

Chapter 8

Conclusions

8.1 Discussion

The Io footprint is a particularly spectacular signature of the Io-Jupiter electromagnetic interaction. In the present work, we demonstrated that a careful analysis of its characteristics can modify our comprehension of the ongoing physical processes. In the framework of this thesis we methodically analyzed the high resolution images acquired by the Hubble Space Telescope in the far UV domain. The very first step consisted in creating a complete and standardized database. Additionally to the image processing, we developed new techniques to retrieve accurate pointing information directly from the images themselves. At the same time as the data were gathered and processed, we generated an exhaustive catalog compiling technical, telemetry and ephemeris parameters. The database and the related catalog have been used extensively in many other studies based on the FUV images of the Jovian aurora.

Numerous models have been proposed to explain various aspects of the auroral footprint of Io. By rigorous measurements of the different footprint characteristics, we can validate or discard these theoretical ideas and thus improve our understanding of the phenomenon. However, in some cases, no existing model is able to explain the new observations. For example, the overall evolution of the IFP spots multiplicity in general and of the inter-spot distance in particular, did not match the expectations of the traditional models. We discovered that a faint spot was systematically seen upstream of the main spot in one hemisphere when only downstream spots were seen in the opposite hemisphere. Moreover, the minimum distance between the first two spots is observed when Io is in the torus center. These observations contra-

dicted all previous models and we thus proposed a new interpretation of the spots multiplicity. This contribution can be considered as the main result of this work. The Io footprint is formed of at least three individual spots and an extended trailing tail in each hemisphere. According to this new framework, one spot, generally the brightest one, is located at the foot of the direct Alfvén wing and we named it the Main Alfvén Wing (MAW) spot. Another spot is related to electrons accelerated away from the planet in one hemisphere, crossing the equatorial plane in the form of electron beams and precipitating in the opposite hemisphere. This spot is called the trans-hemispheric electron beam (TEB) spot. Finally the third spot is located at the foot of the reflected Alfvén wing (RAW) on the torus boundary and is called the RAW spot.

This new interpretation offers the advantage to explain many different observations within a common framework. The electro-magnetic interaction between Io and the incoming torus plasma generates Alfvén waves propagating towards Jupiter in the form of Alfvén wings. Part of these waves is reflected by the plasma density gradient while the remainder escapes the torus. Between the torus border and Jupiter, inertial effects become more and more important, resulting in the acceleration of electrons both toward and away from the planet. As a consequence, some electrons are directly propelled into the Jovian ionosphere at the foot of the Alfvén wing, creating the MAW spot. The electrons accelerated in the opposite direction then form an electron beam and cross the Io orbit plane, as observed in situ by Galileo instruments. Part of the electrons from the beam then precipitate into the opposite hemisphere, generating the TEB spot. When the reflected Alfvén wing reaches the opposite torus boundary, part of the waves can finally escape from the torus and generate the RAW spot. This interpretation explains both qualitatively and quantitatively the evolution of the inter-spot distances as a function of the position of Io in the plasma torus.

However, analysis of the Io footprint does not only provide information on the Io-Jupiter interaction. The detailed study of the Io footprint position brings useful constraints to improve the magnetic field models of Jupiter, since it provides us with information on the surface magnetic field which is inaccessible to magnetometric instruments on board flying-by or orbiting spacecraft. For example, the large divergence of the Io, Europa and Ganymede footpaths around 100° System III longitude in the northern hemisphere is an evidence for a large magnetic field anomaly in this sector. The analysis of the speed of the MAW spot revealed that this anomaly

might be accompanied by a fainter anomaly around 290° System longitude. Finally, we demonstrated that the current magnetic field models are not accurate enough to allow us to estimate the shift between the actual MAW spot position and the location of the foot of the unperturbed field lines passing through Io (i.e. the lead angle). This parameter was supposed to decide which far field interaction model, between the unipolar inductor and the ideal Alfvén wing models, was the best one. However, it appears that the inter-spot distance is a much more reliable tool which showed that none of these models is suitable, as stated above.

