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UV Io footprint leading spot: A key feature for understanding the UV Io footprint multiplicity?

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[1] The electromagnetic interaction between Io and the Jovian magnetosphere generates a UV auroral footprint in both Jovian hemispheres. Multiple spots were observed in the northern Jovian hemisphere when Io was in the northern part of the plasma torus and vice-versa for the South. Based on recent Hubble Space Telescope (HST) measurements, we report here the discovery of a UV leading spot, i.e., a faint emission located ahead of the main spot. The leading spot emerges at System III longitudes between 0° and 100° in the northern hemisphere and between 130° and 300° in the southern hemisphere, i.e., in one hemisphere when multiple spots are observed in the other hemisphere. We propose as one potential mechanism that electron beams observed near Io are related to the generation of the leading spot and the secondary spot in the opposite hemisphere. **Citation:** Bonfond, B., D. Grodent, J.-C. Gérard, A. Radioti, J. Saur, and S. Jacobsen (2008), UV Io footprint leading spot: A key feature for understanding the UV Io footprint multiplicity?, *Geophys. Res. Lett.*, *35*, L05107, doi:10.1029/2007GL032418.

1. Introduction

[2] The first indications of the strong interaction between the volcanic moon Io and the Jovian magnetosphere were discovered in the radio decametric domain [*Bigg*, 1964]. The auroral footprints associated with this interaction were first observed in the infrared wavelength [*Connerney et al.*, 1993] and then in the UV wavelength [*Clarke et al.*, 1996].

[3] The perturbation induced by the motion of Io in the plasma torus is thought to propagate along the magnetic field lines mainly in the form of Alfvén waves and being the root cause for the auroral Io footprint (IFP). Whether the Jovian ionosphere exerts a strong feedback (the unipolar inductor), a partial feedback (a mixed Alfvén wings system) or no feedback (the ideal Alfvén wings) on the current system is still an open question (see review by *Saur et al.* [2004]). Alfvén waves are slower in the dense plasma torus confined around the centrifugal equator than outside the torus. Consequently, the Alfvén wings and their associate current system are tilted with respect to the background magnetic field. The longitudinal angle between the foot of unperturbed field lines passing through Io and the actual location of the footprint is called the lead angle. Moreover, substantial reflections of the waves are expected to occur where sharp density gradients exist, i.e. at the Jovian ionosphere and at the torus boundaries [e.g., *Wright and Schwartz*, 1989].

[4] *Gérard et al.* [2006] showed that the footprint brightness depends on the centrifugal latitude of Io. They also demonstrated that the spot multiplicity and the inter-spot distances were directly linked to the position of Io in the plasma torus. The maximum multiplicity and the largest interval between the spots are observed in the northern hemisphere when Io is close to the northern torus boundary (and vice-versa for the South). However, the maximum distance between the first and the secondary spots is ~4° while linear Alfvén wing propagation models predict angles around 12° [*Dols*, 2001]. Recently, *Bonfond et al.* [2007] reported that fast brightness fluctuations were also observed with timescales of 1–2 minutes in addition to the long timescale variations of the footprint brightness.

[5] Recent observations of the IFP in configurations that had never been observed before reveal a new feature of the UV IFP morphology: a leading spot. Here we describe for the first time a complete set of the Io footprint morphologies and we discuss their interpretation.

2. Data Processing

[6] This study is based on a comprehensive data base of 2120 high-resolution HST UV images acquired with the Space Telescope Imaging Spectrograph (STIS) and the Advanced Camera for Surveys (ACS) from 1997 to 2007. A total of 1619 images were taken during the HST large campaign in Spring 2007. The STIS camera provided the best angular resolution (0.024468 arcsec/pixels compared to 0.0301 arcsec/pixel for ACS) while ACS has the best sensitivity. We considered images acquired with the Strontium Fluoride (F25SRF2) and the Clear filters for STIS, and with the F125LP and the F115LP filters for ACS. The F25SRF2 as well as the F125LP filters reject most of the Ly-α emissions, which are largely contaminated by the geocoronal emissions. We applied dark count subtraction, flat-fielding as well as geometrical corrections to every image considered in this work.

