Wave-Particle Interaction of Alfvén Waves in Jupiter’s Magnetosphere: Auroral and Magnetospheric Particle Acceleration

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Abstract We investigate spatial and temporal scales at which wave-particle interaction of Alfvén waves occurs in Jupiter’s magnetosphere. We consider electrons, protons, and oxygen ions and study the regions along magnetic flux tubes where the plasma is the densest, that is, the equatorial plasma sheet, and where the plasma is the most dilute, that is, above the ionosphere, where auroral particle acceleration is expected to occur. We find that within a dipole L-shell of roughly 30, the electron inertial length scale in the auroral region is the dominating scale, suggesting that electron Landau damping of kinetic Alfvén waves can play an important role in converting field energy into auroral particle acceleration. This mechanism is consistent with the broadband bidirectional electron distributions frequently observed by Juno. Due to interchange-driven mass transport in Jupiter’s magnetosphere, its magnetosphere-ionosphere coupling is expected to be mostly not in local force balance. This might be a key reason for the dominant role of Alfvénically driven stochastic acceleration compared to the less frequently occurring, locally forced-balanced, and thus static mono-energetic unidirectional acceleration. Outside of approximately L = 30, the ion gyroperiod is the dominating scale suggesting that ion cyclotron damping of heavy ions plays a major role in heating magnetospheric plasma. We also present properties of the dispersion relationship and the polarization relationships of kinetic Alfvén waves including the important effects from the relativistic correction due to the displacement current in Ampère’s law.

1. Introduction

The structure and dynamics of Jupiter’s magnetosphere is qualitatively different compared to Earth’s magnetosphere due to Jupiter’s strong magnetic field and the mass source Io, which injects approximately 1 ton/s of plasma into Jupiter’s rotating inner/middle magnetosphere. The resultant radial transport of this mass in the rotational dominated part of Jupiter’s magnetosphere is a key source of perturbations of its magnetospheric field and plasma and the primary reason for the existence of Jupiter’s main auroral oval. Jupiter’s fast rotating plasma is partially subcorotating due to the radial transport of Io’s plasma, which results in radially and azimuthally stretched magnetic field lines as a consequence of centrifugal balance and conservation of angular momentum. The magnetic stresses and the resultant electric currents associated with the breakdown of corotation are generally considered to be the root cause, or generator, of Jupiter’s main auroral oval (Cowley & Bunce, 2001; Hill, 2001). Properties of the auroral particles have been modeled routinely with the Knight relationship prior to the arrival of Juno (Cowley & Bunce, 2001; Knight, 1973; Nichols & Cowley, 2004; Ray et al., 2010). A better understanding of the nature of the acceleration mechanisms of the auroral electrons and ions is one of the primary objectives of the Juno mission.

In addition to the large-scale magnetospheric stresses (e.g., Chané et al., 2013, 2017; Hill, 1979; Vasyliunas, 1983), the radial transport causes small-scale magnetic field perturbations omnipresent in Jupiter’s magnetosphere (e.g., Mauk & Saur, 2007; Saur et al., 2003; Tao et al., 2015). A consequence of the discontinuous flux tube-driven transport is local deviations of the force or stress balance of Jupiter’s magnetosphere-ionosphere system. The magnetic field fluctuations and associated Alfvén waves caused by the transport mediate the
magnetosphere-ionosphere coupling toward stress balance. The field fluctuations travel along Jupiter’s magnetic field lines and are partially reflected at density gradients. The reflected waves nonlinearly interact with each other, which establishes a turbulent cascade of fluctuations toward smaller and smaller spatial and temporal scales. This cascading process is anisotropic and generates waves whose wave numbers $k_\perp$ perpendicular to the background magnetic field grows disproportionally compared to the wave numbers $k_\parallel$ parallel to the background magnetic field (e.g., Goldreich & Sridhar, 1995). Reaching kinetic length and temporal scales, the fluctuations are subject to wave-particle interactions where the electromagnetic energy in the wave fields is converted into particle energy. The locations, where this process is important, their basic qualitative nature, and some of its consequences are the subject of this work.

