# Chapter 3

# Spots multiplicity

## 3.1 Introduction to the Io footprint morphology

The first step in our endeavor to understand the Io footprint is the description of its morphology. What does it look like? What is its shape? Is it monolithic or composed of different structures?

The early detections of the IFP described it as a localized spot. When *Connerney et al.* (1993) first identified the Io footprint with the infrared IRTF telescope, they only observed a brighter area equatorward of the main auroral emissions. In the UV domain, *Prangé et al.* (1996) observed a bright spot associated with the Io footprint on one post-COSTAR FOC image. The authors also identified emission forming a faint arc starting from the brightest Io related emission and extending ∼20° downstream in the direction of Io's motion. These features, i.e. the bright Io spot and its tail, have later been identified on other images from the same instrument (*Prangé et al.*, 1998). The second generation WFPC2 camera showed a higher sensitivity, allowing an easier identification of the IFP on the images (*Clarke et al.*, 1996). While the FOC images rather showed the IFP as a small spot (with a transverse size of 400 (-200,+100) km) barely larger than the projection of Io along magnetic field lines (*Prangé et al.*, 1996; *Prangé et al.*, 1998), the WFP2 data showed the footprint as a much larger spot (1000 to 2000 km), suggesting that the interaction region in the equatorial plane was not restricted to Io but encompassed a broader region around the satellite. *Clarke et al.* (2002) explained the discrepancy between the two datasets by the lower sensitivity of the FOC instrument that only allowed the detection of the brightest part of the emission.

After identification in the IR and in the UV domains, the Io footprint has also been detected in the visible domain with the Solid State Imaging camera on board the Galileo probe (*Ingersoll et al.*, 1998; *Vasavada et al.*, 1999). In the day-side of the planet, the strong solar light reflection prevents any observation of visible auroral emissions. Consequently, the visible aurora can only be observed in the night-side of Jupiter, i.e. from an in-situ observatory, contrary to IR and UV images. Nevertheless, the main strength of these observations is their angular resolution, since the one SSI pixel covers from 26 to 134 km on the planet. *Ingersoll et al.* (1998), based on images from the third Galileo orbit, described the IFP as an ellipsoidal spot (300×500 km FWHM) followed by a fainter downstream tail. On the other hand, *Vasavada et al.* (1999), analysed images from the third and the tenth orbits and described the spot more like a circular patch with a diameter of 450 ±100 km. On images acquired during the eleventh orbit, these authors note that the IFP appears as a pair of patches ~0.5° apart. The estimate of the inter-spots distances as well as the size of the different IFP features on UV images will be described in Chapters 4 and 6 respectively. These visible images provide a crucial indication: the appearance of two spots instead of a single one. Although these observations in the visible provide very interesting information thanks to the original point of view and of the unequaled angular resolution, the available data are scarce and lack sensitivity. Indeed, the next steps forward were brought by the third generation UV camera on board the Hubble Space Telescope.

During the second HST Servicing Mission in February 1997, astronauts installed the Space Telescope Imaging Spectrograph (STIS) instrument. *Clarke et al.* (2002) used this camera to demonstrate that the Io spot was systematically followed, up to 100° downstream, by a faint but extended tail. Additionally, they showed that the bright part of the emission could show two types of morphology: a single spot, sometimes being as large as 15° FWHM in longitude or a pair of spots. Given that the two spots were 12° apart at maximum and that this size corresponds to the extension of the wake of stagnating plasma behind Io, the authors interpreted the IFP morphology, whether the spot is single or dual, as the footprint of the extended interaction region at Io, comprising the wake. Based on the same image dataset, *Gérard et al.* (2006) noticed that the number of spots, as well as the inter-spot distances, evolves with the location of Io in the plasma torus. They showed that the number of spots was larger when Io was away from the torus center. Additionally, they noted that the angular separation between the first and the second spots was decreasing in the northern hemisphere as Io is moving from the northern centrifugal

