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TEMPORAL VARIATIONS OF IO'S MAGNETIC FOOTPRINT BRIGHTNESS

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ABSTRACT

The brightness of Io's magnetic footprint, an indicator of electromagnetic interaction at the satellite, appears to be strongly connected to the satellite's distance from the plasma equator. As a result, the brightest footprints were detected when Io is near the interception location between the satellite's orbital plane and the plasma equator. However, volcanic activities on Io show strong correlation with the equatorward shift of Jupiter's main auroral oval, consequently causing the disappearance of Io's footprint. The same conclusion was suggested via the observation of Jupiter's hectometric radio emission, called HOM, which closely corresponds to Jupiter's auroral activity. The plasma environment near the Jovian satellites was found to vary significantly at different observational epochs. The electron density increased by approximately a factor of three from the Voyager epoch (1979) to the Galileo epoch (1995), while the electron density was found to be significantly higher (∼ 5 times) in the Cassini epoch (2001). In this current study, the magnetic footprints were clearly brighter ten years ago (from peak brightness in 1998–2001) than the footprints detected in 2007. For volcanic activities on Io in 2007, there are two clear activities in February and late May. The magnetic footprint appeared to be dimmer in March 2007, expected to be the result of volcano activities in Feb 2007. However, the magnetic footprint brightness in June appeared to be slightly brighter than the footprints observed in May. The reason could be the time delay between the brightening of the sodium nebula on approximately May 31st and, a while later, the enhancement of flux tube content peaking on approximately June 5th. On the other hand, Io's magnetic footprints were observed during June 1st – 10th when they may not yet have been affected by the increase in mass outflow due to the increase of plasma density.

Key words: Jupiter: Io, Planets and satellites: aurorae

1. INTRODUCTION

Jupiter's aurora is mainly the result of internal processes influenced by its fast rotation and strong magnetic field with a tilt angle ∼9.4 degrees of the magnetic axis from the rotation axis (Connerney et al., 1998). The greatest number of auroral particles are from the planet's atmosphere and Io's volcanically active surface. The interaction between Jupiter's magnetospheric plasma and Io's atmosphere connects to emission at the foot of Io's magnetic flux tube mapped to the location at the lower latitude from the main oval. This feature is called "Io's magnetic footprint". The brightness of Io's magnetic footprint was found to tightly connected to the magnetospheric plasma in the vicinity of the satellite (Wannawichian et al., 2010 and references herein).

In Jupiter's magnetosphere, the region of highest plasma density was found to be located near the magnetic equator. The plasma density decreases with distance away from Jupiter. However, large amounts of plasma emitted from Io causes dense magnetospheric plasma in the vicinity of Io's orbit and forms into a ring shape, called a plasma torus. The center of the plasma torus, or plasma equator, was found to be located approximately 7° degrees tilted from Io's orbital plane (Schneider & Trauger, 1995). Direct observations of Io's magnetic footprint brightness by the Space Telescope Imaging Spectrograph (STIS) and the Advanced Camera for Surveys (ACS), on board the Hubble Space Telescope (HST) showed the vast variability of Io's magnetic footprint brightness over a decade (Wannawichian et al., 2010). Several observing epochs show the variation of the footprint brightness (Figure 1), which strongly varies as a function of the Io system III longitude ($\lambda_{\rm III}$). During some observing epochs, short time variations of the footprint brightness were detected. Our detailed investigation reveals a strong connection between Io's magnetic footprint brightness and the variation of the plasma density near the satellite. The correlation between temporal variation of plasma torus and the interaction strength at Io will be discussed.

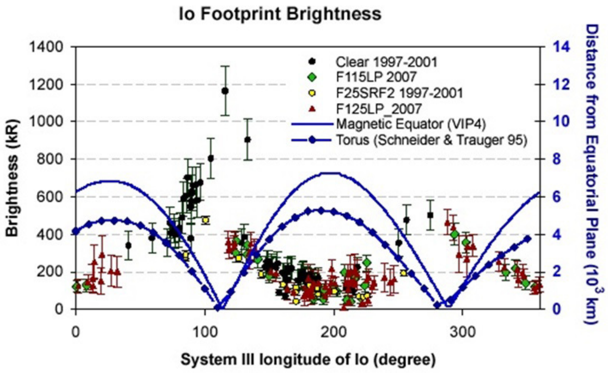

Figure 1. HST's observations from 1997 to 2001 reveal a strong connection between Io's magnetic footprint brightness and the satellite's location, which is designated by Jupiter's system III longitude. The figure was adapted from Wannawichian et al. (2010)