Investigation of wave-particle interactions in Jupiter’s magnetosphere is timely because the Juno spacecraft in a polar orbit around Jupiter measures particles, magnetic fields, and high frequency waves for the first time in the source region where Jupiter’s auroral particles are being generated (Allegrini et al., 2017; Clark et al., 2017; Connerney et al., 2017; Ebert et al., 2017; Kurth et al., 2017; Mauk et al., 2017a, 2017b, 2018; Szalay et al., 2017). Some of the key findings are that often energetic bidirectional electron distributions are measured with energy fluxes at the top of Jupiter’s ionosphere on the order of a few hundred milliwatt per square meter and in some cases reaching values even as high as 3 W/m² (Mauk et al., 2017b, 2018). The resultant distribution functions are also often broadband in nature and frequently show power law energy distributions spanning several keV into the MeV range (Allegrini et al., 2017; Ebert et al., 2017; Mauk et al., 2017b, 2018). However, next to broadband bidirectional electron distributions, potential drops, that is, peaked energy signatures, have been observed on some of Juno’s passes as well (Clark et al., 2017, 2018; Mauk et al., 2017a, 2018). The most intense energy fluxes are often observed together with the broadband distributions (Mauk et al., 2018). While the potential drop signatures could be generated with a static magnetic field-aligned electric field consistent with a description after Knight (1973), Cowley and Bunce (2001), Nichols and Cowley (2004), and Ray et al. (2010), broadband bidirectional distributions could be associated with Alfvénic aurora and stochastic acceleration processes (e.g., Saur et al., 2003).

Another surprising observational property of Jupiter's magnetosphere is that its magnetospheric plasma temperature increases with distance from Jupiter with energetic ions playing a major role in the plasma energy and pressure balance of Jupiter's magnetosphere (Bagenal & Delamere, 2011; Frank & Paterson, 2002; Frank et al., 2002; Mauk et al., 2004; Saur, 2004). In the absence of energization processes, the magnetosphere is expected to adiabatically cool due to the radially expanding plasma from Io. One of the possible energization processes which contributes to the observed radially increasing plasma temperatures could be dissipation of the small-scale magnetic field fluctuations (Saur, 2004).

The existence of the broadband, bidirectional auroral particles distributions and the large temperatures in Jupiter's magnetosphere suggests that stochastic energization due to wave-particle interaction plays an important role in Jupiter's magnetosphere. We therefore investigate the possible occurrence of wave-particle interactions, that is, Landau damping and cyclotron damping, in Jupiter’s magnetosphere. We particularly look at the role and properties of the wave-particle interaction of kinetic Alfvén waves in the auroral acceleration region. A particular property of kinetic Alfvén waves is their large ratio of perpendicular wave number $k_\perp$ to parallel wave number $k_\parallel$ (e.g., Lysak & Lotko, 1996). This is consistent with the anisotropic cascading processes described in the previous paragraph and the increasing wave velocity of the Alfvén waves toward Jupiter. Kinetic Alfvén waves and their role in auroral particle acceleration have been studied extensively at Earth as, for example, discussed in Hasegawa (1976), Goertz and Boswell (1979), Louarn et al. (1994), Lysak and Lotko (1996), and references therein. This study does not consider other types of wave-particle interaction, for example, through whistler waves which can scatter and accelerate electrons such as in the radiation belts of Earth (e.g., Horne et al., 2003) or Jupiter (e.g., Woodfield et al., 2014). The role of whistler interaction over Jupiter’s polar caps has been recently investigated by Elliott, Garnett, Kurth, Clark, et al. (2018) and Elliott, Garnett, Kurth, Mauk, et al. (2018). Other studies looked at the generation of hectometric radio emission caused by the ion cyclotron maser instability driven by antiplanetward electrons (Louarn et al., 2017) or whistler waves driven by electron beams (Tetrick et al., 2017).

The remainder of this work is structured in the following way. In section 2, we begin with a study of the basic scales of wave-particle interaction and discuss the associated plasma processes in Jupiter’s plasma sheet and in the auroral particle acceleration region. In section 3, we then test if the derived scales are relevant scales for wave-particle interaction. Therefore, we apply and discuss the dispersion relationship,
Figure 1. Sketch of Alfvén mode wave-particle interaction regions in Jupiter’s magnetosphere on field lines with equatorial distances between 10 and 40 \( R_J \). Alfvén wave packages communicate stresses between Jupiter’s ionosphere and the magnetospheric plasma sheet. Inside of field lines characterized by approximately \( L = 30 \), Alfvén waves are dominantly dissipated via electron Landau damping in the auroral region above Jupiter’s ionosphere. Outside of that L-shell, Alfvén waves are dominantly dissipated by ion cyclotron damping in Jupiter’s plasma sheet. Magnetospheric transport processes render the magnetosphere and the ionosphere not in local force balance and thus trigger magnetosphere-ionosphere coupling through Alfvén waves, which causes stochastic acceleration of particles by electron Landau and ion cyclotron damping.

