Energetic electrons in the inner part of the Jovian magnetosphere and their relation to auroral emissions

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[1] The energetic particle distribution in the magnetosphere of Jupiter changes significantly between the inner and the middle magnetosphere. One of the most prominent changes is a transition of the electron pitch angle distribution (PAD) from a pancake to a bidirectional distribution. The transition is a persistent and localized feature defining a distinct spatial boundary between 10 and 17 $R_J$. We discuss the possible relation between the PAD boundary and some of the observed structures in the Jovian aurora. A comparison between the Hubble Space Telescope observations and the predicted ionospheric footprints of the PAD boundary indicates a good correlation, with a discrete belt of emissions equatorward of the main auroral oval. Furthermore, the precipitation energy flux associated with the energetic electron distribution at the PAD boundary is compatible with the brightness range of these auroral emissions. 

INDEX TERMS: 2756 Magnetospheric Physics: Planetary magnetospheres (5443, 5737, 6030); 2704 Magnetospheric Physics: Auroral phenomena (2407); 2716 Magnetospheric Physics: Energetic particles, precipitating; 2730 Magnetospheric Physics: Magnetosphere—inner; KEYWORDS: energetic particles, auroral phenomena, electron precipitation, Jupiter’s magnetosphere, planetary magnetospheres


1. Introduction

[2] The Jovian magnetosphere is dominated by internal sources of plasma and energy; driving intense auroral emissions that have been widely observed by the Hubble Space Telescope (HST) in the last years [Pallier and Prangé, 2001; Clarke et al., 2002; Grodent et al., 2003a].

[3] The different nature of the auroral emissions (main oval, secondary oval, footprint aurora, and polar patches) suggests that they are generated by a variety of processes, which are far from being understood. In situ energetic particles observations in the Jovian magnetosphere are a very powerful tool to investigate these processes and their primary plasma sources.

[4] Our knowledge of the Jovian magnetosphere, prior to the Galileo mission, came from flyby missions such as Voyager, Pioneer, and Ulysses, which, although constrained in their local time coverage, indicated among other features a change in the pitch angle distributions of electrons from pancake-like distributions (maximum flux at 90°) closer to the planet, to a distribution with maximum fluxes at small pitch angles (dumbbell distribution) [Goertz and Thomsen, 1979] at larger distances.

[5] A new era in investigating the properties of energetic particles in the Jovian magnetosphere started in 1995 with Galileo, the first orbiting spacecraft in an outer planet’s magnetosphere. In particular, the Energetic Particles Detector (EPD), on board Galileo, greatly advanced our knowledge of the energetic particle population in the Jovian magnetosphere.

[6] The instruments on board provide full three-dimensional electron and ion distributions in a wide energy range (above 15 keV for electrons and 22 keV for ions). In addition, they separate protons, helium, sulfur and oxygen channels in the keV to MeV range. A complete description can be found in the work of Williams et al. [1992].

[7] On the basis of EPD data collected on 33 Galileo orbits, a topological study of the energetic particle characteristics confirmed distinct changes in the electron and ion energy spectral slope and pitch angle distributions [Tomás et al., 2004]. The most pronounced boundary is given by the change in the electron pitch angles from a pancake or trapped distribution (maximum fluxes at 90°) to a distribution which maximizes at pitch angle away from 90° (bidirectional or butterfly distributions). The transition occurs abruptly within a fraction of an $R_J$ and is persistently
observed between 10 and 17 \( R_J \) in the equatorial plane, at all local times covered by the Galileo orbits.

[8] Now we would like to link the Galileo EPD observations in the equatorial plane with the HST observations in the auroral regions of the planet. The auroral emissions observed by the HST consist of three major types of structures. The main and the secondary auroral oval [Grodent et al., 2003a], the footprints of the satellites, Io (6 \( R_J \)), Europa (9 \( R_J \)) and Ganymede (15 \( R_J \)) [Clarke et al., 2002], and polar emissions observed inside the ovals [Grodent et al., 2003b].

[9] The main auroral oval consists of a very stable belt of emissions, colocated around both poles and observed to rotate with Jupiter. Its origin has been connected to the enforcement of partial corotation on the plasma by upward Birkeland currents [Cowley and Bunce, 2001; Hill, 2001].

[10] The main auroral oval lies poleward of Ganymede’s footprint [Clarke et al., 2002], which is located at approximately 15 \( R_J \). Thus its origin in the magnetosphere can be traced to distances between 15 \( R_J \) and several tens of \( R_J \).