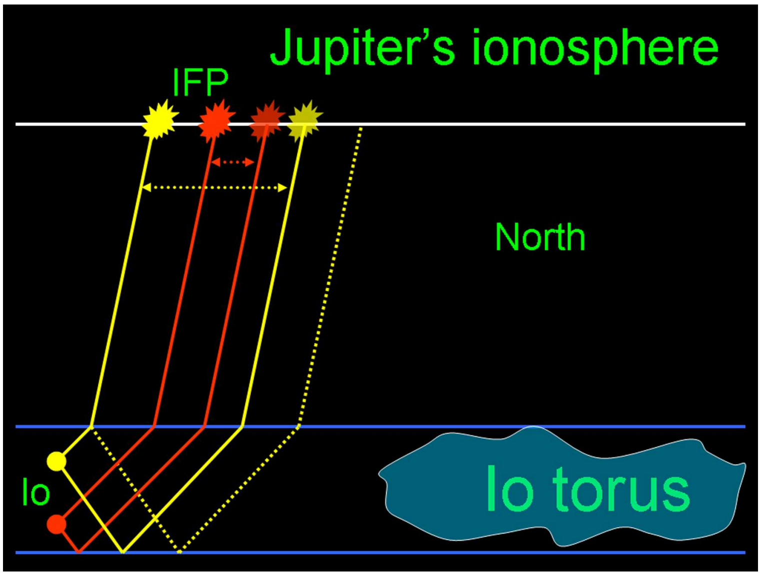


Figure 3.1: Illustration of the evolution of the spots separation in the Alfvén wings reflections scenario. For the northern spots, the inter-spot distance decreases as Io moves southward. (from *Gérard et al.* (2006))

latitudes towards the torus center. Alternatively, the inter-spot distance in the South increases as Io moves from the torus center to the southern most centrifugal latitudes. They attributed this evolution of the angular separation of the spots to reflections of the Alfvén wings on the torus borders. Considering the northern footprint, when Io is in the northern most part of the torus, the direct Alfvén wing immediately escapes from the torus while the reflected Alfvén waves have to cross the torus twice. The resulting propagation delay between the direct and the reflected path leads to a maximum separation angle. As Io moves toward the torus center, the direct wing cross a longer part of the torus while the reflected path length decreases, leading to smaller inter-spot distances (see Figure 3.1). We nevertheless note that the study of the northern footprint was mainly restricted to configurations in which Io has positive centrifugal latitude and vice-versa for the South.

In 2005, a HST observation program[1] of the northern Jovian aurora was executed in order to study a possible magnetic field anomaly in the 100° System III longitude sector. By chance, the Io footprint is clearly visible on some of these images. An intriguing faint emission was observed to prolong the main spot upstream. This faint emission was presented under the name "precursor" by *Grodent et al.* (2005b)

[1]Observation program "10140".

at the MOP meeting at Leicester. We shall see in the next section that these faint emissions, sometimes observed as a detached spot, occur systematically in one hemisphere when Io is in a particular position in the plasma torus. Strictly speaking, a precursor is a message announcing something that will appear later in time. The faint spot we are discussing here does not appear previously to anything, but is just located upstream of the main spot, thus leading the brightest emissions. This is the reason why I consider the expression “precursor” as inappropriate and have replaced it by the term “leading spot”.

When the Spring 2007 “10862” observation campaign was designed, *Gérard et al.* (2006) had just highlighted the fact that the Io footprint morphology was varying with the centrifugal latitude of Io. But it was also evident that only half of the possible Io configurations in the Io torus had been observed and that consequently, half of the story was missing. In the northern hemisphere, IFP observations were only available when Io was in the northern part of the torus and vice-versa for the South. One of the only few exceptions were the 2005 images mentioned above.

