sinusoidal function to Io longitude, because the torus is inclined by 7 degrees to the Io's orbital plane.

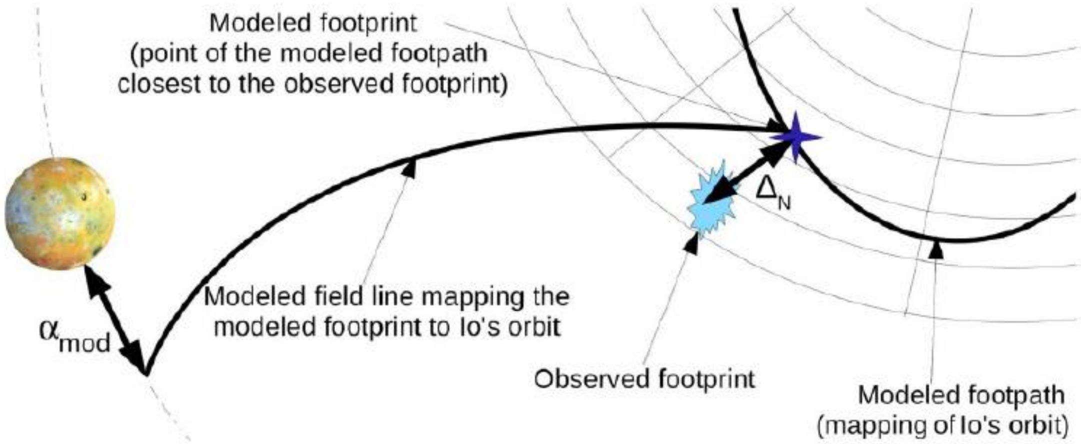


Figure 3.2 Illustration of model Io footpath and observed footprint. Δ_N is angular distance and α_{mod} is lead angle (Hess et al., 2011).

The relation between Io's footprint brightness in kilorayleighs and Io's lead angles from both hemispheres, based on the observed data and tracing model, are shown in figure 3.3 and 3.4. The error of lead angle is 0.1 degree based on the iteration level from tracing method.

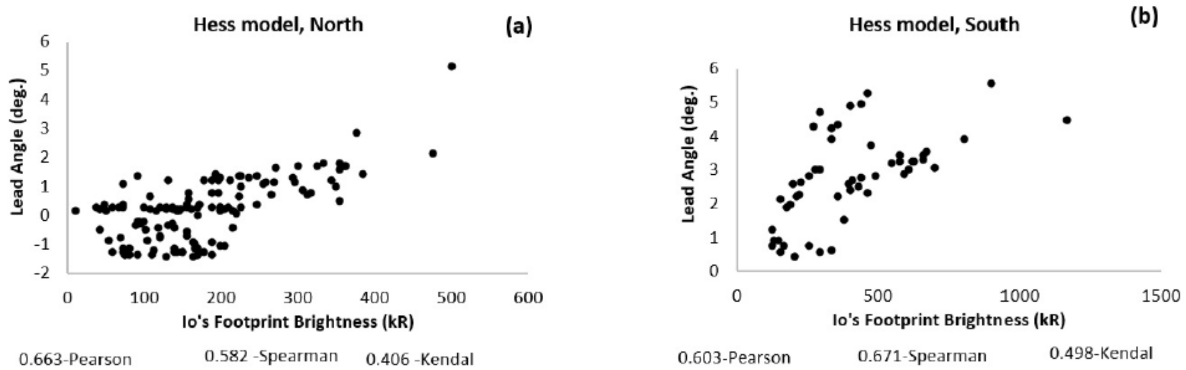


Figure 3.3 The relation between lead angle and Io's footprint brightness based on model by Hess et al. (2011) for footprints in (a) North pole and (b) South pole.