[11] Recent HST observations [Grodent et al., 2003a] clearly indicate the existence of a discrete belt of emissions equatorward of the main auroral oval, the secondary oval, which is thought to be associated with regions in the magnetosphere close to or inside 15 \( R_J \).

[12] The emissions of the secondary oval are less bright and more variable than the main auroral oval. They are not related with the diffuse emissions adjacent to the main oval, which have decreasing brightness toward the equator. They are also distinct from transient events, such as those observed by HST and which have been associated with the injection of magnetospheric electrons [Mauk et al., 2002].

[13] Previous studies by Bhattacharya et al. [2001] investigate the possibility that the diffuse auroral emissions are caused by strongly scattered electrons. The authors analyzed EPD data in the region from 10 to 25 \( R_J \) for electrons in the energy range of 15—884 keV. They have found precipitation fluxes above \( \sim 10 \) ergs \( \text{cm}^{-2} \text{s}^{-1} \) in the region 10—25 \( R_J \).

[14] In contrast to investigating the broad region of diffuse emissions adjacent to the main auroral oval, which seem to be the result of a more gradual process, in this study we focus on the boundary in the magnetosphere at which the prominent change in the electron pitch angle distribution occurs, close to the equatorial plane of the planet. By directly comparing the predicted ionospheric footprints of the PAD boundary (in the equator) with the recent HST observations (in the ionosphere), we relate this sharp transition to the discrete secondary oval. We will therefore constrain this study to the physical processes at the origin of the secondary oval, estimating whether the precipitation energy flux carried by the electron population at the PAD boundary is sufficient to cause the secondary oval emissions.

2. Tracing of the Magnetic Field Lines

[15] An example for the distinct change in the electron pitch angle distribution observed in the inner part of the Jovian magnetosphere is shown in Figure 1. We show two representative pitch angle distributions for electrons in the energy range between 29 and 42 keV. In the inner part (top) at a radial distance of 9 \( R_J \) the electrons exhibit a pancake distribution with a maximum at 90° pitch angle, which is in agreement with a population stably trapped in the magnetic field. In the core plasma sheet region (bottom), for a radial distance of 24 \( R_J \), the PADs suggest that the electron fluxes are predominantly directed parallel or antiparallel to the magnetic field (In the following analysis we will consider the fluxes in this region to be field aligned).

[16] The PAD boundary can also be seen on the normalized pitch angle distribution during a characteristic Galileo passage through the inner magnetosphere. Figure 2 shows in the top panel the pitch angle distribution of an electron channel in the energy range 304 keV to 527 keV on orbit G7 (days 1997 90—98), inside 40 \( R_J \) of the planet. Although this particular example suggests a dawn-dusk asymmetry in the ‘distinctness’ of the electron bidirectional PADs, this is not a common feature to all the orbits and was therefore not interpreted as a persistent dawn-dusk asymmetry. (A detailed analysis is given by Tomás et al. [2004].) The bottom panels show the PAD boundary in the dusk region and the correspondent frequency-time spectrogram portraying the intensity of the electric field component of the waves measured by the wave instrument on board Galileo.

[17] In the frequency time spectrogram we can see two distinct increases in the wave intensity. The first one (between 0600 and 0800 UT) is related to the encounter with Ganymede and the second enhancement (between 0800 and 1000 UT) is clearly associated with the PAD boundary.
The location of the PAD boundary, i.e., the position of the distinct change from a pancake to a bidirectional distribution was obtained for the majority of the 33 Galileo passages through the inner magnetosphere. Figure 3 shows the distance and local time of the PAD boundary projected in the equatorial plane of Jupiter. For reference the orbit of Io is shown by the solid line. The Sun is to the right of the figure. The dotted circles indicate distances of 10, 15 and 20 $R_J$. The PAD boundary is located between 10 and 17 $R_J$ and essentially is independent of local time. The orbital parameters of Galileo in this radial range provide a good coverage for nearly all local times with exception of the premidnight sector.

Using currently existing magnetic field models of the Jovian magnetosphere we can trace the magnetic field lines from the PAD boundary in the equatorial plane and locate the corresponding footprints in the Jovian high-latitude ionosphere. We use the VIP 4 model [Connerney et al., 1998], which combines the O6 internal field model with an external field due to currents related with the magnetodisc.

For each of the derived PAD boundary locations the field line threading the boundary in the equatorial plane was traced into the ionosphere. The results are shown in Figure 4, together with the location of the secondary oval derived from HST observations. The solid lines indicate the footprints of Io and the footprints from distances of 25 $R_J$, and the dotted circles indicate planetocentric latitudes of 80°, 60°, and 45°.

