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Evolution of the Io footprint brightness I: Far-UV observations

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ABSTRACT

The Io footprint (IFP) is a set of auroral spots and an extended tail resulting from the strong interaction between Io and the Jovian magnetosphere. For the first time, we present measurements of the brightness and precipitated power for each individual spot, using the image database gathered from 1997 to 2009 with the Hubble Space Telescope in the Far-UV domain. We show that the relative brightness of the spots varies with the System III longitude of Io. Moreover, our novel measurement method based on 3D simulations of the auroral features allows to derive the precipitated energy fluxes from images on which the emission region is observed at a slant angle. Peak values as high as 2 W/m^2 are observed for the main spot, probably triggering a localized and sudden heating of the atmosphere. Additionally, strong brightness differences are observed from one hemisphere to another. This result indicates that the location of Io in the plasma torus is not the only parameter to control the brightness, but that the magnetic field asymmetries also play a key role. Finally, we present new data confirming that significant variations of the spots' brightness on timescales of 2–4 min are ubiquitous, which suggests a relationship with intermittent double layers close to Jovian surface.

1. Introduction

Io, Jupiter's volcanic moon, releases approximately one ton of SO_2 every second. Half of this material, once ionized, temporarily remains in the Jovian magnetosphere, while the other half undergoes charge exchange and rapidly escapes in the form of energetic neutral atoms (e.g. Bagenal and Delamere, 2011). Newly ionized particles are brought to corotation with the magnetic field and form a dense plasma torus around Io's orbit before being transported radially outward in the magnetosphere. Following the tilt of the magnetic dipole of Jupiter, the plasma torus centrifugal equator is tilted relative to the Io orbital plane by ~6.7 degrees (Gledhill, 1967). As a result, Io is located alternately close to the dense torus center or close to its southern or northern boundaries. Io's orbital period is around 42 h, while plasma torus particles rotate around Jupiter in ~10 h (Jupiter's rotational period). As a consequence, Io and its conducting ionosphere act as an obstacle to the plasma flow (e.g. Saur et al., 1999). The disturbance and the related electric currents propagate along magnetic field lines in the form of Alfvén waves (see reviews by Kivelson et al., 2004 and Saur et al., 2004). The combination of the motion of the flux tubes relative to Io and the comparatively low Alfvén speed in the dense plasma torus, causes the paths of these waves, called the Alfvén wings, to be tilted towards the downstream direction in a reference frame fixed with Io. Powerful auroral emissions, called the Io footprints (IFP), are found at the Jovian extremities of these Alfvén wings in each hemisphere (Connerney et al., 1993; Prangé et al., 1996; Clarke et al., 1996).

In each hemisphere, the Io footprint consists of several individual spots followed by a fainter tail extending as far as 100° of longitude downstream in the corotational direction (Clarke et al., 2002). Recent studies showed that the relative location of these different spots varies with the position of Io in the plasma torus (Gérard et al., 2006; Serio and Clarke, 2008; Bonfond et al., 2008, 2009). Bonfond et al. (2008) distinguished three different spots and associated them with three different mechanisms. The Main Alfvén Wing (MAW) spot is associated with the direct Alfvén wing connecting Io to the Jovian ionosphere. This MAW spot is generally the brightest feature and corresponds to the part of the Alfvén wave's energy that directly escapes the plasma torus. The other

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part undergoes reflections on the latitudinal torus density gradient (Neubauer, 1980; Gurnett and Goertz, 1981). A fraction of these reflected waves can then escape the torus through the opposite boundary, leading to the Reflected Alfvén Wing (RAW) spot. Finally, the Alfvén waves are presumed to accelerate electrons not only directly towards the planet, but also in the opposite direction, in the form of electron beams (Swift, 2007; Jones and Su, 2008; Hess et al., 2010). These beams of electrons cross the plasma torus and eventually precipitate in the atmosphere, generating the Trans-hemispheric Electron Beam (TEB) spot. Wilkinson (1998) offered a similar explanation for the periodicity of the Io-related decametric radio emissions. Additionally, it should be noted that these electron beams have been observed by the Galileo spacecraft as it flew by Io (e.g. Williams and Thorne, 2003) and simulations by Jacobsen et al. (2010) showed that the geometry of the Alfvén wave propagation and the electron beam path are consistent with both the auroral observations at Jupiter and the *in-situ* observations at Io.

The IFP results from a long chain of processes (see Fig. 1), and various parameters can impact the brightness of the different components of the IFP. This chain of processes along the magnetic field line was first decomposed and modeled by Hess et al. (2010) and is the object of a companion paper (Hess et al., this issue, hereafter Paper II) which addresses the modeling issues related to the observations presented here. It can be summarized as follows. First of all, the power of the electro-magnetic interaction at Io depends on the density of the plasma, which varies as Io moves across the torus. Secondly, the location of Io in the plasma torus also impacts the geometry of the wave propagation and the time required for the waves to cross the plasma torus before they escape towards the poles. This effect could be crucial if a significant damping of these waves occurred within the torus. Another critical point is the reflection ratio by the torus density gradient. Wright (1987) showed that the amount of reflection could be very significant. Hence, Hess et al. (2010) showed that the transmission coefficient could tremendously increase as the scale of the Alfvén waves decreases. Following Chust et al. (2005), they argued that only a significant filamentation of the Alfvén waves could explain the observed power of the IFP. The efficiency of the energy transmission between the Alfvén wave and the electron acceleration varies as well, as a function of the magnetic field strength. Finally, the magnetic field strength also controls the size of the loss cone, and thus the amount of electrons that ultimately precipitate into the atmosphere. It is noticeable that all these parameters vary with the System III (S3) longitude of Io, and thus the footprint brightness is expected to be a function of this longitude system. A more detailed study of those processes and of their dependency on Io's S3 longitude can be found in Paper II (this issue).