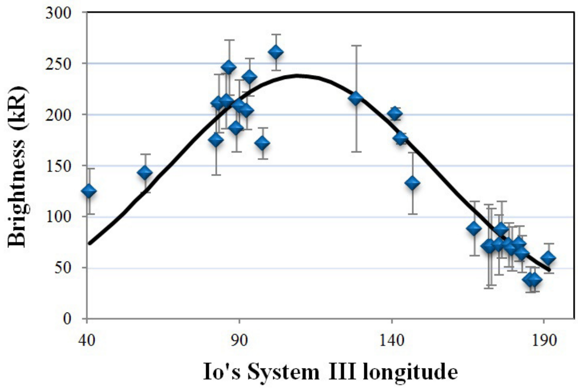

Figure 2. Io's magnetic footprint brightness observed in January 2001, fitted to the formulation of the brightness variation according to Equation (1) for the first peak ($20° < \lambda_{\rm III} < 200°$). The variation was fitted as a function of Io's system III longitude.

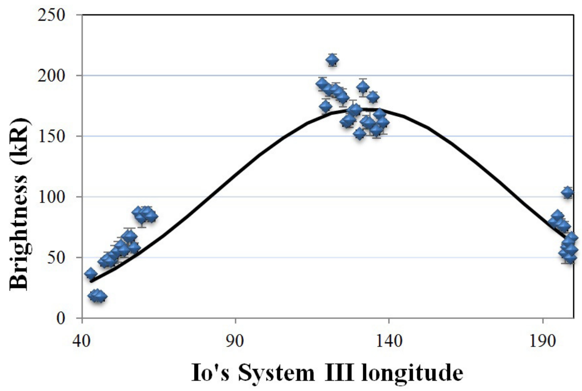

Figure 3. Io's magnetic footprint brightness observed in February 2007, fitted to the formulation of the brightness variation as for Figure 2.

2. OBSERVATIONS AND DATA REDUCTION

For a decade the 25 MAMA (Multi Anode Micro channel Array) detector on board HST has been taking images of Jupiter's aurora in FUV (115-170 nm). Moreover, two instruments, STIS and ACS, were separately used during 1998–2004 and 2005–present, respectively. The reduction procedure was modified at Boston University and the University of Liége (Grodent et al., 2008; Wannawichian et al., 2008). The signal to noise ratio was enhanced via subtracting a simulated background. The background simulation is according to the Minnaerth formulation, which employs modified empirical coefficients from direct-observed images (Vincent et al., 2000; Clarke et al., 1998). In addition, linear fitting for the background near the located footprint is used before measuring the footprint brightness.

3. DATA ANALYSIS

The detection of Io's magnetic footprints was assisted by a magnetic field model called VIP4 (Connerney et al., 1983). For the assumption of an optically thin atmosphere for Jupiter, a limb brightening correction was applied to the calculation of the footprint brightness. The limb brightening correction factor, for which the emission scale height equals 600 km, was based on the application in Serio & Clarke (2008).

Based on a clear connection between the magnetic footprint brightness and Io's location in Figure 1, one possible influence could be the plasma density in the vicinity of the satellite. It is plausible to estimate the variation of density, ρ, as an exponential function (Hill & Michel 1976). Therefore, the auroral footprint brightness (I), when Io was at different system III longitude ($\lambda_{\rm III}$), was fitted to Equation (1) for maximum brightness ($I_{\rm max}$). The maximum brightness can be acquired from the fitted parameter A_0 and A.

$$I(\lambda_{\rm III}) = A_0 \left(1 + Ae^{-\left(\frac{\lambda_{\rm III}-\lambda_{\rm max}}{\Delta\lambda}\right)^2}\right) \qquad (1)$$

Another fitted parameter is $\Delta\lambda$, which gives the full width at half maximum (FWHM), $2\sqrt{ln2}\Delta\lambda$, of the brightness variation. The fitted Io's longitude at maximum brightness is $\lambda_{\rm max}$. Since the emission variations are clearly separated into two peaks (Figure 1), the emissions were separated into two regions, (1) where $20° < \lambda_{\rm III} < 200°$ for the first peak and (2) where $200° < \lambda_{\rm III} < 360°$ for the second peak.

4. RESULTS

Io's magnetic footprint emissions at different epochs were fitted (Figure 2 - 8) for the brightness at the peak of the emission distribution ($I_{\rm max}$), as well as Io's system III longitudes ($\lambda_{\rm max}$), where the brightest emissions were detected. In addition, the FWHM of the emissions from the fit present the broadening of the emission variation.