In general, the ionospheric footprints of the PAD boundary are closely colocated with the location of the PAD of electrons (304–527 keV) during the G7 orbit (days 1997 90–98) in a range of 40 $R_J$ around the planet. (bottom) Frequency-time spectrogram portraying the intensity of the electric field component of waves for the time period corresponding to the pitch angle boundary on the dusk side (black line).

Figure 2.

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The best agreement is seen in the region from 160° C176 to 190° C176, which is within the region where the secondary oval is most clearly seen in the HST images [Grodent et al., 2003a].

Other regions of the secondary oval are harder to detect due to lower brightness or because of merging with the main auroral oval. In these regions the ionospheric footprints of the PAD boundary slightly deviate from the secondary oval.

3. Precipitation Energy Flux

In order to further establish the PAD boundary as a source region for the secondary oval, we have estimated the precipitating energy flux carried by the energetic electron population at the PAD boundary.

The electron energy spectrum can be described by a power law of the form

\[ j \propto E^{-\gamma}, \quad (1) \]

where \( j \) is the electron flux, \( E \) is the energy, and \( \gamma \) is the spectral index. The precipitation energy flux [Thorne, 1983] is then given by

\[ \varepsilon = \int_{E_{\text{min}}}^{E_{\text{max}}} Ej(r, E) dE \quad (2) \]

(in units of ergs cm\(^{-2}\) s\(^{-1}\)).

The energy ranges from \( E_{\text{min}} = 55 \text{ keV} \) to \( E_{\text{max}} = 188 \text{ keV} \) and from \( E_{\text{min}} = 55 \text{ keV} \) and \( E_{\text{max}} = 304 \text{ keV} \) were considered, since they cover the energy of the electrons believed to be responsible for the secondary oval emissions. Furthermore we assumed the strong pitch angle diffusion limit and scattering of electrons by whistler waves to be the scattering mechanism.

Wave-particle interactions can drive the distribution to the strong pitch angle diffusion limit [Kennel and Petschek, 1966]. The needed energy for wave generation is provided by an anisotropic pitch angle distribution. As a consequence, wave growth will lead to particle diffusion until a limit is reached when the pitch angle distribution becomes isotropic, indicating strong diffusion. In order for the waves to reach significant amplitudes for unstable wave growth and to increase the scattering of particles, it is necessary that the electron flux exceeds a critical limit [Thorne and Tsurutani, 1979].

We have estimated the critical flux, given by \( J_c \propto 10^{16}(L^{-4}/E) \), where \( J_c \) is the critical flux, \( L \) is the radial distance, and \( E \) is the electron energy in keV. In the estimation we considered the electron channels in the EPD energy range from 55 to 304 keV. For each channel, the critical flux was calculated in the PAD boundary range (10–17 \( R_J \)), assuming an average energy. It was then compared to the electron flux measured by the EPD instrument. The measured flux is always higher than the critical flux, indicating that the production of waves in this region of the magnetosphere is possible.

This is confirmed by the wave instrument, as shown in the frequency-time spectrogram of Figure 2. We can see the evolution of the spectral density of the waves during the PAD boundary region. The presented example is one of the most prominent cases of wave intensity enhancement at the PAD boundary. For other boundary crossings the increase may be less pronounced, but as shown below, the wave intensities measured in this region are sufficient to cause strong diffusion.

In order to verify the strong diffusion limit we have estimated the pitch angle diffusion coefficient. This is determined according to [Thorne and Tsurutani, 1979]

\[ D_{\text{crit}} \propto 2\pi f_c \left( \frac{B'}{B} \right)^2 \varepsilon, \quad (3) \]

where \( B' \) is the resonant wave power which can be obtained from the intensity of the electric field component of the wave.

![Figure 3](image-url) Location of the derived PAD boundary in the equatorial plane, indicated by crosses. The dotted circles indicate the distance to Jupiter in Jovian radii (10, 15, and 20 \( R_J \)), and the solid circle indicates the orbit of Io. The mentioned time refers to local time.