Even if the core of the “10862” proposal was the measurement of the solar wind influence on the Jovian and Kronian aurorae, the LPAP team strongly insisted to dedicate 10 out the 128 Jupiter orbits to the study of the Io and Ganymede footprints. Therfore these 10 orbits were specially requested to observe the Io and Ganymede footprints in configurations known to be unfavorable for the viewing of the remaining of the aurora. Out of these 10 orbits, 8 were devoted to the Io footprint and 2 to the Ganymede footprint. Given the promising results acquired with the time-resolved time-tag sequences (see *Bonfond et al.*, 2007), but acknowledging that the STIS instrument was out of order since 2004, we chose to reduce the integration time to 30 seconds (instead of 100 for the 118 remaining orbits) in order to enable the study of the short timescale IFP brightness dynamics (see Chapter 7). The next section describes the outcome of this observation campaign and discusses their consequences in terms of interpretation of the footprint morphology and multiplicity.

## 3.2 Publication: *The UV Io footprint leading spot: A key feature for understanding the UV Io footprint multiplicity?*

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### 3.2.1 Abstract

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.

### 3.2.2 Introduction

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).

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).

*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 $\sim 4°$ 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.

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.

### 3.2.3 Data Processing

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-$\alpha$ 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.

### 3.2.4 Observations

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. Figure 3.2 presents an example of leading spot in each hemisphere. Figure 3.3 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.

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 pixels 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 3.4.

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

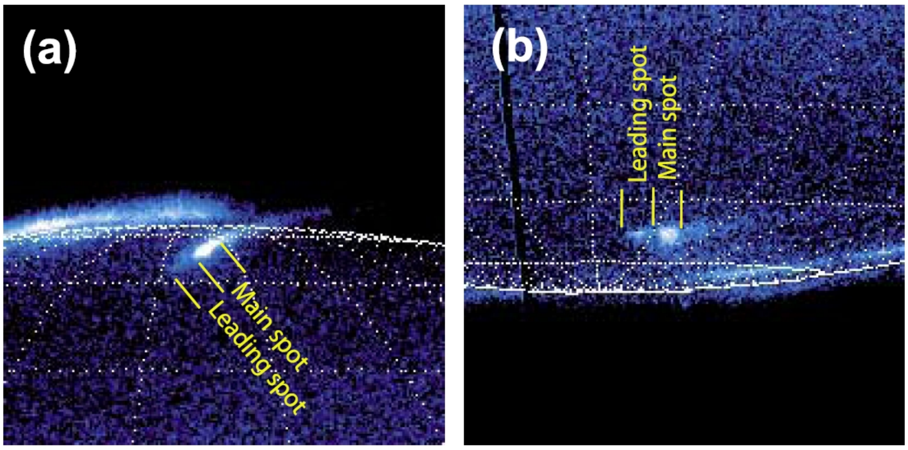


Figure 3.2: Example of leading spot (a) in the northern hemisphere (S3 longitude: ~50°) and (b) in the southern hemisphere. (S3 longitude: ~170°)

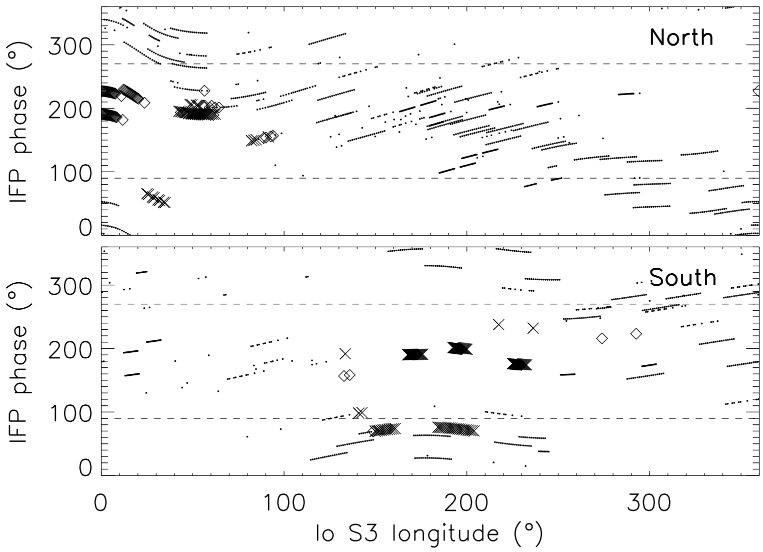


Figure 3.3: Occurrence of the leading spot in the northern hemisphere (Top panel) and in the southern hemisphere (Bottom panel). The dots represent the available observations, the crosses represent the cases where the leading spot is observed and the diamonds represent the uncertain cases.