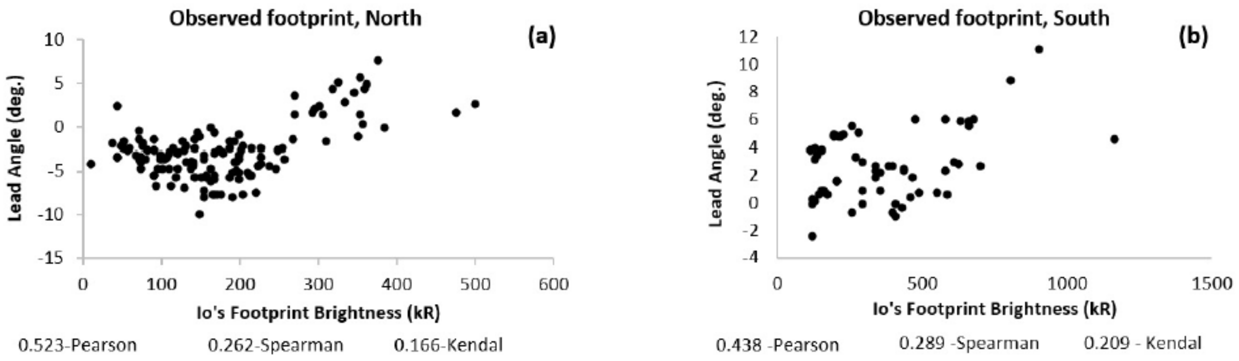


Figure 3.4 The relation between lead angle and observed Io's footprint brightness for footprints in (a) North pole and (b) South pole.

Results in these figures are constrained by the same observed Io's longitudes. Therefore the data may not span over all 360 degrees due to the limited number of observations. We have 2 sets of lead angle data, one from the observed data and one from Hess et al. (2011). Both calculations refer to the same observed brightness and Io's longitudes.

We obtained the correlation coefficients between lead angle and footprint brightness in each hemisphere from 3 different correlation formulas. All three correlations are Pearson, Spearman and Kendall, as shown above. For observation data in both hemispheres, all three correlation coefficients suggest that Io's footprint brightness and lead angles have positive relation between each other, although, the correlation coefficients are very low. From lead angle data according to Hess et al. (2011), all three correlation coefficients suggest the same positive relation as our observed lead angle data, but with higher correlation coefficients in all three types and in both hemispheres. We can conclude from the correlation coefficients between lead angle and footprint brightness that they have slight positive relation to each other. These correlation coefficients support our hypothesis that the more lead angle means the further distance of bending magnetic field line along the Io torus. Hence more of picked-up auroral particles could be the reason for brighter auroral emission.

Output: ***Chaiyaporn S., S. Wannawichian, Correlation between Io's lead angle and the satellite's magnetic footprint, Journal of Physics: Conference Series, 901(1),012012, 2017***

Conclusion and Discussion

1. The study of Jupiter's aurora: bright spot variation in active region

The bright spots seem to have unstable behavior. In contrast it seems to have clear evolution. The bright spots tend to fixed at the same position in System III longitude. The latitudes and longitudes are found to slightly varied within 3 degrees for each DOY. There are reappearances of bright spots during the same day suggesting to the occurrence in phase. The origins in magnetosphere were determined to be at radial distances more than 70 RJ, while the local times were mostly considered to be daytime, especially near noon. The origins possibly locate in region beyond dayside magnetopause, which can be related to Jovian polar cusp process as previous study suggested before (i.e. Pallier and Prange, 2001; Bunce et al., 2004). It should be noted that this dataset has long exposure time that some information might not include to this discussion. Later observation and more data analysis of better resolution images will provide more understanding on its evolution, size, shape, including the responsible process in deep details.

The time variation of brightness and size are plotted to explore its relation. The brightness variation shows that time scale for the minimum and maximum brightness is ~150s, which might be one of the pulsating cycle of quasiperiodic flares as presented by Bonfond et al. (2016). This sudden change could be caused by some dynamics between Jupiter's magnetosphere or external process, for example the reconnection with solar wind.

2. Angular Extension of Io Magnetic Footprint in Corresponding to Io’s Longitudinal Variation

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 2.4. 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 [Bonfond et al., 2019; 2010; Clarke et al., 2002; Yoneda et al., 2013] 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.

3. Analysis of Io's magnetic footprint features using VIPAL magnetic field model

From different correlation coefficients in four data sets, we conclude that lead angle and Io's footprint brightness has a positive relation to each other. On the other hand, correlation coefficients between footprint brightness and magnetic field strength show disagreement of correlation coefficient between both hemispheres. One explanation could be the negative relationship between magnetic field strength and the number of precipitating auroral particles. It is clear that, while magnetic field strength and magnetic field configuration can play a controlling role in the footprint brightness, other influences should be taken into consideration for detail analysis.