![Figure 4](image-url) Polar view of the Jovian north auroral zone. For reference, the foot points of Io and 25 \( R_J \) (obtained with the VIP4 model) are shown by solid lines. Crosses, ionospheric foot points of the pitch angle boundary; diamonds, Hubble Space Telescope secondary oval.
waves ($E'$), with $B = (nE'/c)$ [Scarf et al., 1979]. The $c$ parameter gives the fraction of the electron orbit spent in resonance, small values indicating confinement in the torus. We have verified both limiting cases in our estimation. An average of the measured magnetic field ($B$) in the equatorial plane region from 10 to 17 $R_J$ (in the order of 350–50 nT, respectively), as well as the estimated values of the electron gyrofrequency ($f_e$) in the same region ($10^5–10^3$ Hz, respectively) were used. For the electric field component of the waves we considered values in the range from 1.0 mV/m to 0.1 mV/m.

[30] This coefficient was then compared with the critical value for the case of strong diffusion, given by $D_{diff} = (v/4R_J)$ ($1/L^4$) (in the work of Thorne and Tsurutani [1979]). We obtained values one to two orders of magnitude higher. This means that we satisfy the conditions for strong pitch angle diffusion.

[31] For simplicity we calculated the strong diffusion limit in a dipolar field approximation. We consider this to be an acceptable approximation for the PAD boundary since we are within a few Jovian radii of the dipolar region, and the estimated diffusion coefficient is well above the strong diffusion limit.

[32] To compare with the HST measurements we have converted the precipitation flux into brightness, considering that 1 ergs cm$^{-2}$ s$^{-1}$ corresponds to 10 kR [Grodent et al., 2001]. By considering the two energy intervals previously mentioned we found brightness ranges of 32–115 kR and 60–320 kR, respectively. In the previous work, Bhattacharya et al. [2001] considered a wider range of energies for the precipitating electrons. The authors found precipitation fluxes of ~100 kR in the region of 10–25 $R_J$.

[33] The VIP4 magnetic field model indicates that the field lines in the region between 10 and 17 $R_J$ map into the region of the ionosphere where a discrete belt of auroral emissions (secondary oval) is observed. This belt is located equatorward of the main auroral oval, from which it is decoupled. Furthermore the precipitation energy flux estimated from the measured electron fluxes in the plasma sheet center, under the assumption of strong diffusion, corresponds in brightness to the secondary oval emissions, without the need of field aligned currents.

[34] These values, specifically those for the extended energy range, are somewhat above the mentioned 40 kR value for the secondary oval. However, taking into account that we have derived the upper threshold for the brightness, assuming the strong pitch angle diffusion limit, the correspondence is reasonable.

[35] The location of the PAD boundary (in terms of radial distance, local time and system III longitude), and the estimated precipitation flux (for both energy intervals) are indicated in Table 1. Given the uncertainty in placing the PAD boundary, and the error inherent to the fit calculation we estimate an error in the precipitation fluxes of the order of 25%. It can be seen that the precipitation flux shows no particular dependence with system III longitude, or local time.

4. Summary and Discussion

[36] On the basis of a topological study of the energetic particle population in the inner part of the Jovian magnetosphere, the change in the electron pitch angle distribution from a pancake to a bidirectional distribution peaking at small pitch angles emerges as a persistent feature of the magnetosphere. The transition most probably reflects an enhanced ionospheric precipitating flux.

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[38] Contrary to previous studies by Bhattacharya et al. [2001], which considered a wide region of the Jovian magnetosphere (from 10–25 $R_J$) as source region for the broad region of diffuse auroral emissions, we estimated the precipitation energy flux from the electron distribution right at the PAD boundary, i.e., in a spatially very confined region. In addition, we considered only those electron energies which are believed to be responsible for the secondary oval emissions, i.e., in an energy range ~100 keV, and not the total energy range of the EPD instrument. In this way we constrain the physical processes at the origin of these auroral emissions and we link the PAD change with the observed discrete oval.

[39] The origin of the PAD change from a pancake-like distribution to a nearly field-aligned distribution is not clearly understood. Possible explanations are the enhanced scattering of locally trapped particles toward smaller pitch angles which would produce the observed distribution.
Observational evidence for enhanced wave activity in the respective region exists [Tsurutani et al., 1993], which could lead the distribution to the strong pitch angle diffusion limit [Kennel and Petschek, 1966].

Another mechanism which can explain the change of the pitch angle distribution is in principle inherent in the circulation model for the Jovian energetic particle population [Nishida, 1976]. This model suggests a process of transporting particles outward from the radiation belts without significant loss of energy. It involves the scattering of particles at low altitudes causing particle diffusion toward higher latitudes which, in turn, produces a bidirectional anisotropy. This global model for the transport of energetic particles in the Jovian magnetosphere will be considered in future work on a complete study of the physical processes for the origin of the PAD change.

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