3. Observations

[7] One of the multiple objectives of the recent HST campaign carried out with the ACS camera was to complete the System III (S3) coverage of the footprints. In particular, observations of the northern footprint when Io is close to the southern edge of the torus as well as observations of the southern footprint when Io is close to the northern edge of the torus were missing. We find that images of the IFP in these configurations systematically show a faint emission ahead of the main spot, which we call the leading spot.

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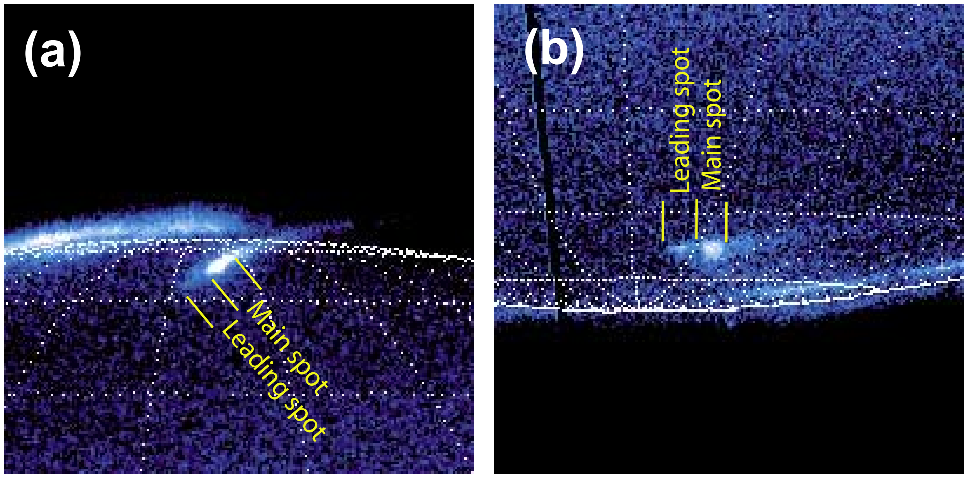

Figure 1. Example of leading spot (a) in the northern hemisphere (S3 longitude: ~50°) and (b) in the southern hemisphere. (S3 longitude: ~170°).

Figure 1 presents an example of leading spot in each hemisphere. Figure 2 illustrates the occurrence distribution of the leading emission as a function of S3 position of Io for the northern and the southern footprints. It is seen that the leading spot is present at S3 longitude ranging from 0° to 100° in the North. In this range, Io is located close to the southern edge of the torus. The cases around 10° are more complex to interpret because the viewing geometry is such that the footprint appears near the limb and its emission overlaps the main auroral emissions. In these cases, a careful look of the animation sequences from these image sets reveals a bright spot constantly ahead of the main Io spot. The longitude of the occurrences of the southern leading spot ranges from 130° to 300°. This corresponds to configurations where Io is located northward of the torus. The UV H_2 emitted power of the leading spot ranges from 0.6 GW to 1.9 GW, with a typical value of 0.7 GW.

[8] The recent ACS observations complete the partial scheme of the UV footprint morphologies shown in Figure 5 of *Gérard et al.* [2006]. We extracted 21-pixel wide stripes from the background subtracted images and stretched them in order to display the footprint shape as a function of the longitude mapped to Io's orbital plane. For this mapping, we used the VIP4 magnetic field model [*Connerney et al.*, 1998]. The result is shown in Figure 3.

[9] The Io footprint multiplicity follows a systematic scheme; when Io is close to the northern edge of the plasma torus, at S3 longitudes around 200°, three spots can be seen in the northern hemisphere while a faint leading spot appears ahead of the southern main spot. Similarly, when Io is close to the southern edge of the plasma torus, at S3 longitudes around 20°, three spots clearly stand out from the tail emission in the southern hemisphere. In the North, a faint leading spot appears ahead of the main spot. The second spot in the South is generally brighter than in the