2. Scales of Wave-Particle Interaction

Resonant wave-particle interaction can be subdivided into two families of damping processes, which are Landau and cyclotron damping. These families are characterized through

\[
\omega - k \cdot v = n \Omega_\epsilon, \quad n \in \mathbb{N},
\]

with \( \omega \) being the wave frequency, \( k \) the wave vector, and \( v \) the particle velocity parallel to the magnetic field \( B \), and \( n \) is an integer number. If the resonance condition for \( n = 0 \) is fulfilled, Landau damping occurs, and for \( n > 0 \), cyclotron damping can occur with \( \Omega_\epsilon \), the electron or ion cyclotron frequency, respectively.

2.1. Overview of Scales and Principle Idea for Comparison

Wave-particle interaction generally occurs when the time and length scales of the waves propagating in the plasma are similar to the basic scales of the plasma. Therefore, we investigate in this subsection fundamental temporal and spatial scales of the plasma in Jupiter’s magnetosphere. Jupiter’s magnetosphere is full of small-scale Alfvénic fluctuations (Saur et al., 2002; Tao et al., 2015), which propagate along the magnetic field lines and communicate momentum and energy between Jupiter’s ionosphere and the magnetospheric plasma sheet (see also Figure 1). Counterpropagating Alfvén wave packages interact with each other and break up into smaller and smaller wave packages as studied in various plasma environments, for example, Jupiter’s and Saturn’s magnetospheres (Kaminker et al., 2017; Saur et al., 2002; Tao et al., 2015; von Papen & Saur, 2016; von Papen et al., 2014), the solar wind, laboratory plasmas, and in numerical simulations (e.g., Howes et al., 2011; Howes & Nielson, 2013; Drake et al., 2013).

Jupiter’s magnetosphere is constantly perturbed due to the radial transport of plasma, which occurs in a nonsteady way through flux tube interchange. The perturbation of this transport is associated with spatial scales of roughly the scale of Jupiter or fractions thereof (e.g., Kivelson et al., 1997). These perturbations also excite Alfvén waves, which subsequently travel along the magnetic fields. Through wave-wave interaction, the wavelengths, the wave periods, and the wave amplitudes get smaller and smaller. When the scales of waves reach kinetic scales, wave-particle interaction can become important, and wave energy is converted into plasma heating and particle acceleration. Thus, the main objective of this section is to study and sort the various kinetic plasma scales by their lengths and durations. The largest of these scales is of particular relevance because it will be reached first when the Alfvén waves cascade down to smaller and smaller scales.

The gyrofrequency of the species \( j \), where we consider \( j = e^- \), \( H^+ \), \( O^+ \), that is, electrons, protons, and oxygen ions, respectively, is given by

\[
\Omega_j = \frac{q_j B}{m_j}.
\]

The mass and the charge of the particles are denoted by \( m_j \) and \( q_j \), respectively. The ion composition in Jupiter’s plasma sheet is dominated by \( O^+ \) and \( S^{++} \) ions (Bagenal, Adriani, et al., 2017; Bagenal, Dougheerty, et al., 2017; Yoshioka et al., 2014), which have both the same mass to charge ratios and thus the same gyrofrequencies. Because the exact composition of the various plasma sheet ions and their charge states is not exactly known and the ions originally mostly stem from Io’s \( SO_2 \), we assume in the reminder of this work for simplicity that the dominant ion in the plasma sheet is \( O^+ \).

The plasma frequency of species \( j \) is given by

\[
\omega_pj = \left( \frac{n_j q_j^2}{e_0 m_j} \right)^{1/2},
\]
with \( n_j \) the number density of species \( j \) and \( \epsilon_0 \) the permittivity of free space. The electron and ion inertial length scales are given by

\[
\lambda_j = \frac{c}{\omega_j},
\]

with \( c \) being the speed of light. The electron and ion gyroradii are denoted as

\[
r_j = \frac{v_{j\parallel}}{\omega_{j\parallel}},
\]

with the particle velocity \( v_{j\parallel} \) perpendicular to the magnetic field. Thermal velocities are related to the temperature of the various species by \( 1/2 \, m_j v_{j\perp}^2 = k_BT_j \) with the Boltzmann constant \( k_B \).

