Satellite-induced electron acceleration and related auroras

S. L. G. Hess[1,2]

P. A. Delamere[2]

Abstract. Several cases of interactions between planetary magnetospheres and satellite atmospheres have been observed in the giant planet magnetospheres. Io, Europa, Ganymede and Enceladus generate observable auroral emissions on their parent planet. This implies an efficient power transfer between the satellite – where the interaction occurs – and the planet – where the emission occurs. In this chapter, we discuss the power generation at the satellite, the transport of energy and momentum along the magnetic field lines via Alfvén waves and the transfer of wave power to electrons. We relate the power generated at the satellite to the power of the observed auroral emissions.

1. Introduction

Auroral evidence of interactions between satellites and the magnetospheres of their parent planet have been gathered since the discovery of the Io-related Jovian decameter radio emissions [*Bigg*, 1964]. Infrared observations of Jupiter revealed aurorae at the foot of the magnetic field lines crossing Io [*Connerney et al.*, 1993]. Later observations were performed in the UV [*Clarke et al.*, 1996; *Prangé et al.*, 1996], which revealed finer structures in the Io footprint [*Gérard et al.*, 2006], as well as auroral footprints related to Europa and Ganymede [*Clarke et al.*, 2002; *Grodent et al.*, 2006, 2009]. Claims of auroral emissions triggered by Callisto have also been made, based on radio observations [*Menietti et al.*, 2001]. Recently, an Enceladus auroral footprint on Saturn was observed [*Pryor et al.*, 2011]. It thus appears that the satellite-triggered aurorae are a common phenomenon in our solar system.

Although the origin of the interaction was established as being the motion of the satellite relative to the planetary magnetic field [*Goldreich and Lynden-Bell*, 1969], its Alfvénic nature was only revealed decades later [*Neubauer*, 1980; *Goertz*, 1983], and the details of the interaction are not completely understood. Nevertheless, progress has been achieved, thanks to in-situ spacecraft measurements and improved observations of the auroral emissions they trigger. Radio and UV observations of the Io aurora reveal fine structures: quasi-periodic radio bursts and bright spots inside the footprint in the UV. Both tell the same story: the interaction between Io and Jupiter is carried by Alfvén waves which periodically accelerate electrons, generate quasi-periodic radio bursts [*Su et al.*, 2006; *Hess et al.*, 2007a] and bounce between interfaces in the system leaving auroral spots at each bounce on the Jovian ionosphere, as illustrated in panels a-b of Fig. 1 [*Gérard et al.*, 2006; *Bonfond et al.*, 2009].

The details of the auroral structures related to the satellite-magnetosphere interactions are discussed in the chapter by Bonfond (this volume). In the present chapter, we discuss the current generation and propagation between the satellites and the planets, and how they trigger the electron accelerations needed to power the observed auroral emissions.

[1]now at: LATMOS - Université Versailles St-Quentin, IPSL/CNRS, France

[2]LASP - University of Colorado at Boulder, USA

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2. Local interaction and current generation

Satellite-magnetosphere interactions occur when a satellite orbits deep inside the magnetosphere. The satellite moves with a velocity v_{sat} relative to the ambient magnetic field B_{sat}, which leads to the generation of an electric field E_{sat} across the satellite :

$$E_{sat} = -v_{sat} \times B_{sat}. \tag{1}$$

If the satellite is conducting, this electric field generates a current (panel c of Fig. 1). This mechanism was first proposed by *Piddington and Drake* [1968] and soon thereafter *Goldreich and Lynden-Bell* [1969] to describe the Io-Jupiter interaction, known at that time through Io-modulated radio emissions [*Bigg*, 1964]. The brief and over-simplified description of the current generation we give here is sufficient to give a correct estimate of the power generated at the satellite. However, the local interaction in the satellite vicinity may involve contributions from a magnetic field internal to the satellite [*Gurnett et al.*, 1996; *Kivelson et al.*, 1996], or to magnetospheric plasma flow perturbations caused by several processes, such as atmospheric sputtering, electron impact ionization or most importantly charge exchange [*Saur et al.*, 1999, 2002a; *Saur*, 2004; *Delamere et al.*, 2003; *Dols et al.*, 2008]. In any case, the current generator is the region which is not in corotation with the magnetic field (Panel c of Fig. 1).