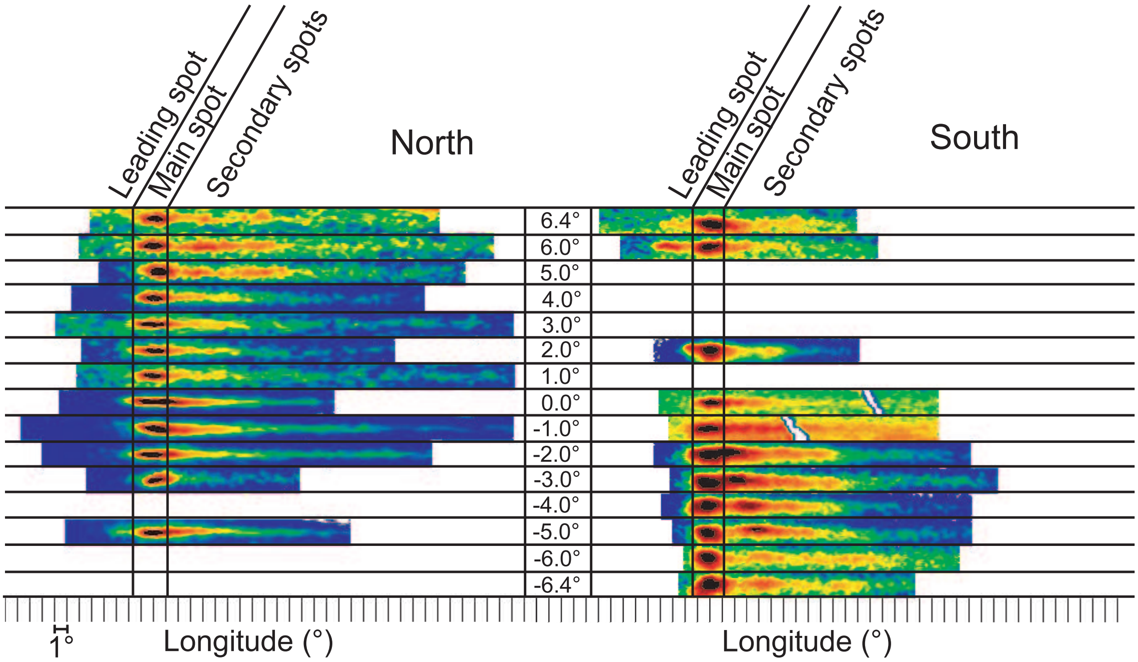


Figure 3.4: Scheme of the Io morphology as a function of the centrifugal latitude of Io in the torus. This Figure completes the scheme of the Io footprint morphologies as a function of the Io centrifugal latitude. The color table of each stripe is scaled individually for a clearer illustration of the 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.

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 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.

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°.

In Figure 3.4 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.

### 3.2.5 Interpretation and discussion

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 interpretation 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, 3) the bright southern secondary spot.

The main idea driving this interpretation rests on the assumption that the leading and the secondary spot 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 3.5). 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 relative 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.

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 there exists a direct relationship 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 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 in *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 3.5. 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