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APPENDIX

Output
Presentation in International Conference

1. ***Haewsantati. K., S. Wannawichian, J. T. Clarke, J. D. Nichols, Auroral bright spot in Jupiter's active region in corresponding to solar wind dynamic, Journal of Physics: Conference Series, 901(1), 012013, 2017***

Bright Spot morphology in Jupiter's Polar Aurora

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Abstract

The bright spot is a feature of aurora emission which is usually found in the polar region of Jupiter's aurora. The auroras in the polar region have unstable behaviors. Accordingly, unclear developments are typically found for these emissions. Therefore, the bright spot is chosen to study for more understanding about this region. Images of Jupiter's aurora were observed by the Advanced Camera for Surveys (ACS) on board the Hubble Space Telescope (HST). Specifically on Jupiter's auroras in the northern hemisphere, eight bright spots were clearly found in Jupiter's aurora images taken during May-June 2007. There were two bright spots appearing on the same day. The variation of locations and the approximated sizes of the bright spots were analyzed to study its evolution. The ionosphere's location of eight spots was found to vary within 10 degrees. There was noticeable that bright spots have certain formation development, starting from an unclear shape, taking the form of a spot and then dropping in brightness until reaching totally disappear. The spots' mapped locations in magnetosphere were usually found at distances more than 70 Jovian radii at the local time near noon. These results suggested that the bright spots were related to polar cusp process.

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INVITATION LETTER

Ms. Kamolporn Haewsantati
Astronomical Laboratory
Department of Physics and Materials Science
Chiang Mai University, Thailand

March 6, 2019

On behalf of the Local Organizing Committee, we cordially invite you to
the Conference on Magnetospheres of the Outer Planets 2019 (MOP 2019)
held on 3-7 June 2019
at Tohoku University, Sendai, Japan.

From 1974, this meeting has enhanced our understandings for the magnetospheres of outer planets, by world-wide exchanges of recent studies, discussions, and collaborative researches.
Meeting information is summarized in the following websites.
http://pparc.tohoku.ac.jp/sympo/mop/
http://lasp.colorado.edu/home/mop/resources/mop-conference/

Ms. Kamolporn Haewsantati will give a poster presentation with a title of
Bright Spot morphology in Jupiter's Polar Aurora.
We are looking forward to seeing the interesting presentation which can stimulate our research fields.

Sincerely yours,

Yasumasa Kasaba

Yasumasa Kasaba (Chair of the 'MOP 2019' Local Organizing Committee)
Professor and Director
Planetary Plasma and Atmospheric Research Center
Graduate School of Science
Tohoku University

2. ***Wannawichian S., J. T. Clarke, J. D. Nichols, Brightening Behavior of Io's Magnetic Footprint, Presentation at The Conference on Magnetospheres of the Outer Planets 2019, June 3 – 7, 2019, Tohoku University, Sendai, Japan***

Brightening Behavior of Io's Magnetic Footprint

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Abstract

The interaction between Io's extended atomosphere and Jupiter's fast rotating magnespheric plasma causes picked up currents to travel along the magnetic field lines from interaction region toward the planet's ionosphere. The precipitating particles accordingly result the emission, in auroral region, which is called Io's magnetic footprint. With the 9.4 degrees tilt angle between magnetic axis and rotation axis, Io experiences different plasma environment, in the plasma torus, throughout its orbital path. At system III longitudes near 110 degrees and 290 degrees, Io is expected to feels very dense surrounding plasma, since it should be near the center of plasma torus. Previous studies of Io's auroral magnetic footprint's brightness showed there is general brightness variation trend suggesting strong interaction in those longitudes. However the picked up currents travel along the magnetic flux as a form of Alfvèn waves, which perform wave's properties, e.g., refraction and reflection. As a result, there were clear observations of mulitplicity and swirling patterns of Io's auroral magnetic footprint. In this work, the size and the brightness of Io's Main Alfvèn wing spot (MAW), will be analyzed based on FUV imaging by STIS (Space Telescope Imaging Spectrograph) and Advanced Camera for Surveys (ACS) instrument on Hubble Space Telescope (HST). The analysis will focus on images of Jupiter's auroral regions, which were taken in 1998, 2000, 2001, and 2007 during HST's campaigns. The short-time variations of Io's magnetic footprint, when Io was near 110 degrees and 270 degrees will be investigated in detail. The result would show the development of Io's footprint emission, in size and brightness, when strong interactions at the satellite was expected.