To compute the current running across the interaction region one needs to know the conductivity of the whole current circuit. Namely, the Pedersen conductivity of the planet's ionosphere – where the current is supposed to close – and the conductivity of the interaction region, usually limited to the Pedersen conductance of the satellite ionosphere [*Saur*, 2004]. The conductance along the magnetic field lines, which can be estimated using the Knight relation [*Knight*, 1973] or one of its derivatives [*Ergun et al.*, 2009, and chapter by Ray and Ergun in the present book], was at first neglected, except for estimating the parallel electric field accelerating the auroral electrons. Models of electron acceleration by electric potential structures along Io flux tube have been performed [e.g. *Su et al.*, 2003].

However, these calculations were missing an important factor in that they assumed a steady-state current circuit. In a magnetized plasma, the information is spread across current circuits by Alfvén waves. Hence, a steady-state current system can only be established after an Alfvén wave has propagated at least once along the whole circuit. In the mean time, the current system is transient, and the current is carried by Alfvén waves rather than by global motion of the electrons [*Neubauer*, 1980; *Goertz*, 1983, panel b of Fig. 1]. This leads to a different calculation of the current delivered by the satellite-magnetosphere interaction, and to a different way of accelerating electrons. In the present chapter we ignore the case of a quasi-steady-state interaction between the satellite and magnetosphere and concentrate on the transient circuits, which are responsible for all cases of satellite-related aurora observed so far, although a weaker steady-state current may exist in the satellite wake.

The transient current system involving Alfvén waves leaves an imprint on the morphology of the Io-related UV aurora [*Gérard et al.*, 2006, panel a of Fig. 1], which present several spots with decreasing intensities. These spots are understood as the footprints of the Alfvén wing generated at Io, which bounces several times [*Neubauer*, 1980; *Goertz*, 1983; *Bonfond et al.*, 2009, panel b of Fig. 1]. An elongated continuous tail is added to the spots, which is thought to be generated by a steady-state current system [*Ergun et al.*, 2009]. In the UV, the brightness of the main spots dominate the other features, which implies that the Alfvén waves carry a lot of power. The current system associated with the diffuse tail and the secondary spots involves the nonlinear dispersion of Alfvén waves with time, reflections in the plasma torus [*Jacobsen et al.*, 2007, 2010], and the nonlinear build-up of the steady-state current. The Io footprint tail, which is several tens of degrees long, emits more power than the main spot although its brightness is far weaker [*Gérard et al.*, 2006]. The power partition between the main spot and the other features of the other satellite footprints is not known because of the low tail brightness.

Satellite current circuits are large ($> 10^5$ km) and the duration of the interaction between the satellite and a given flux tube – estimated as the time needed by a magnetic field line to pass the interaction region – is short (typically 1 minute). Alfvén waves propagating at velocities close to the speed of light would be able to establish a steady-state current system in a much smaller timescale than the interaction duration. However, the Alfvén velocity depends on the magnetic field strength B and the mass density ρ of the medium through which they travel:

$$v_a = \frac{B}{\sqrt{\mu_0 \rho + \frac{B^2}{c^2}}} \tag{2}$$

At the giant planets, this relativistic expression of the Alfvén velocity is necessary, because v_a is close to the speed of light out of the equatorial plane in the inner magnetosphere of these planets. By contrast, the satellites responsible for observed aurorae all are embedded in relatively dense plasma sheet, which can be created by the satellite itself (Io, Enceladus) or by a satellite on an inner orbit (Io for Europa and Ganymede). This results in a large density in the equatorial plane, and hence to small Alfvén velocity (as low as a few hundred of km/s). The current systems associated with the known satellite magnetosphere interactions are thus mostly transient and carried by Alfvén waves, although a weaker steady-state current may exist in the satellite wake.

The Alfvén wave packet is generated at the satellite as a perturbation of the magnetic field because of the current running across the interaction region. This current, which cannot depend on remote conductances (e.g. Pedersen conductance of the planet ionosphere) is then mostly limited by the Pedersen conductance around the satellite Σ_P (from the satellite's ionosphere, magnetosphere or a volcanic plume) and the Alfvén conductance Σ_A [*Neubauer*, 1980; *Goertz*, 1983], given by:

$$\Sigma_A = \sqrt{\frac{\rho}{\mu_0 B^2}} \tag{3}$$

where ρ is the plasma density. The integrated current carried by the Alfvén waves can be obtained from the Ohm current-voltage relation. According to the calculations of [*Saur*, 2004], the current for each hemisphere is :