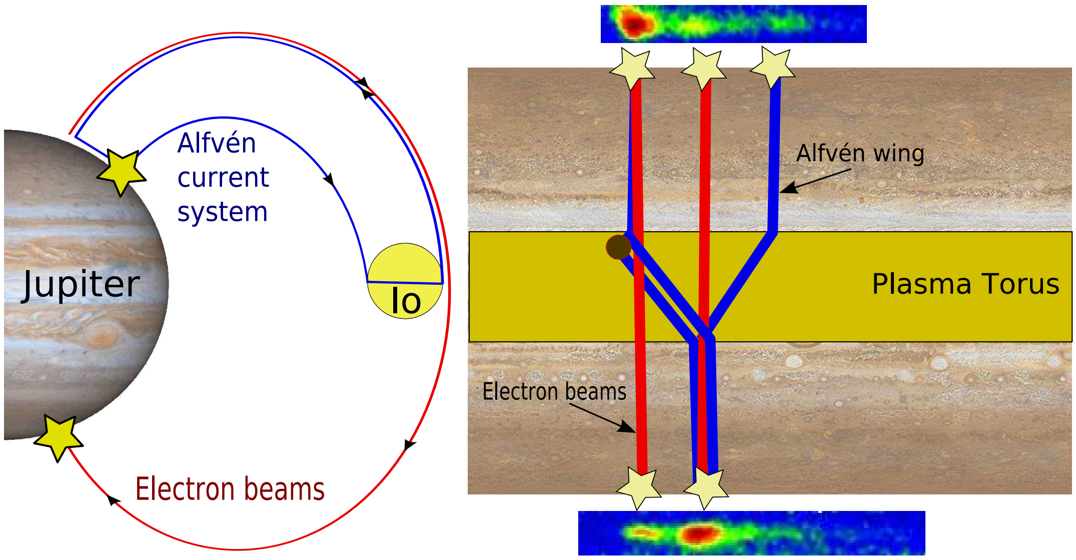


Figure 3.5: Illustration of the suggested mechanism that could explain the presence of the leading spot. The blue line shows the current flowing trough Io, then along the Alfvén wings and finally in the Jovian ionosphere. The electron beams are shown in red and the IFP spots are represented by stars. The left panel is 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. The right panel illustrates 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 from one hemisphere to the other, generating the leading and the first secondary spots.

a fully saturated Alfvén wing).

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.

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).

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).

The hypothesis of electron precipitation occurring upstream of the foot of the Alfvén wing has already been 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.

### 3.2.6 Conclusions

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.

## 3.3 Complementary results on the Io footprint morphology

### 3.3.1 Particular cases

We have seen that the interpretation of the footprint in *Clarke et al.* (2002) as the signature of an extended interaction region or as a combination of different spots like in *Gérard et al.* (2006) or in *Bonfond et al.* (2008) are radically different. *Clarke et al.* (2002) probably based their conclusions on the finding of extremely large single spots. We confirm that such morphologies are indeed observed in some particular cases in the southern hemisphere when Io lies around 120°-140° S3 longitude (Figure 3.6a). However, images of the IFP acquired in the same region but at a different time show a slightly different picture, with a smaller main spot preceded by a tongue of fainter emission and followed by an extended zone of fainter emissions (Figure 3.6b). The longitude range under consideration corresponds to a sector where Io moves northward from the torus center and where we expect the leading spot to slowly emerge from the main one. One possible explanation is that the relative intensity of the different spots can vary from a period to another and we suggest that the extended footprint morphologies are in fact the result of the combination of bright spots close to each other, but unresolved in the STIS images.

### 3.3.2 The leading spots as seen by New Horizons

A confirmation of the systematic appearance of the leading spot when Io is close to the torus boundary has been presented by *Gladstone et al.* (2007). We have seen that Spring 2007 HST observing campaign was motivated by the simultaneous fly-by