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INVITATION LETTER

Dr. Suwicha Wannawichian
Astronomical Laboratory
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Chiang Mai University, Thailand

March 6, 2019

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Dr. Suwicha Wannawichian will give a poster presentation with a title of
Brightening Behavior of Io's Magnetic Footprint.
We are looking forward to seeing the interesting presentation which can stimulate our research fields.

Sincerely yours,

Yasumasa Kasaba

Yasumasa Kasaba (Chair of the 'MOP 2019' Local Organizing Committee)
Professor and Director
Planetary Plasma and Atmospheric Research Center
Graduate School of Science
Tohoku University

Output (Acknowledge the Thailand Research Fund)
International Journal Publication

1. Wannawichian, S., A. Laphirattanakul, Influence of plasma in the vicinity of Io on Brightness and Angular Extension of Io's Magnetic Footprint, Chiang Mai J. Sci., 2019, 46(2), 408-416

Chiang Mai J. Sci. 2019; 46(2) : 408-416
http://epg.science.cmu.ac.th/ejournal/
Contributed Paper

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

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2. Chaiyaporn S., S. Wannawichian, Correlation between Io's lead angle and the satellite's magnetic footprint, Journal of Physics: Conference Series, 901(1), 012012, 2017

Siam Physics Congress 2017 (SPC2017) IOP Publishing
IOP Conf. Series: Journal of Physics: Conf. Series **901** (2017) 012012 doi:10.1088/1742-6596/901/1/012012

Correlation between Io's lead angle and the satellite's magnetic footprint

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Chiang Mai J. Sci. 2019; 46(2) : 408-416
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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].

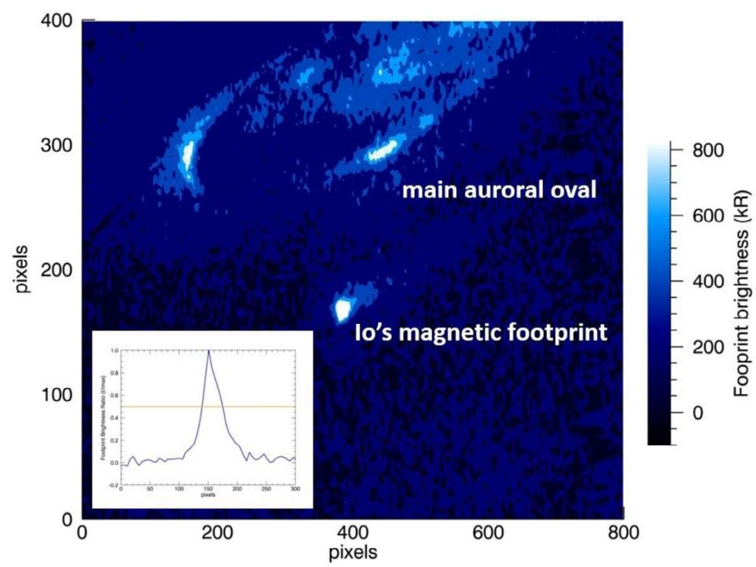

Figure 1. This FUV image of Jupiter's northern auroral region was taken in March 2, 2007 at universal time 07:12:29 by an ACS instrument onboard the HST. Io's magnetic footprint is clearly seen at a lower latitude from the main oval emission. The image was taken when Io was located at a system III longitude 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].

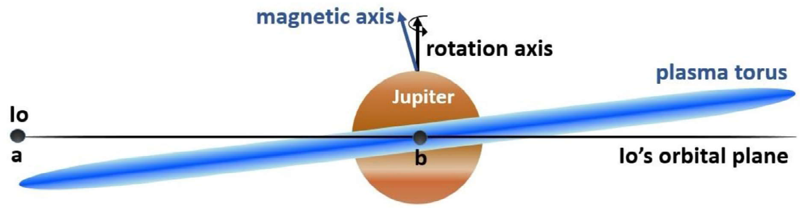

Figure 2. Under the influence of the tilted magnetic axis at approximately 10° from the rotation axis [13], Io experiences a dramatic change of plasma density in the vicinity of the satellite. During the course of orbiting Jupiter, Io is periodically located far from the center of the plasma torus (a), 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.