The summary for the fitted result is shown in Table 1. The brightest emission, $I_{\rm max}$, in 1998 and 2000 appears to be brighter than those observed at the 2007 epoch. The emissions in 2007 vary slightly in different months. On a month-to-month basis, the brightest emission in

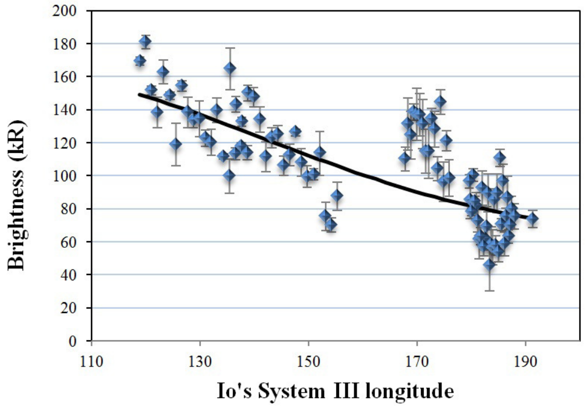

Figure 4. Io's magnetic footprint brightness observed in March 2007, fitted to the formulation of the brightness variation as for Figure 2.

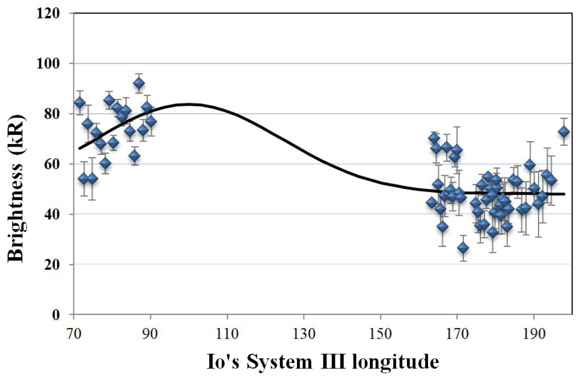

Figure 5. Io's magnetic footprint brightness observed in May 2007, fitted to the formulation of the brightness variation as for Figure 2.

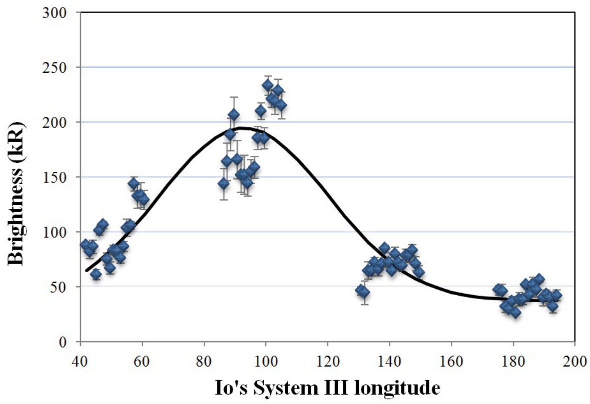

Figure 6. Io's magnetic footprint brightness observed in June 2007, fitted to the formulation of the brightness variation as for Figure 2.

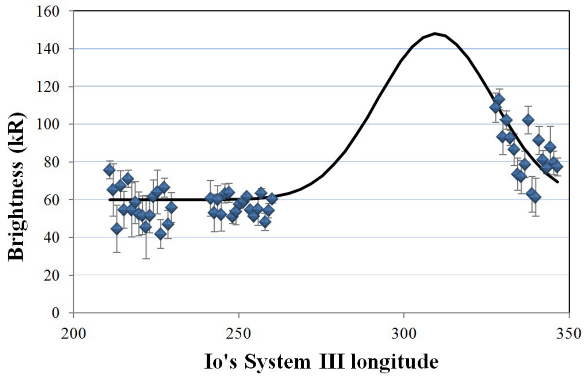

Figure 7. Io's magnetic footprint brightness observed in May 2007, fitted to the formulation of the brightness variation according to Equation (1) for the second peak ($200° < \lambda_{\mathrm{III}} < 360°$). The variation was fitted as a function of Io's system III longitude.

March appears to be fainter than that in February. On the other hand, the brightest emission in June appears to be brighter than that in May. This short time variations will be discussed accordingly in Section 5.

5. DISCUSSION

The locations of Io for which the brightest emissions were detected (λ_0) would imply the plausible locations of very dense plasma in the vicinity of Io. From Table 1, the expected dense regions in the plasma torus varies in different HST observation epochs. The results confirm the azimuthal variation of plasma density in the plasma torus, which was directly measured by Steffl et al. (2008).