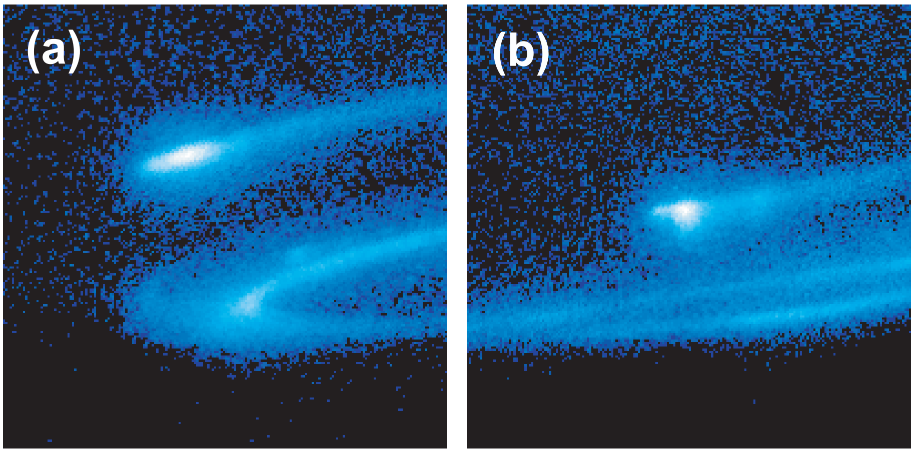


Figure 3.6: Comparison of two observations of the southern footprint in similar configuration. The System III longitude of Io is equal to 132.8° in the first case (a) and to 133.5° in the second case (b). In the first case, the spot appears as a very long but unique spot while in the second case, the main spot is reduced but preceded and followed by fainter emissions.

of Jupiter by the New Horizons probes en route to Pluto. During this fly-by, the LORRI panchromatic camera acquired images of the night side Jovian aurora in the visible wavelength (350 nm to 850 nm). Among these images, one shows a vertically elongated bright spot preceded upstream and followed downstream by two fainter spots. The upstream spot is called "precursor", following the terminology from *Grodent et al.* (2005b). In their study, the authors claim that no UV counterpart of this "precursor" spot can be seen in the HST images. Indeed, HST images have been acquired at the same time but only the Io tail can be seen on them, since the expected Io main spot phase angle is 52° (see table 4.1), that is out of the view of HST. However, HST/ACS images of the southern hemisphere taken when Io was in the same S3 sector clearly show the leading spot in this region. Thus the spots configuration on this LORRI image, including the secondary spot appearing downstream of the main emission, is totally consistent with the the general Io footprint morphology scheme we drew in this chapter.

### 3.3.3 Epilogue

The data acquired during the large "10862" observation campaign, considerably increased our Io footprint images database and provided us with images of the footprint in previously unexplored configurations. Dedicated observation orbits in