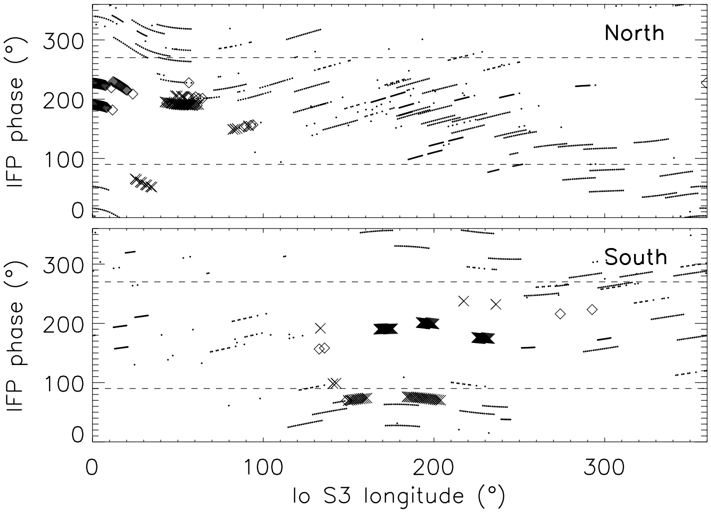

Figure 2. Occurrence of the leading spot (top) in the northern hemisphere and (bottom) in the southern hemisphere. The dots represent the available observations, the crosses represent the cases where the leading spot is observed and the diamonds represent the uncertain cases.

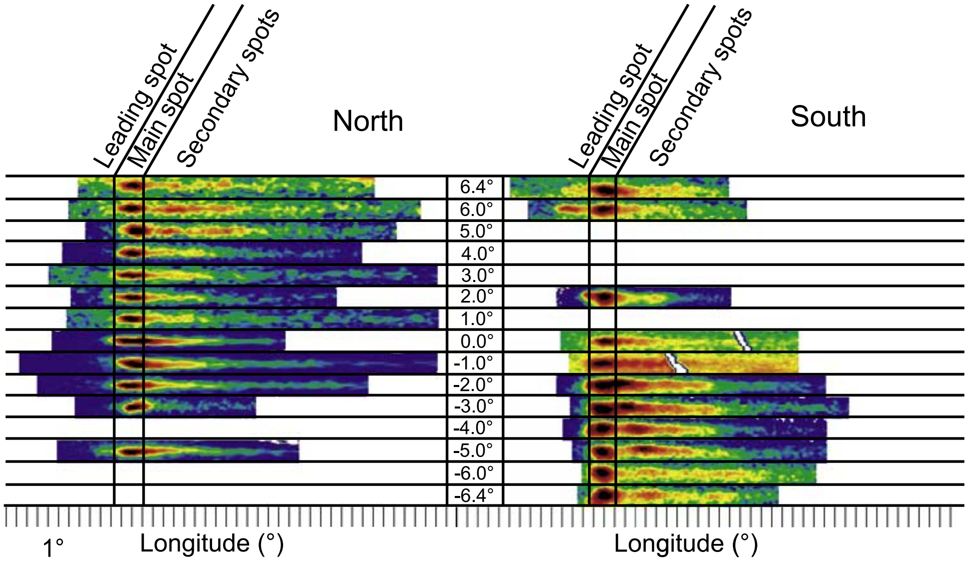

Figure 3. Scheme of the Io morphology as a function of the centrifugal latitude of Io in the torus. This figure completes the scheme of the IFP morphologies shown in Figure 5 of *Gérard et al.* [2006]. The color table of each stripe is scaled individually for a clearer illustration of the morphology. The longitudes are not measured on the planet, but mapped to the equatorial plane along the magnetic field lines according to the VIP4 model for an easier comparison of both hemispheres.

North. On the other hand, when Io is located in the center of the torus, i.e. at longitudes around 110° or around 290°, only one bright spot sometimes followed by a fainter one can be seen in both hemispheres and no leading spot is observed.

[10] At a given time, the distance between the leading spot and the main spot in one hemisphere is almost identical to the distance between the first and the secondary spots in the opposite hemisphere. For example, on 5 March 2007, a southern footprint image was acquired at 09:02 UT and then a northern spot image was acquired at 09:10 UT. In the South, the angular separation between the main spot and the leading spot on the planet is about 3.1° when mapped back in the equatorial plane. In the northern hemisphere, the separation between the main spot and the first secondary spot is about 3.4°.