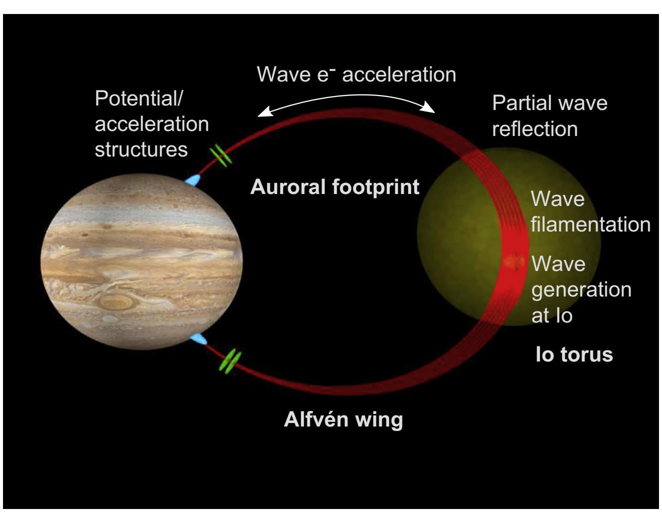

Fig. 1. Scheme of the chain of processes leading to the Io footprint auroral spots. First Alfvén waves are generated close to Io as a result of the interaction between Io and the magnetized plasma of the torus. These waves then propagate towards Jupiter, forming Alfvén wings. They first undergo filamentation, as the large scale waves break into smaller scale structures, before being partially reflected at the torus latitudinal density gradient. Once out of the torus, the Alfvén waves enter the inertial regime and accelerate electrons in both directions along the magnetic field lines. Before they precipitate into the atmosphere and create the auroral footprint, the electrons go through additional potential acceleration structures in the Jovian ionosphere. More details about this long chain of processes and how they affect the spots' brightness can be found in Paper II (this issue).

In the study describing the first detection of the Io footprint, Connerney et al. (1993) suggested that the apparent lack of detection of the infrared (IR) northern IFP in the 90°–240° S3 longitude range is related to the expected high surface magnetic field strength in this region. Early studies relating the first observations of the UV IFP, observed either with the Faint Object Camera (Prangé et al., 1996, 1998) or the Wide Field and Planetary Camera 2 (WFPC2) (Clarke et al., 1996) on board the Hubble Space Telescope (HST), the datasets were considered too sparse to show any signature of the variations of the footprint brightness as a function of Io's longitude. Subsequent WFPC2 observations demonstrated the existence of a northern footprint in the 90–240° longitude range (Clarke et al., 1998), contrary to the first results in the IR. The first conclusive relationship between the brightness and Io's longitude was reported by Gérard et al. (2006), based on observations from the Space Telescope Imaging Spectrograph (STIS) on board HST acquired between December 2000 and February 2003. They showed that the maximum IFP brightness increases when Io's centrifugal latitude approaches 0°. The authors attributed the brightening of the IFP as Io settles into the dense torus center to the expected enhancement of the Io-magnetosphere interaction. Serio and Clarke (2008) studied the evolution of the footprint UV brightness on STIS images acquired from August 1999 to January 2001. They concluded, like Gérard et al. (2006), that the energy radiated away from the local interaction at Io, which is controlled by the plasma torus density at the satellite, is the main driver for the mean IFP brightness. Wannawichian et al. (2010) performed a similar study, but included a much larger dataset acquired with the Advanced Camera for Surveys (ACS) onboard HST. They also observed two brightness peaks, at 110° Io SIII longitude and 290° Io SIII longitude, i.e. when Io is close to the torus center, and reached the same conclusion. The previously reported IFP brightness and emitted powers are summarized in Table 1. The variations of the energy fluxes generated at Io as a function of the Io S3 longitude have been recently studied by Saur et al. (2013) and Wannawichian et al. (in press). However, the local variations may not be sufficient

Table 1
List of the published emitted and electron precipitated power for the FUV Io footprint. For Gérard et al. (2006), the printed value is 0.4–8 GW but, after verification, it appears that this 10 times smaller value came from a typo in a conversion coefficient. We thus consider here the corrected value.

	Emitted power (W)	Input power (W)	Brightness (kR)
Prangé et al. (1996)	5×10^{10}	$2–3\times10^{11}$	700
Clarke et al. (1996)		10^{11}	60–120
Prangé et al. (1998)		$0.8–5\times10^{11}$	
Clarke et al. (1998)			35–250
Gérard et al. (2006)		$0.4–8\times10^{10}$	25–220
Serio and Clarke (2008)			40–480
Wannawichian et al. (2010)			5–390
This study[1]	$0.4–5\times10^{10}$	$2–25\times10^{10}$	2500–20,000

[1] These numbers are for the MAW spot only.