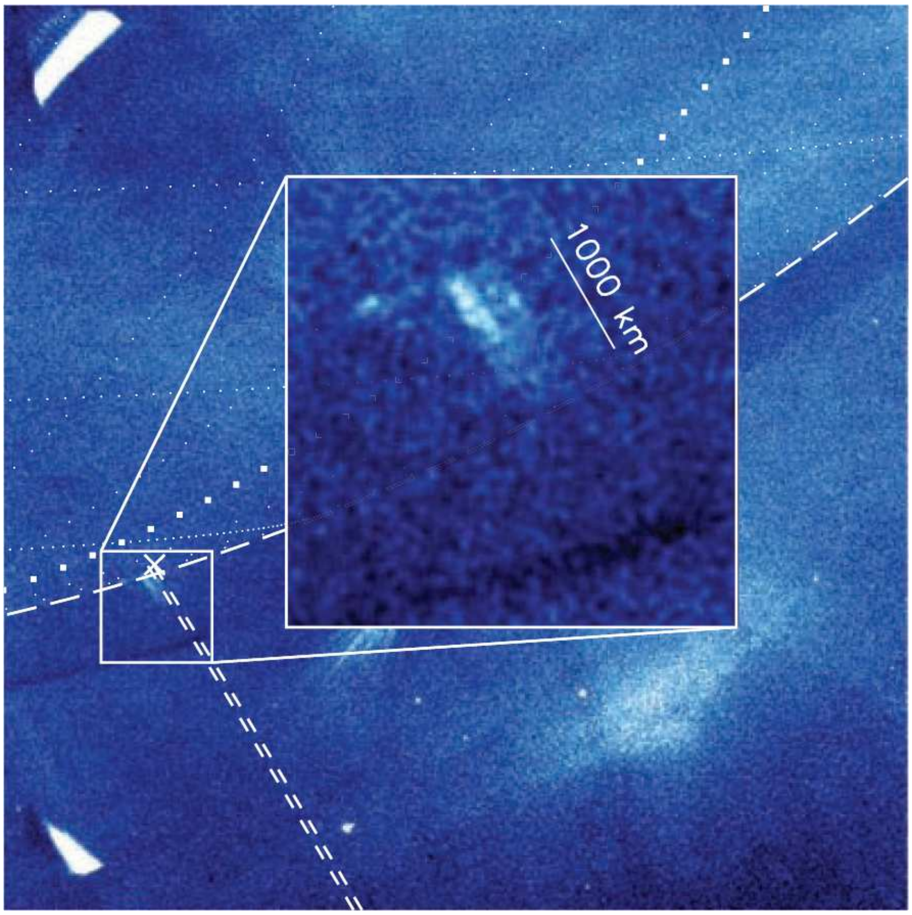


Figure 3.7: Zoom on the Io footprint as imaged by the LORRI pan-chromatic camera onboard the New-Horizons probe. (from *Gladstone et al.* (2007))

the 0° sector in the North and in the 150° sector in the South helped us to confirm and analyze the occurrence of a faint spot appearing upstream of the main Io spot. The coverage of the footprint evolution as a function of the position of Io in the Jovian magnetic field is now almost complete. It has become obvious that the footprint is composed of several spots (at least three), which move with respect to each other, plus a long fainter trail. I shall dedicate a complete Chapter to this later feature (Chapter 5).

It is possibly desirable to clarify here the terminology used in this thesis because there is considerable confusion in the literature. The term footprint is here used to designate the complete signature of the Io-Jupiter interaction in the Jovian aurorae. Depending on the context, Io footprint is used to designate both northern and southern features. For example, when I discuss electron acceleration mechanisms generating the Io footprint, I refer to the footprint phenomenon in general, whatever the hemisphere. However, I also use the term Io footprint to designate the Io-related auroral features in one specific hemisphere, particularly when I describe specific images (see Figure 3.7 for example). Thus, in each hemisphere, the footprint is composed of several spots and an extended downstream tail. The brightest spot is generally called the main spot. The downstream spots in the direction of the planetary rotation are called secondary spots. When a spot appears upstream of the main spot, as justified before, it is called the leading spot. The only exception concerns cases in the southern hemisphere for which one secondary spot progressively and momentarily becomes as bright or brighter than the main one (see Figure 1.8 in the South at -2.68° for example). However, since we can track the variations of the footprint brightness and since it is obvious that the brightness of the second spot is increasing with time, it would not make sense and it would be confusing to shift the appellations from one image to another in these very peculiar cases. These terms are phenomenological names for the different spots, free from any interpretation. It turned out that these names were confusing in the framework of the trans-hemisphere electron beams theory, because secondary spots can have different origins while leading and secondary spots could be caused by the same mechanism. Consequently, we proposed another terminology directly linked to this particular interpretation framework. The spot associated with the direct Alfvén wing is called the Main Alfvén Wing spot (MAW spot), the spot linked to the electron beam is logically designated as the Trans-hemisphere Electron Beam spot (TEB spot) and the spot related to Alfvén wave reflections on the torus boundaries is called the Reflected

Alfvén Wing spot (RAW spot).

Regularly during the short story of the Io UV footprint, new data substantially modified our understanding of the Io-Jupiter interaction. A signature of an extended interaction region or reflections of Alfvén waves cannot (at least not completely) explain the observed evolution of the IFP morphology as a function of the Io location. Consequently, we proposed a new interpretation of the IFP morphology, implying the precipitation of trans-hemispheric electron beams. These electron beams were already known to play a major role in the chemistry of the plasma ionization at Io (*Saur et al.*, 2002; *Dols et al.*, 2008). Our observations suggest that these beams also play a key role in the auroral footprint morphology. We have seen that a strong argument in favor of our new interpretation of the Io footprint morphology is the evolution of the inter-spot distances. The quantitative study of these distances will be the subject of a particular section of the next chapter.