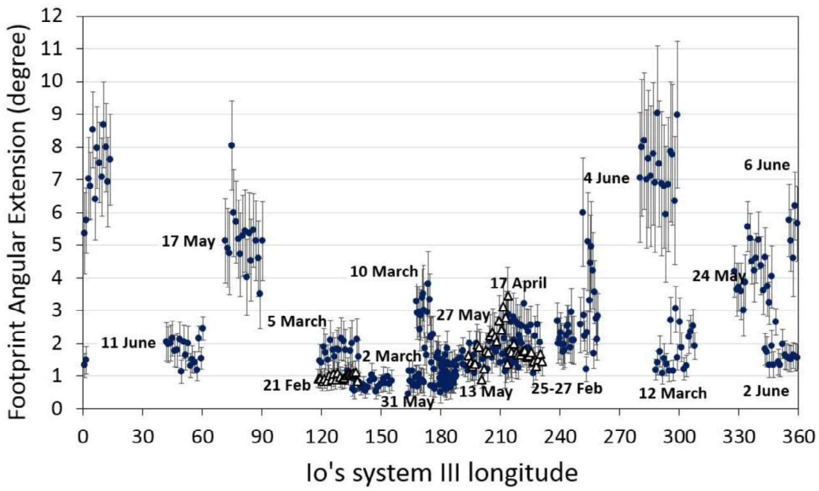

Figure 3. The angular sizes of Io's magnetic footprint from several observations by HST during 2007 campaign. The angular size was obtained by an analysis of Full Width at Half Maximum (FWHM) of each MAW spot, as seen in Figure 1. For clarification, the data on February 21, 23, and 26 were plotted with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

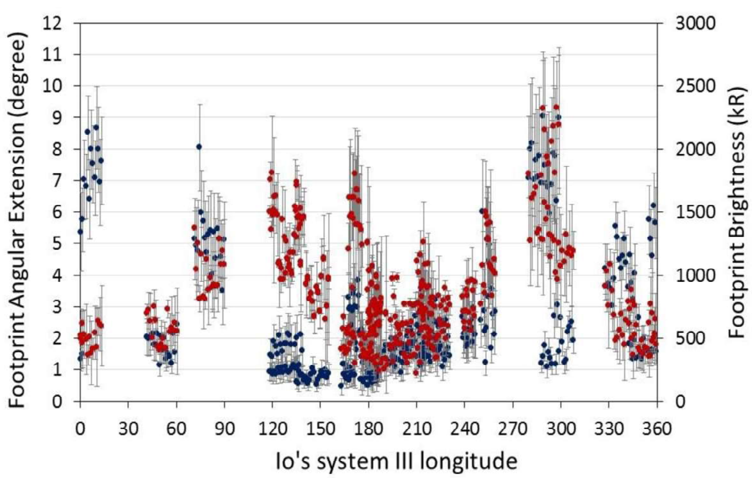

Figure 4. The angular sizes of Io's magnetic footprint (blue dots) from several observations by HST during the 2007 campaign, as shown in Figure 3, are compared with the magnetic footprint brightness (red dots). The unit of brightness is in kilorayleighs (1 kR = 10^9 photon $cm^{-2}s^{-1}$ into 4π steradians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

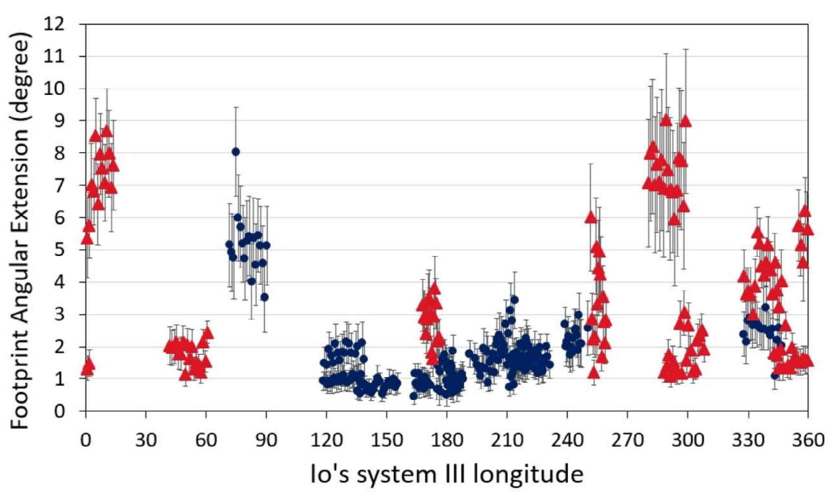

Figure 5. The angular sizes of Io's northern magnetic footprint (blue dots) from several observations by HST during the 2007 campaign, as shown in Figure 4, are compared with the angular size of southern magnetic footprint (triangular symbols).