$$J \sim 4E_{sat}R_{sat}\frac{\Sigma_A \Sigma_P}{2\Sigma_A + \Sigma_P} \sim 4E_{sat}R_{sat}\Sigma_A \ (for\ \Sigma_P >> \Sigma_A) \tag{4}$$

where R_{sat} is the satellite radius. In all known cases of satellite-magnetosphere interactions, the conductance around the satellite is large ($\Sigma_P >> \Sigma_A$). The power radiated as Alfvén waves by the satellite-Jupiter interaction is estimated from the current:

$$P \sim (4E_{sat}R_{sat})^2 \Sigma_A \tag{5}$$

Table 1 shows the power estimates for several Jovian and Kronian satellites, computed using Eq. 5 and the magnetic field and density parameters given by *Neubauer* [1998] (Jovian satellites) and *Saur and Strobel* [2005] (Kronian satellites). In the Ganymede case, we used $R_{sat} = 2R_{Ganymede}$ to take into account the Ganymede magnetosphere.

Both the bounce time of the Alfvén wave and the Alfvén wave power are proportional to v_a^{-1} (the latter through Σ_A), meaning that a low Alfvén velocity ensures a long and intense transient regime and that satellite-magnetosphere interactions can generate intense auroral spots. However, the power transfer efficiency from satellite to auroral electron precipitation has to be of the order or larger than 10% according to the estimates of the power generated at the satellites, and to the estimates of the power precipitated into the ionosphere (see Table 1).

Early computations [*Wright*, 1987; *Delamere et al.*, 2003] showed that ~ 80% of the Alfvén wave power is reflected back in the Io torus at its boundary, long before reaching the Jovian auroral region where the acceleration is thought to occur (panel d of Fig 1 and section 4). The reflection is due to the large gradient of the Alfvén velocity between the inside of the plasma torus and the outside, where the Alfvén velocity is approximately the speed of light. This means that a lower Alfvén velocity in the torus has two opposite effects regarding the power carried by the waves to the planet ionosphere, summarized by panel a of Fig. 2: (1) increasing the transition regime duration and giving a large power to the Alfvén waves, and (2) inducing a reflection of the Alfvén wave power before it reaches the planet ionosphere.

3. Alfvén wave propagation

On their way to the planet ionosphere, the Alfvén waves that carry the current encounter several changes in the plasma parameters, which lead to strong variations of the Alfvén wave phase velocity (e.g. increasing magnetic field flux, plasma torus boundaries, planetary ionosphere,..). The Alfvén wave phase velocity is given by [*Lysak and Song*, 2003]:

$$v_{\phi,a}^2 = v_a^2 \frac{(1 + k_\perp^2 \rho_s^2)}{(1 + k_\perp^2 \lambda_e^2)} \tag{6}$$

where $k_\perp$ is the perpendicular component of the wavevector, ρ_s is the ion acoustic gyroradius and $\lambda_e = c/\omega_{pe}$ is the electron inertial length. The variation of the plasma parameters causes the partial reflection of the wave packet as a function of the wavelength. Early computations used the WKB (short wavelengths) or the discontinuity (long wavelengths) approximations to compute the reflection coefficient, which led to very weak or very strong reflections, respectively. The range of wavelengths of the Alfvén waves generated by the satellite-planet interactions cover an intermediate range, not described by either of the above approximations [*Wright*, 1987]. An approximation for the reflection coefficient describing the intermediate wavelengths, and in agreement with WKB and discontinuities approximations is given by *Hess et al.* [2010]:

$$R_\epsilon(s,\mathbf{k}) = \frac{1}{\lambda_\parallel}\left(\int_{s-\frac{\lambda_\parallel}{2}}^{s+\frac{\lambda_\parallel}{2}} \frac{\nabla_s \ln(c/v_{\phi,a}(\mathbf{k}))}{2} ds\right)^2 \quad (7)$$

This expression explicitly depends on the parallel wavelength ($\lambda_\parallel$), and depends on the perpendicular wavelength through $v_{\phi;a}$ (Eq. 6): short wavelengths are slightly reflected whereas long wavelengths are strongly reflected. Since the reflection coefficient depends on the parallel wavelength, the wavelength distribution of the Alfvén waves close to the satellite plays a crucial role.