The increased amount of available data also allowed us to resolve some apparent contradictions in the literature concerning the the size of the Io MAW spot. Some authors suggested that the footprint had approximately the projected size of Io along unperturbed field lines. Others claimed that the footprint size was much larger and reflected the size of an extended interaction region at Io which includes the wake of stagnating plasma. Recognizing that the Io footprint is a three-dimensional structure made of several distinct features, we carefully selected the favorable observing geometries to derive the length (~ 900 km), the width (< 200 km) and vertical extent (scale height: ~ 400 km, peak altitude: ~ 900 km) of the MAW spot. The measured length is three to four times larger than the length of an unperturbed Io flux tube, in accordance with simulations taking the non-linear effects in the Alfvén waves propagation into account (*Jacobsen et al., 2007*). The width roughly corresponds to the projected width of Io, which also agrees with model expectations. The large scale height of the MAW emissions implies a broad distribution of the impinging electrons, which strengthens the hypothesis of electron acceleration mainly driven by inertial Alfvén waves. The peak altitude is nevertheless surprisingly high since spectral observations showed some methane absorption while the methane homopause was expected to lie around 250 km. Similar peak altitudes and scale heights have been found for the tail. We modeled the vertical emission profile based on several theoretical electron energy distributions and the best fit was achieved with a kappa distribution with $\kappa = 2.4$ and a mean energy of ~ 1 keV. This result is even more puzzling since a recent model postulated that a quasi-static electric field is the cause for the tail emission (*Ergun et al., 2009*), which would have led to a much more peaked electron distribution. This result suggests that the electron acceleration in the tail also originates from Alfvén waves. Finally, the altitude of the TEB spot appears to be 200 km lower than the MAW spot of the tail.

As far as the brightness of the IFP is concerned, we studied two different timescales

for which significant variations can be found. The shortest timescale is on the order of one minute and systematically observed fluctuations are on the order of 30% of the mean brightness but can reach up to 50%. Correlated variations of the MAW and the TEB spots suggested that the mechanism leading to these rapid fluctuations should be located close to the Jovian surface. On timescales of tens of minutes to hours, the different spots nevertheless appear to behave independently, confirming the hypothesis of a different origin for these spots. Additionally, even if the brightness peaks when Io is near the torus center, strong asymmetries are observed between the hemispheres. The global behavior favors the idea that the interaction strength at Io and/or the mixing of the spots are the main drivers for the MAW spot brightness, but the asymmetries suggest that the surface magnetic field strength also plays a significant role.

8.2 Future work and perspectives

So far, the new measurement method for the spots brightness and emitted power only provided preliminary results and additional ones are expected in the near future. When its reliability will be fully assessed, even for faint emissions, it will be interesting to study in detail the evolution of the brightness for all the spots, which could help confirming the scenario of the trans-hemispheric electron beams.

Indeed, our new interpretation of the secondary spot as being related to trans-hemispheric electron beams solves many problems related to the understanding of the Io-Jupiter electro-magnetic interaction. For example, this interpretation simultaneously explains the evolution of the inter-spot distances in the ionosphere and the observation of electron beams at Io. However, this model requires further improvements to be completely validated. First of all, this interpretation postulates that electrons are accelerated in both directions in the acceleration region. If bi-directional electron acceleration is known to be possible in the presence of inertial Alfvén waves, it should nevertheless be demonstrated 1) that a sufficient amount of energy can escape the torus in the form of Alfvén waves and 2) that the inertial Alfvén waves are accelerating the electrons with an adequate efficiency in both directions. Galileo in situ measurements of radio emissions suggested that filamentation of the Alfvén waves should take place in the plasma torus (*Chust et al., 2005*). *Hess et al.* (in preparation) *Hess et al.* (in preparation) claim that this filamentation is indeed necessary for the energy to leave the torus in the form of Alfvén waves but

that it also considerably increases the efficiency of the electron acceleration at high latitude.