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.

Acknowledgements

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Correlation between Io's lead angle and the satellite's magnetic footprint

Correlation between Io's lead angle and the satellite's magnetic footprint

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Abstract. This research studies the nature of auroral feature on Jupiter, especially which connects to one of its satellite, Io. Jupiter has a large magnetosphere, as a result of strong magnetic field strength. This magnetosphere corotates with Jupiter and extends over all of Galilean satellites. The interaction between Jupiter's rotating magnetic field and Io causes plasma particles to flow along the magnetic field lines in directions toward both north and south hemispheres. Some particles will penetrate into Jupiter's ionosphere and collide with atmosphere particles, leading to aurora emission, at the position of Io's auroral footprint. Io is surrounded along its path, by a cloud of plasma particles with high density, which is called Io torus. This torus enhances the effect of bending magnetic field lines when they pass Io and result in inaccuracy of the prediction of longitudinal position of Io footprint. This shift of longitudinal prediction can be mapped to the shifted position of Io, which is called lead angle. Our objective is finding the relation between all three parameters, which are magnetic field strength, Io's footprint brightness and lead angle at the same footprint position or the same Io's longitude. We use VIPAL magnetic field model to trace along the magnetic field line and to find magnetic field strength at any given position. This tool is vital for determination of the relation between magnetic field strength, Io footprint brightness and lead angle.

1. Introduction

Jupiter is the biggest planet in our solar system both in mass and volume, 1,898 $\times 10^{24}$ kg and 1.431 $\times 10^{15}$ km^3 respectively [1]. It is beneficial to study the consequences from Jupiter's massive mass and size, which is much bigger than other planets.

Aurora is the phenomenon that occur in the planet that has sufficient atmosphere and strong internal magnetic field. It is electromagnetic wave emission from collision of high-energy charged particles with planet's atmospheric particles [2]. In this research, we focus on Io's auroral emission, which is caused by auroral particles that are originated from the vicinity of Io.

In Jupiter magnetosphere, magnetic field lines form as an enormous sphere that corotates with Jupiter. In order to determine the magnetosphere's structure, magnetic field models are created to simulate Jupiter's magnetic field. We use VIPAL magnetic field model [3] as our tool in this project. The name, VIPAL, refers to Voyager, Io footprint, Pioneer observations and modelling of the lowest orders of the magnetic anomaly and corrects for the longitudinal position of the magnetic field line mapping to Io's orbit.

The magnetic field strength varies between the magnetic field lines of Jupiter. Magnetic field is strong at the poles and weak around equator plane. Particles move from the equator which has the weakest magnetic field strength to the polar region, which has the strongest magnetic field strength. Experiencing stronger magnetic field strength along the path, some particles do not have enough parallel velocity to penetrate into ionosphere. Therefore they are reflected at the mirror point. This effect is called magnetic mirror. The magnetic field strength at Io's footprint position should cause lower footprint brightness due to this effect.

Due to high volcanic activity on Io, the plasma torus is formed around Io's orbit. The effect from Io torus can be defined as equatorial lead angle. Equatorial lead angle is the different of two Io longitudes, both corresponding to the same footprint but with and without Io torus. Because Io position in plasma sheet is inconsistent along the torus, the lead angle in each longitude will also be varied according to the changing of magnetic field bending in the torus. The lead angle therefore should have positive relation with footprint brightness due to the longer travel time in torus.