The simplest distribution expected for a satellite-magnetosphere interaction is a gaussian spectrum centered on waves with a satellite length-scale $k_0 = \pi/R_{sat}$:

$$f_0(k) \propto e^{-\frac{(k-k_0)^2}{2k_0^2}} \quad (8)$$

However, *Chust et al.* [2005] provided observations showing a possible filamentation of the Alfvén waves in the Io flux tube. Then, the wavelength distribution of the Alfvén waves should follow a power law corresponding to the turbulent filamentation of the previous gaussian distribution [e.g. *Champeaux et al.*, 1998; *Sharma et al.*, 2008]. Power law distributions generally assume a Kolmogorov cascade, implying a spectral index of $-5/3$. This kind of cascade is, strictly speaking, only valid for non-magnetized plasma. For highly magnetized plasma a spectral index of -2 has been theorized by *Galtier* [2009] and has been observed by *Saur et al.* [2002b] at Jupiter. However, the threshold at which the spectral index changes is largely unknown, and the only published observation of filamented Alfvén waves [*Chust et al.*, 2005] was unable to provide an estimate. In any case, the distribution presents a power-law spectrum between the energy injection scale k_0 (satellite length scale) and the dissipation (ionic) scale $k_i = \omega_p/(m_i c)$:

$$\begin{aligned} f_{1;\alpha}(k) &\propto e^{-\frac{(k-k_0)^2}{2k_0^2}} \quad for\ k < k_0 \\ f_{1;\alpha}(k) &\propto k^{-\alpha} \quad for\ k_0 > k > k_i \end{aligned} \quad (9)$$

with $\alpha = 5/3$ or 2 depending on the spectral index assumed for the distribution. The gaussian distribution is hereafter referred to as the long-scale distribution, in comparison to the power law distributions. The Alfvén wave power transmitted from the satellite to the acceleration region is computed by numerically integrating the Alfvén wave reflection coefficients along the magnetic field lines. The dependence of the transmitted power on the parallel wavelength is pronounced, whereas the perpendicular wavelength plays a less important role, even if smaller wavelengths are slightly less reflected than larger ones [*Hess et al.*, 2010, 2011c].

Table 1 shows the power integrated over the Alfvén wavenumber k transmitted along the magnetic field lines from the satellite to the acceleration region for the f_0, $f_{1;5/3}$ and $f_{1;2}$ distributions. To compute these values, we used the VIP4 [*Connerney et al.*, 1998] and SPV [*Davis and Smith*, 1990] internal magnetic field models for Jupiter and Saturn, respectively. The density profiles along the Jovian satellite flux tubes were approximated from the torus models of *Bagenal* [1994] and *Moncuquet et al.* [2002] and the ionospheric profile from the simulations by *Su et al.* [2003]. The density profile along the Kronian satellite flux tubes are approximated from Enceladus torus models [*Sittler et al.*, 2008; *Fleshman et al.*, 2010, and references therein] and assumes a Saturn ionosphere scale-height of ∼1600 km.

The power transmission along the field lines for the long-scale f_0 distribution varies more than for the filamented $f_{1;\alpha}$ distributions, because the power in the f_0 distribution is more concentrated at longer wavelengths, so that a slight increase of the gradient of the Alfvén velocity will have greater impact. The power-law distributions have typical transmission of 35%-50% for the Jovian satellites and 25%-30% for the Kronian satellites.

4. Particle acceleration

Most of the electron acceleration occurs at high latitudes [*Jones and Su*, 2008; *Hess et al.*, 2010, 2011c] and is due to the parallel electric field associated with the Alfvén waves. The parallel electric field is due to the inertial terms in the Alfvén phase velocity (Eq. 6) and thus can be approximated by [*Lysak and Song*, 2003]:

$$\delta E_\parallel \simeq \omega_a k_\perp \lambda_e^2 \delta B \quad (10)$$

where ω_a is the Alfvén frequency, and δB the magnetic field perturbation associated with the wave. The perpendicular scale is assumed proportional to the flux tube cross-section ($k_\perp \propto B^{1/2}$), to be consistent with an Alfvén wave propagating inside a converging flux tube. Smaller perpendicular wavelengths result in stronger acceleration. The parallel electric field profiles for the inertial Alfvén waves peak where the density is low and the magnetic field intense. This corresponds to altitudes between ∼0.5 and ∼1 planetary radius from the planet's ionosphere [*Hess et al.*, 2010, 2011c, and references therein], depending on the planet and satellite involved, and on the magnetic field and ionospheric density models. Panel d of Figure 1 shows a typical profile of the parallel electric field associated with Alfvén waves whose wavelength is $\lambda_\parallel = \lambda_\perp = 0.1\ R_{sat}$ (Io case), and computed using the density profile along the field line shown below.