[11] In Figure 3 some northern spots appear to be elongated downstream. This effect is caused by limb brightening because of the viewing geometry of these cases. Consequently, these elongations should not be considered as intrinsic. Similarly, some stripes are slightly contaminated by the background auroral emissions (e.g. the top stripe in the North). Nevertheless, this scheme has the advantage of extracting the footprint morphology from the context of the global image for easier morphological comparisons.

4. Interpretation and Discussion

[12] The parallel evolution of the inter-spot distance in both hemispheres suggests that the leading spot and the first secondary spot are related. In this section, we present a possible interpretation of the footprint morphology taking the new observational features described before into account. This interpretation attempts to provide an explanation for three issues that were not solved with the previous interpretations of the footprint multiplicity: (1) the existence of the leading spot and its evolution with the centrifugal latitude of Io, (2) the small maximum inter-spot distance, and (3) the bright southern secondary spot.

[13] The main idea driving this interpretation rests on the assumption that the leading and the secondary spots stem from a common mechanism. The electron precipitation related to the main spot is thought to be associated with upward current carried by the Alfvén wing. It is suggested that the downward segment of the current loop accelerates electrons towards the other hemisphere (see Figure 4). These accelerated electrons can then reach the other hemisphere within a few tens of seconds and precipitate into the ionosphere. When Io is close to the northern edge of the torus, the lead angle of the northern IFP is small while the lead angle of the southern IFP is large. Accordingly, the electron beam generated on the northern hemisphere would essentially follow the field lines whereas the Alfvén wing is tilted relatively to the background field. Consequently, the beam would reach the southern hemisphere upstream from the southern main spot, creating the leading emission. On the other hand, the northward electron beam would reach the northern hemisphere downstream of the main spot, leading to the first secondary spot.

[14] This scenario is supported by the Galileo spacecraft in-situ measurements of electron beams in the energy range from 100 eV to 150 keV [*Williams et al.*, 1999; *Frank and Paterson*, 1999]. The origin of the beams has been attributed to electron acceleration related to the Jupiter-ward part of the current loop, by analogy to similar electron beams observed at Earth [*Mauk et al.*, 2001]. These observations first suggested that a direct relationship exists between these beams and the auroral emissions. However, this hypothesis was later questioned because the electron beams were found unable to carry enough power to generate the observed IFP, given the assumed extent of the beams close to Io [*Mauk et*