2. Methods

2.1. Tracing along the magnetic field line

Initially, the position of Io was put into VIPAL model. Next the model will give the magnetic field strength in three spherical coordinates, under assumption of static process. Because charge particles flow in the magnetic field direction, therefore from the magnetic field strength in each coordinate can be used to calculate the magnetic field direction at Io position. Accordingly, the magnetic field vector was altered to move a little to a new position. At new position, the new magnetic field direction was calculated and moved to the next position by a constant distance. Iterating this process, we continuously trace along the magnetic field line until we reach the end point in Jupiter's ionosphere, which is the position of Io footprint. Furthermore, we completed the footpath by repeating the process with various positions of Io. The magnetic field direction of Jupiter can be traced from Io to either north or south poles. Therefore, if we trace one magnetic field direction, and reach south hemisphere footprint, tracing opposite direction would reach the north hemisphere footprint.

2.2. Finding Equatorial Lead Angle

First we acquire footprint positions from tracing model, in this research we calculated 3600 points in 360 degrees. Therefore we have 0.1 degree precision in our calculation. To find the lead angle at specific Io position, first we located the modeled footprint which has the closest distance to the observed footprint corresponding to given Io position. From given Io's footprint, we acquire the associated modeled longitude of Io. The modeled longitude was subtracted by actual longitude of Io to obtain the lead angle. Finally the process was iterated to find the lead angles from other longitudes of Io.

3. Results and Discussion

3.1. Correlation between lead angle and footprint brightness

The relation between Io's footprint brightness in kilorayleighs (1 kR = 10^9 photon $cm^{-2}s^{-1}$ into 4π steradians [2]) according to previous work [4] and Io's lead angles from both hemispheres, based on the observed data and tracing model, are shown in figure 1 and 2.

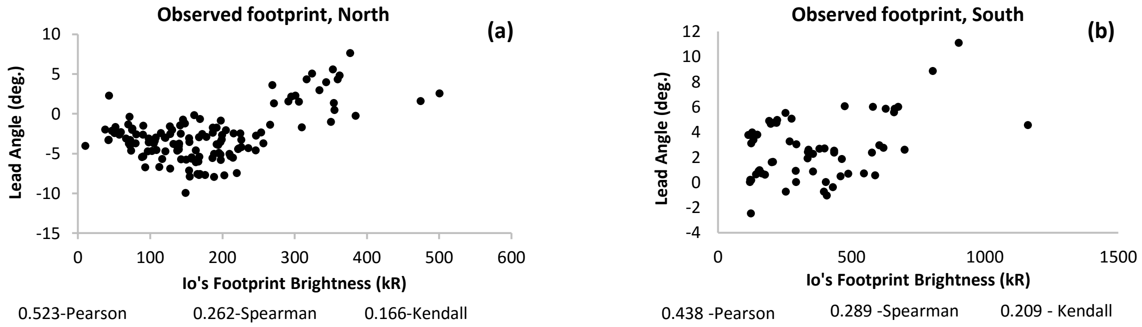

Figure 1 shows the relation and correlation coefficients between lead angle and observed Io's footprint brightness in (a) North pole and (b) South pole.

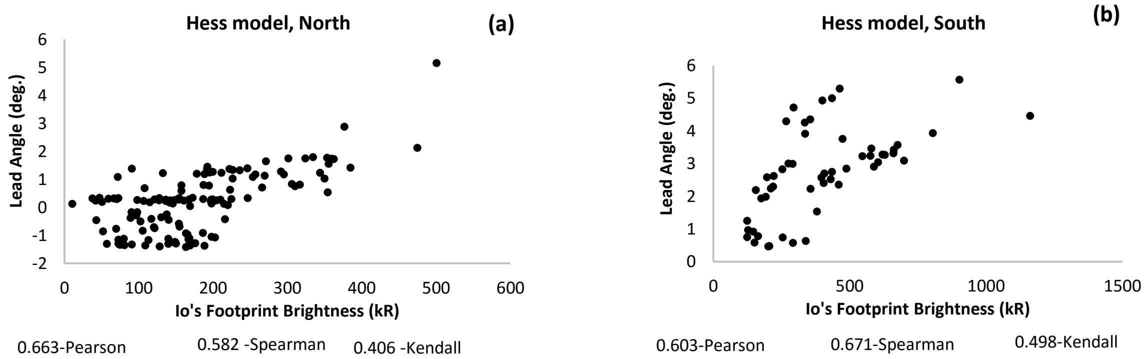

Figure 2 shows relation and correlations coefficients between lead angle and Io's footprint brightness based on VIPAL magnetic field model for footprint in (a) North pole and (b) South pole.