The resonance of the inertial Alfvén wave with the electrons in the auroral regions is considered in many models of particle acceleration at Earth [*Watt and Rankin*, 2008]. In the terrestrial case, the Alfvén velocity (∼0.1 c) is comparable to the particle velocity ($1-10$ keV, ∼0.1 c) so that a resonant wave-particle interaction is possible. However, at Jupiter and Saturn the Alfvén phase velocity (∼c) is much larger than the characteristic particle velocities (∼0.1 c) due, in part, to the strong planetary magnetic field. Therefore, a resonant interaction is generally not possible, particularly for a wavelength spectrum scaled by the satellite radius.

Because most of the wave power in the acceleration region consists of parallel wavelengths ($\lambda_\parallel$) on the order of or larger than the gradient scale length of the parallel electric field ($\|\delta E_\parallel\|$), the electron acceleration is due to the limited extent of the electric field. The long parallel wavelengths ensure that electrons accelerated during one phase of the wave can escape the acceleration region before the wave phase changes. In the opposite limit, where $\lambda_\parallel << \|\delta E_\parallel\|$, the electrons would be accelerated and subsequently decelerated with no net particle flux out of the acceleration region. The electron distribution obtained from this acceleration process has an almost unperturbed core with extended tails parallel to B, i.e. a Kappa-like or a beam-like distribution [see discussion in *Hess et al.*, 2010]. The acceleration process is independent of the direction of the Alfvén wave propagation, accelerating electrons both toward and away from the planet. This implies the existence of anti-planetward electron beams, which are observed in the wakes of Io [e.g. *Williams et al.*, 1996; *Frank and Paterson*, 1999; *Mauk et al.*, 2001] and Enceladus [*Pryor et al.*, 2011]. The exact shape of the electron distribution may not be computed analytically, but is computed numerically [*Swift*, 2007; *Hess et al.*, 2007a]. We assume that (1) the acceleration occurs where the parallel electric field peaks, (2) all electrons crossing the acceleration region (assumed infinitely small along the magnetic field) gain the same energy from the parallel electric field associated to the Alfvén wave, (3) the acceleration happens only once for each electron and stands for half a period of the wave. The power transferred from the Alfvén wave to the particles is then [*Hess et al.*, 2010]:

$$P_e = n v_{th} \frac{m}{2} \left(\frac{\pi}{2} \frac{(-e)\delta E_{\parallel}}{\omega_a m} \right)^2 A = \frac{\pi^2}{8} \frac{\omega_p^2}{\omega_a^2} \epsilon_0 v_{th} \delta E_{\parallel}^2 A \quad (11)$$

with A the cross-section of the flux tube, n the density in the acceleration region and v_{th} the electron thermal velocity. The power of the wave on a section of the flux tube is given by the wave's Poynting flux:

$$P_w = \frac{\delta E \times \delta B}{\mu_0} A = \frac{v_{\phi,a} \delta B^2}{\mu_0} A \quad (12)$$

Using Equations 10 and 12, the efficiency of the transfer of power from the satellite interaction to the particles – including the loss by partial reflections of the wave – is given by [*Hess et al.*, 2010, 2011c]:

$$\frac{P_e}{P_w} = \int \min \left(\frac{\pi^2}{8} \frac{v_{th}}{v_{\phi,a}} k_\perp^2 \lambda_e^2 \ ; \ 1 \right) T(\mathbf{k}) f(\mathbf{k}) d\mathbf{k} \quad (13)$$

where $T(\mathbf{k})$ is the Alfvén wave power transmission function computed numerically from Equation 7 by integrating the wave reflection coefficient along the magnetic field line. The *min* function assures that electrons cannot gain more power than what can be provided by the wave. The power transfer efficiency depends not only on the Alfvén wave characteristics and on the magnetic field, but also on the warm plasma density and temperature in the acceleration region. The temperature for the warm electrons is generally assumed to be a few hundreds of eV in both cases [*Bagenal*, 1994; *Moncuquet et al.*, 2002; *Su et al.*, 2003; *Sittler et al.*, 2008; *Fleshman et al.*, 2010]. At Jupiter, the warm component density is about 1 cm^{-3} [*Moncuquet et al.*, 2002], whereas at Saturn its varies between ~ 0.3 cm^{-3} at Enceladus and ~ 0.1 cm^{-3} at Rhea [*Saur and Strobel*, 2005, and references therein].