The full width at half maximum, $2\sqrt{ln2}\Delta\lambda$, reveals the nature of the brightness distribution of Io's magnetic footprint brightness, consequently referring to density-dominated electromagnetic interactions. The narrow distribution peaks were detected in the Dec 2000, May 2007, and June 2007 epochs, while the broader distribution were found in the Jan 2001, Feb 2007, and March 2007 epochs. The broadening of the distribution could indicate the strength of the variability of the electron density, i.e. slow or rapid decay with distance from plasma torus.

One possible controlling factor is the volcanic activity on Io. A strong correlation between the volcanic activities on Io and the equatorward shift of the Jupiter main auroral oval was detected (Bonfond et al., 2012). On the other hand the hectometric radio emission (HOM) revealed the influence of volcanic eruptions on Io that caused the dimming of the main auroral emission (Yoneda et al., 2013). The electron density increased over time by a factor of three in the Voyager epoch (1979) to the Galileo epoch (1995) and became significantly higher (~ 5 times) in the Cassini epoch (2001) (Steffl et al., 2006). As shown in Table 1, this work shows that the magnetic footprints were brighter ten years ago, in comparison to the footprints detected in 2007. For two clear volcanic activities on Io in February and May 2007, the magnetic footprint appears to be dimmer in March 2007, but slightly brighter in June. The reason could be the time constraint for the effect of plasmas ejected by the volcanoes, leading to the amount of mass picked up from Io's interaction region. The brightening from sodium in the plasma torus in May 31st take 5 days to cause an enhancement of the flux

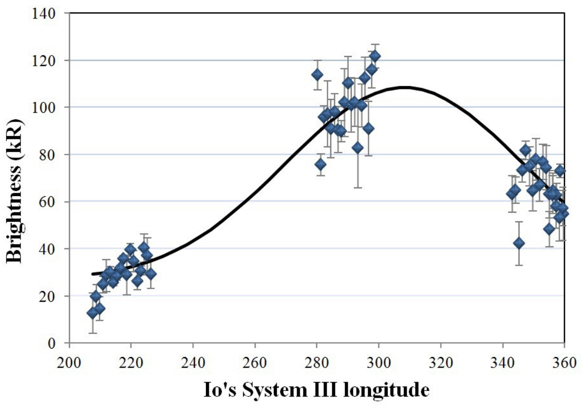

Figure 8. Io's magnetic footprint brightness observed in June 2007, fitted to the formulation of the brightness variation as for Figure 7.

Table 1
BRIGHTNESS VARIATION OF IO'S MAGNETIC FOOTPRINT

Epoch	$I_{\max}$[a]	$\lambda_{\max}$[b]	FWHM[c]	correlation[d]
FIRST PEAK[e]				
Dec 2000	194.8	123.1	81.8	0.94
Jan 2001	237.8	109.9	102.8	0.95
Feb 2007	172.5	131.6	112.2	0.82
March 2007	142.1	93.5	114.6	0.73
May 2007	83.8	100.1	57.7	0.77
June 2007	194.6	92.9	64.5	0.92
SECOND PEAK[f]				
Dec 2000	142.9	295.9	69.0	0.84
Jan 2001	165.0	279.7	92.1	0.88
Feb 2007	92.7	238.3	65.9	0.44
March 2007	170.1	277.7	102.5	0.86
May 2007	148.1	309.6	41.1	0.84
June 2007	108.4	308.2	90.3	0.94

[a] Maximum brightness in units of kRayleigh (KR) = 10^9 photon $\sec^{-1}$ cm^{-2} per $4\pi sr$
[b] Io's system III longitude, corresponding to the fitted maximum brightness
[c] Distribution of full width at half maximum, $2\sqrt{ln2}\Delta\lambda$
[d] Pearson correlation coefficient
[e] For fitted emission where $20° < \lambda_{\rm III} < 200°$
[f] For fitted emission where $200° < \lambda_{\rm III} < 360°$

tube content. Consequently, in this work, Io's magnetic footprints observed during June 1st–10th may not yet be affected by the increasing outflow mass.

6. CONCLUSIONS

The results from the present work provide direct evidence of the variation of the locations where the plasma density is expected to be highest, which was indicated by Io's magnetic footprint emission. Io's system III longitudes at which the density is expected to be highest, appear to vary in time. The variation of peak emissions from different observational epochs suggests that the variation of plasma density could play a major role in controlling the auroral emission. Detailed modeling of the electromagnetic interaction at Io should be able to explain the variation in detail.

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