Another theoretical issue is the location of the observed electron beams. These beams have not only been observed downstream from Io but also above the polar caps. The unipolar inductor scenario could explain why the beams are falling back on Io, but it is unable to explain the occurrence of secondary spots. On the other hand, the ideal Alfvén wing model would locate the beams much downstream from the places where they were observed. *Jacobsen et al.* (submitted) show that simulations realistically computing the non-linear effects on the Alfvén waves propagation can reproduce convincingly both the location of the electron beams at Io and the inter-spot distances in the Jovian ionosphere.

Other issues deserve further attention. One of the most intriguing finding of this thesis consists in the short timescale variations and the correlated brightness variations of the MAW and the TEB spots in the southern hemisphere. One important question on these rapid variations concerns their periodicities. Are they related to bursty events or are they repetitive? If they are quasi-periodic, is this period varying and what could drive these variations? The simultaneous evolution of adjacent spots suggests that the mechanism driving this short timescale variability is located relatively close to the planetary surface. However, the number of observed cases is extremely limited and more observations are required to confirm this observation and to precise the conditions needed for these simultaneous variations. For example, we would like to know if the distance between the spots should remain below a given threshold. Thanks to the recent restoration of the STIS instrument, new time-tag sequences of the southern Io footprint have been acquired in late August-early September 2009 with the above questions in mind, but the data have not been processed yet.

Another interesting topic is the link between the Io footprint and the Io related decametric radio emissions. Our new Io reference contour and the measured inter-spot distances are of considerable help in this domain since it pinpoints the exact spots location when radio emissions are observed (*Hess et al.*, in preparation). Additionally, the magnetic field anomalies that we highlighted in this work and the subsequent magnetic field model improvements could also be useful to better understand location of the active regions as well as the shape of the radio arcs on the dynamic spectra.

Moreover, footprint observations in the infrared domain, and particularly spec-

tra, could provide a wealth of precious information on the state of the atmosphere. We found that both the hydrocarbon profile and the pressure-altitude relationship in the polar regions in general and at the Io footprint are not similar to the ones measured near the equator. Information on the temperature and on the hydrocarbon profile could be retrieved from these spectra. Simulations of the atmospheric response to the sudden and massive input of energy related to the Io footprint could also be necessary to fully understand the observations. Finally, no systematic analysis of the Io footprint has been made on IR auroral images. Future studies could verify that the overall morphology is evolving similarly to the FUV morphology, and, possibly more interestingly, that the relative spot brightness is also varying in the same way.

8.3 Final words

The present work is currently the most detailed study of the Io UV footprint. The measurements reported here and their interpretation helped to clarify some controversial issues, dissipated some misunderstandings and significantly modified our view of the Io-Jupiter interaction in general and of the Io footprint in particular. One of the most striking results, if confirmed, is the identification of auroral emissions caused by electrons originating from the opposite hemisphere. Similar emissions are expected to occur on Earth as well (e.g. *Carlson et al.*, 1998), but they are much more complex to demonstrate since we cannot track the electron beams from one hemisphere to the other. Moreover, electron beams are also observed in the Kronian magnetosphere (*Saur et al.*, 2006; *Mitchell et al.*, 2009) as well as in other places in the Jovian magnetosphere (*Mauk and Saur*, 2007), suggesting that anti-planetward electron acceleration is a universal process. However, contrary to all these examples, the geometry of the field lines is known with a much better accuracy at Io, which allows us to relate more easily auroral and equatorial observations. Consequently, the Io-Jupiter case is not only the paradigm of systems consisting in a conducting celestial body orbiting a strongly magnetised one. It also appears to be a natural laboratory to study some physical processes related to Alfvén waves, such as their reflection on density gradients, their filamentation and the electron acceleration that is related to them.