The efficiency of the power transfer from the satellite interaction to the electrons is shown in Table 1. For each satellite, the long-scale distribution leads to an acceleration efficiency that is orders of magnitude lower than that of the filamented cases. Filamented distributions transfer power at rates ranging from 2% up to 25%, which means that in some cases (like Rhea) almost all the power reaching the acceleration region is transferred to electrons. These differences are explained by the dependence of the acceleration efficiency on $\lambda_e^2 k_\perp^2$ (Eq. 13), which depends on the interaction parameters as:

$$\lambda_e^2 k_\perp^2 \propto \frac{\mu}{n R_{sat}^2} \quad (14)$$

where μ is the mirror ratio, i.e. the ratio between the magnetic flux at the top of the planet's ionosphere and at the satellite. Thus, smaller satellites generate a more efficient electron acceleration, denser flux tubes generate less efficient acceleration and a larger mirror ratio increases the efficiency.

Since the acceleration occurs in both directions, only half of the power is transmitted to electrons directly precipitating in the ionosphere. The other half forms transhemispheric electron beams (TEB) precipitating in the opposite hemisphere [*Bonfond et al.*, 2008]. These TEB spots are distinct from the main Alfvén wing (MAW) spot in Jovian satellite cases due to the tilt of the jovian magnetic dipole. The Saturn magnetic dipole is aligned with the rotation axis. Hence, the Kronian satellites TEB and MAW spots form a single spot, powered half by the electron acceleration in their own hemisphere, and half by the electron acceleration in the opposite hemisphere. Accordingly, electron beams are observed at the equator close to Enceladus [*Pryor et al.*, 2011, and chapter by Gurnett and Pryor in the present book].

5. Discussion

5.1. Comparison with observations

Table 1 shows estimates of the power precipitated into the main spots obtained from observations of the four known cases of satellite-magnetosphere interactions. Most of these estimates come from UV observations [*Bonfond et al.*, 2009; *Grodent et al.*, 2006, 2009; *Pryor et al.*, 2011]. Only the power emitted by the Io interaction can be estimated over a large spectrum of radiation, extending from UV to low frequency radio [*Queinnec and Zarka*, 2001]. Moreover the plasma environment surrounding Io has been explored by Galileo, unveiling the existence of keV electron beams accelerated close to Jupiter and associated with the main UV spot [e.g. *Williams et al.*, 1996; *Frank and Paterson*, 1999; *Mauk et al.*, 2001]. From these observations, *Hess et al.* [2010] estimated the power transmitted by the main Alfvén wing to the electrons to be a few 10^{10} W, both toward Jupiter and anti-planetward. Europa [*Clarke et al.*, 2002; *Grodent et al.*, 2006], Ganymede [*Clarke et al.*, 2002; *Grodent et al.*, 2009] and Enceladus [*Pryor et al.*, 2011] footprint brightness in the UV can be translated to precipitation power according to the calculation presented by *Gérard and Singh* [1982] (1 $mW.m^{-2}$ gives 10 kR) and assuming a surface for spots which are not resolved (we used the surface of the interaction region magnetically mapped on the planet).

In any case, the filamentation of the Alfvén waves explains the power emitted in the UV by the satellite-magnetosphere interactions.

Such computations for satellite-magnetosphere interactions that have not yet been observed are also instructive. According to Table 1, Callisto emissions should only be 2-3 times weaker than Europa and Ganymede. This estimate supports claims of Callisto radio emissions [*Menietti et al.*, 2001]. At Saturn, Tethys and Dione interactions should lead to stronger emissions than Enceladus, but they are not observed. These satellites may have low Pedersen conductances [*Saur and Strobel*, 2005]. The calculations, performed assuming $\Sigma_P >> \Sigma_A$, may overestimate the power generated at these satellites by orders of magnitude. In the Rhea case, the Pedersen conductivity of the satellite ionosphere should not significantly impact the result [*Saur and Strobel*, 2005]. One possible explanation for the non-detection of a Rhea footprint may then be that the faint Rhea spot is close to the bright and highly variable UV emissions from the main auroral oval of Saturn.