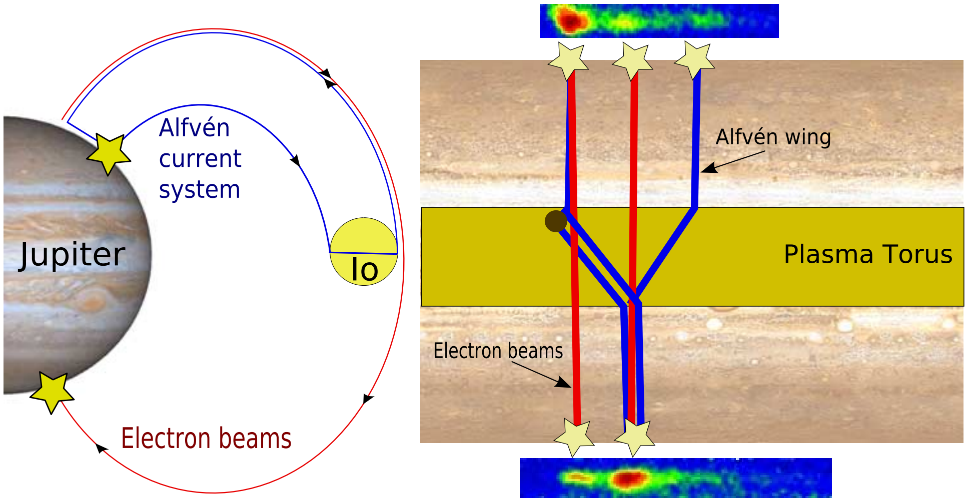

Figure 4. Illustration of the suggested mechanism that could explain the presence of the leading spot. The blue line shows the current flowing trough Io, then along the Alfvén wings and finally in the Jovian ionosphere. The electron beams are shown in red and the IFP spots are represented by stars. (left) A simplified side view of the conventional Alfvén current system. Some of the beam's electrons can precipitate if their mirror point is low enough, creating the leading spot. (right) The geometry of the Alfvén wings propagation and their reflection against the inner boundary of the torus. In contrast to the Alfvén waves, the electron beams are not affected by the high torus density, which enables them to propagate rapidly form an hemisphere to the other, generating the leading and the first secondary spots.

al., 2001]. In this work we, however, need to compare the electron beam energy with the energy of the faint leading spot. Based on the spectra from *Mauk et al.* [2001], we find that the energy flux contained in the electron beams can deliver 30 mW/m^2 into Jupiter's ionosphere.The leading spot size on the images is approximately 350 × 150 km^2, so that the total power reaches ~1.6 GW. Assuming a ~15% efficiency [*Grodent et al.*, 2001], the injected power leads to ~0.24 GW emitted power, on the same order but somewhat smaller than typical values of 0.7 GW for the leading spot. Since the beams have been observed in the center of Io's wake and during polar flybys, the current system might be more complex than illustrated in Figure 4. Alternatively, we can consider the energy radiated towards Jupiter by the Poynting-flux, which is distributed over the whole interaction region. This energy is converted, in parts, into electron heating and acceleration. Note, this does not affect the principles of our interpretation since electron beams and Alfvén wings follow different directions (except in the center of a fully saturated Alfvén wing).

[15] Another argument in favor of this interpretation is the brightness of the second spot in the southern hemisphere, which can sometimes be brighter than the first one. The S3 longitude range where the southern secondary spot is very bright corresponds to the region of weaker surface magnetic field. As a consequence, the secondary spot appears more affected by the surface field strength than the first one. If the pitch angle distribution of the electron beams is larger than the loss cone, as suggested by the Galileo observations, then the decrease of the surface field strength could significantly increase the number of precipitated electrons.

[16] The third spot which is observed in both hemispheres at maximum 12° downstream of the main spot could be the spot related to the Alfvén wing reflection on the plasma torus boundary. Accordingly, the observed angular separation between the first and the third spot would agree with the results of linear simulations based on realistic torus density profiles [e.g., *Dols*, 2001].

[17] Other mechanisms could also explain the structures described above. For example, a possible interpretation could be that the leading spot is actually a faint primary spot. As a result, the feature that we consider as the main spot may be seen as a very bright secondary spot. The intense emission of the second spot compared to first one could stem from constructive interferences of the Alfvén waves predicted by the models describing strong interaction between Io and the torus and modeling the non-linear effects [*Jacobsen et al.*, 2007].

[18] The hypothesis of electron precipitation occurring upstream of the foot of the Alfvén wing was already proposed by *Queinnec and Zarka* [1998] to explain the weak trailing arc of radio B arcs. These authors suggested that electron leakage on the Alfvén wing could be produced by parallel electric fields associated with the magnetic perturbation. However, it is difficult to link this process with the leading spot because the trailing arc originates from the northern hemisphere while the leading emissions are observed in the South for the same longitude range.

5. Conclusions

[19] Recent observations of the Io UV footprint in previously unexplored configurations reveal a new feature of the Io footprint. The feature, that we name the leading spot, consists of a faint emission upstream of the main spot and appears in one hemisphere when Io is close the opposite border of the plasma torus. It is suggested that this leading spot is produced by the same mechanism as the previously

described secondary spot. These two spots would not be related to reflection of Alfvén waves on the torus border but would be caused by electron beams generated by downstream currents in the opposite hemisphere. These beams, probably linked to those observed by Galileo, could precipitate in the opposite Jovian hemisphere, creating a spot ahead or behind the main spot depending on Io's location in the torus. This conclusion is supported by the observation that the secondary spot appears brighter in the South when the southern surface magnetic field is weaker.

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