Based on Hubble space telescope's observations of Jupiter auroral region in 2007, Io's footprint brightness variation [4] was detected. Accordingly, results in Figure 1 and Figure 2 are constrained by the same observed Io's longitudes. Therefore the data may not span over all 360 degrees due to the limited number of observations. We have 2 sets of lead angle data, one from the observed data and one from VIPAL magnetic field model [3]. Both calculations refer to the same observed brightness and Io's longitudes. We obtained the correlation coefficients between lead angle and footprint brightness in each hemisphere from 3 different correlation formulas. All three correlations are Pearson product moment, Spearman's rank-order and Kendall's Tau [5], as shown in figure 1 and Figure 2. For observation data in both hemispheres, all three correlation coefficients suggest that Io's footprint brightness and lead angle have positive relation between each other, although, the correlation coefficients are very low. From lead angle analysis by previous work [3], all three correlation coefficients suggest the same positive relation as our observed lead angle data, but with higher correlation coefficients in all three types and in both hemispheres. We can conclude from the correlation coefficients between lead angle and footprint brightness that they have slight positive relation to each other. These correlation coefficients support our hypothesis that the more lead angle means the further distance of bending magnetic field line along the Io torus Hence more of picked-up auroral particles could be the reason for brighter auroral emission.

3.2. Correlation between footprint brightness and magnetic field strength

The relation between observed footprint brightness and magnetic field strength in both hemispheres is shown in figure 3.

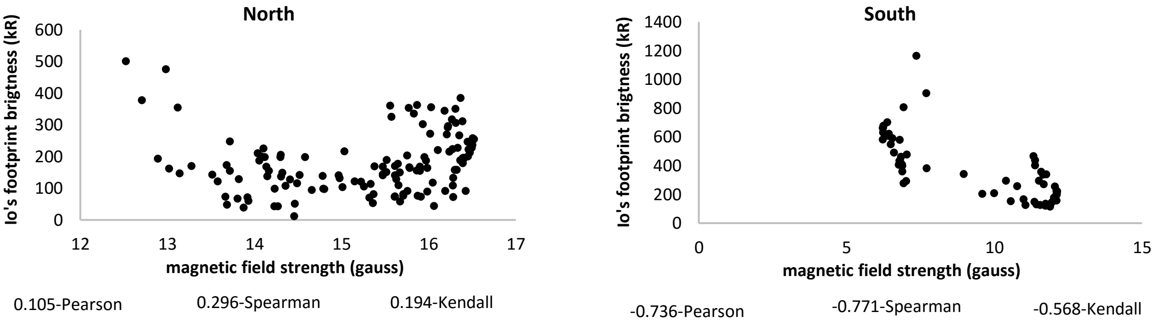

Figure 3 shows relation and correlation coefficients between magnetic field strength and observed Io's footprint brightness.

Io's footprint brightness and magnetic field strength at the footprint in Figure 3 are constrained by the same positions on Jupiter's surface. That is the position of observed footprint for the corresponding position of Io. We find correlation coefficients between footprint brightness and magnetic field strength in each hemisphere from 3 different correlation coefficients, which are Pearson product moment, Spearman's rank-order and Kendall's Tao as shown in Figure 3. In the north hemisphere, all correlation coefficients suggest positive relation between footprint brightness and magnetic field strength at footprint position. However, all three values indicate that the relation between these two are very low, the maximum value is Spearman rank-order is 0.297. In the south, all three correlation coefficients have the opposite trend in comparison to those of northern footprint. Pearson and Spearman correlation suggest very strong negative relation, -0.736 and -0.771 respectively. Kendall correlation suggest moderate negative value of -0.568. With disagreement between 2 sets of data, we conclude that the magnetic field and footprint brightness have low correlation between each other. These correlation coefficients suggest that the magnetic mirror have no significant effect on Io footprint brightness.

4. Conclusions

From different correlation coefficients in four data sets, we conclude that lead angle and Io's footprint brightness has a positive relation to each other. On the other hand, correlation coefficients between footprint brightness and magnetic field strength show disagreement of correlation coefficient between both hemispheres. One explanation could be the negative relationship between magnetic field strength and the number of precipitating auroral particles. It is clear that, while magnetic field strength and magnetic field configuration can play a controlling role in the footprint brightness, other influences should be taken into consideration for detail analysis.

5. Acknowledgments

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