5.2. Further studies

We presented above the power transfer between the satellite interaction and the electrons responsible for the main (MAW) and trans-hemispheric electron beams (TEB) spots. The numerical results we present here correspond to a given longitude of the satellite. However, in the case of the Jovian satellites, the tilt of the magnetic field introduces a modulation of the interaction with longitude. The position of the satellites relative to the torus center varies with the satellite longitude, and the magnetic fields at the satellites and the mirror ratios between the satellite and the acceleration region are also modulated. The brightness modulation of the Jovian satellite footprints in UV is observed [*Serio and Clarke*, 2008; *Wannawichian et al.*, 2010]. Models of Jupiter's magnetic field [*Connerney et al.*, 1998; *Hess et al.*, 2011a] predict a variation of the mirror ratio μ by almost a factor of 2 with longitude, which translates as a modulation of almost the same amplitude of the footprint brightness (Eq. 14). This modulation is close or even slightly larger than that due to the modulation of the power generation (Eq. 5). On-going work is being performed to study in detail the origin and amplitude of the footprint brightness modulation with longitude.

The reflection coefficient along the Io flux tube peaks in a narrow region around 1 R_J of the torus center (at torus borders). This narrowness is needed to form a coherent structure (wing). However, Alfvén waves are reflected along the whole field lines. There is thus part of the Alfvén wave packet power which does not contribute to the brightness of the MAW, TEB or to reflected Alfvén wing (RAW) spots, but rather powers the footprint tail. The Alfvén wave interference pattern in Io's wake was modeled by *Jacobsen et al.* [2007, 2010] (panel b of Fig. 1), but with a simplified model of the density and magnetic field variation between Io and Jupiter, and without taking into account Alfvén wave filamentation and dissipation by electron acceleration. Hence, the actual morphology of the current system in the wake of the satellites still remains to be modeled.

The dissipation of the Alfvén wave power does not only occur by direct acceleration of the electrons. Currents are generated when the Alfvén waves reach the planet ionosphere, generating currents and power losses by Joule heating [*Codrescu et al.*, 1995], generating Infrared emissions [*Lystrup et al.*, 2007]. Moreover, non-linearities in the ionospheric response to the current carried by the Alfvén waves leads to the generation of electric potential structures, which produce an additional acceleration of the electrons (up to $\sim$ 1 keV). These potential structures are deduced from the changes in drift rate they impose to the short radio bursts generated by the Io interaction [*Hess et al.*, 2007b]. These potential structures move at the speed of sound and seem to occur quasi-periodically [*Hess et al.*, 2009], and may be related to pulsations observed in the UV spots [*Grodent et al.*, 2009], although neither the origin of the quasi-period or the link with UV aurorae are understood.

5.3. Alfvén wave filamentation

For the four cases of satellite-magnetosphere interactions for which we can compare predictions and observations, the filamentation of Alfvén waves in the vicinity of the satellite appears to be necessary to explain the observed power emitted in UV from the main Alfvénic spot and, in the case of Io, of radio and infrared emissions as well [*Hess et al.*, 2010, 2011c]. The filamentation of current carrying Alfvén waves has also been proposed in association with the fast inward motion of empty flux tubes in the Jovian inner magnetosphere [*Hess et al.*, 2011b]. The flux of anti-planetward electrons accelerated by the Alfvén waves may be at the origin of the System III modulation of the hot electrons and of the ionization state of sulfur ions in the Io torus [*Steffl et al.*, 2008].

This filamentation explains how sufficient power can escape the plasma torus. The Alfvén velocity inside the torus controls both the duration of the Alfvénic transition regime and its power, but also affects in an opposite way the efficiency of the transfer to the precipitating electrons. A low Alfvén velocity near the satellite ensures a long and powerful Alfvénic interaction, but it traps the Alfvén waves inside the torus, preventing intense auroral emissions. The filamentation of the Alfvén waves breaks this paradox by allowing the short wavelengths to pass through the torus. Moreover, these short wavelengths accelerate the electrons more efficiently, generating more intense emissions, even if a large part of the Alfvén wave power remains trapped in the equatorial plasma torus. Figure 2 summarizes the effects of shorter parallel and perpendicular wavelength on the power transmission.

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LATMOS, 11 Avenue D'Alembert, Guyancourt, France

Figure 1. Sketch summarizing the interaction between a satellite (here Io) and a planetary magnetosphere, and the related auroral footprints of the Io flux tube [*Gérard et al.*, 2006]. The footprints are composed of sub-spots (Main and Reflected Alfvén Wing spots, Trans-hemispheric Electron Beam spots) which translate the Alfvénic nature of the current circuit between the satellite and the planet, simulated by *Jacobsen et al.* [2010] (b). c) The interaction is due to the motion of the satellite with respect to the planetary magnetic field and the frozen-in plasma. Around the satellite the plasma flow is decelerated through several processes, leading to the generation of a current which propagates along the field lines as an Alfvén wave packet.(Courtesy of F. Bagenal and S. Barlett). d) The Alfvén waves develop a parallel electric field along the magnetic field lines (top panel), with a narrow peak just above the ionosphere where the density (bottom panel) has a minimum.

Figure 2. Sketch summarizing the power transfer during the Alfvénic phase of the satellite magnetosphere interaction. a) In the case of a large Alfvén velocity near the satellite, the Alfvénic phase is short and do not carry much power. It mostly serves to initiate the steady-state current system downstream. In the case of a low Alfvén velocity near the satellite, the Alfvénic phase is long and the Alfvén waves carry substantial power, but most of it is trapped in the torus if there is no Alfvén wave filamentation. b) and c) summarize the influence of the parallel and perpendicular wavelengths of the power transmission from the Alfvén waves generated near the satellites and the accelerated electrons. The parallel wavelength affects the Alfvén wave transmission through the density gradients, in particular at the torus border, whereas the perpendicular wavelength affects the parallel electric field associated with the Alfvén waves.

Satellite	Power generated[a]	Distribution	Power escaping the torus[b]	Power transfer to electrons	Power precipitated Computations[a,c]	Power precipitated Observations
Io	$\sim$ 1000 GW	Long-scales	17%	9×10^{-3}%	$\sim 10^{-2}$ GW	a few tens of GW
		Filamented	45% to 50%	2% to 5%	$\sim$ 20 GW	
Europa	$\sim$ 100 GW	Long-scales	3%	2×10^{-3}%	$\sim 10^{-3}$ GW	a few GW
		Filamented	36% to 40%	3% to 8%	$\sim$ 3 GW	
Ganymede	$\sim$ 100 GW	Long-scales	2%	3×10^{-4}%	$\sim 10^{-4}$ GW	a few GW
		Filamented	34% to 38%	2% to 6%	$\sim$ 2 GW	
Callisto	$\sim$ 10 GW	Long-scales	9%	4×10^{-2}%	$\sim 10^{-3}$ GW	no confirmed
		Filamented	46% to 49%	20% to 25%	$\sim$ 1 GW	observation
Enceladus	$\sim$ 300 MW	Long-scales	5×10^{-3}%	4×10^{-5}%	$\sim 10^{-4}$ MW	a few tens of MW
		Filamented	25% to 34%	20% to 25%	$\sim$ 70 MW	
Thetys	$\sim$ 1000 MW	Long-scales	2×10^{-3}%	1×10^{-5}%	$\sim 10^{-4}$ MW	not observed
		Filamented	25% to 30%	11% to 16%	$\sim$ 100 MW	
Dione	$\sim$ 500 MW	Long-scales	6×10^{-4}%	1×10^{-5}%	$\sim 10^{-5}$ MW	not observed
		Filamented	26% to 32%	19% to 24%	$\sim$ 100 MW	
Rhea	$\sim$ 200 MW	Long-scales	1×10^{-4}%	4×10^{-5}%	$\sim 10^{-4}$ MW	not observed
		Filamented	25% to 30%	22% to 27%	$\sim$ 50 MW	

Table 1. Summary of the power transmission through the torus and of the efficiency of the power transferred to the particles for different distributions of the Alfvén wavelengths (for power laws, the numbers correspond to $\alpha = 5/3$ and 2 respectively). (a) Assuming $\Sigma_P >> \Sigma_A$. (b) Power reaching the acceleration region, i.e. ~1 planetary radius above the planet ionosphere. (c) In Kronian satellite cases, it includes the power of the electrons accelerated in the opposite hemisphere which precipitate on the MAW spot, due to the axisymmetric magnetic field of Saturn.