We investigate these scales in the magnetospheric plasma sheet and at high latitudes. We refer to the high latitude or auroral region, where the plasma density along a flux tube assumes its lowest values and auroral particle acceleration is expected to occur. We compare the spatial and temporal scales with each other. Therefore, we assume Alfvén waves carry energy and momentum back and forth from the equator to the acceleration region. If an Alfvén wave has a perpendicular length scale \( l_{\parallel,0} = 1/k_{\perp,0} \) at the acceleration region (subscript 0), which we assume to be located for simplicity just above the ionosphere of Jupiter, then the associated scale near the magnetic equator (subscript eq) is

\[
l_{\perp,eq} = l_{\perp,0}(2L_3)^{1/2}.
\]

In expression (6), we assume that the wave is confined within a magnetic flux tube and that Jupiter’s magnetic field is described for simplicity by a spin-aligned dipole field. This field can thus be characterized by the L-shell parameter, that is, the distance of dipole magnetic field lines from the center of Jupiter measured in units of planetary radius. These simplifications are made because the aim of this work is to provide a very basic investigation into the role of wave-particle interaction by Alfvén waves in Jupiter’s magnetosphere. Based on the dispersion relationship for shear Alfvén waves, the parallel scales of the Alfvén waves in these regions are related through

\[
l_{\parallel,eq} = l_{\parallel,0} \frac{v_{A,eq}}{v_{A,0}} = l_{\parallel,0} \left( \frac{\rho_0}{\rho_{eq}} \right)^{1/2},
\]

with the parallel length scales \( l_{\parallel,0} \), the Alfvén velocity \( v_{A,0} \), the magnetic field strength \( B \), and the plasma mass density \( \rho \).

We assume that the perpendicular and the parallel scales of the Alfvén waves are related by

\[
k_{\perp} \delta v_{\perp} = k_{\parallel} v_{A,0}.
\]

Physically, equation (8) reflects the equality of time scales associated with the perpendicular and parallel dynamics of the waves. If a wave oscillates in the perpendicular direction during a time interval \( t_{wave} = 1/(k_{\perp} \delta v_{\perp}) \), the wave sweeps a distance \( l_{\perp} = 1/k_{\perp} \). During \( t_{wave} = 1/(k_{\parallel} \delta v_{\parallel}) \), the wave propagates a distance \( l_{\parallel} = 1/k_{\parallel} \) parallel to the magnetic with velocity \( v_{A,0} \). Condition (8) is referred to in MHD turbulence theory as the critical balance assumption (Goldreich & Sridhar, 1995). In an Alfvén wave, the parallel velocity fluctuations \( \delta v_{\perp} \) are equal to the perpendicular magnetic fluctuations measured in units of the Alfvén velocity, that is, \( \delta v_{\perp} = \delta v_{A,\perp} = \delta B_{0\perp}/\sqrt{\mu_0 \rho} \). Assuming that the spectral energy density distribution of the magnetic field fluctuations is given by a power law \( P(k_{\perp}) \propto k_{\perp}^{-2} \delta B_{0\parallel}^2 \) (e.g., Galtier et al., 2000; Ng & Bhattacharjee, 1997; Saur et al., 2002), then we find that parallel and perpendicular structures of the Alfvén waves are related by

\[
k_{\parallel} = \frac{\delta B_{0\parallel}^{1/2} k_{\parallel}^{1/2} k_0}{B_0^{1/2} k_0},
\]

with \( k_0 \) the perpendicular wave number corresponding to Alfvén waves with amplitude \( \delta B_0 \). We assume \( l_0 = k_0^{-1} \) to be approximately 1 R\(_J\) and the Alfvén waves to have an amplitude of \( \delta B_0 = 3–5 \) nT (Saur et al., 2002; Tao et al., 2015).

In order to compare spatial with temporal scale, we again use the Alfvénic nature of the fluctuation. Based on the dispersion relationship of shear Alfvén waves \( \omega = k \cdot v_{A,0} \), which relates wave frequency with wave vector...
Figure 2. Inertial length scales (labeled with $\lambda$) and gyroradii (labeled with $r$) for electrons and ions calculated for the equatorial plasma sheet and the auroral acceleration region. The values for the auroral region (with subscript "aurora") are subsequently projected into the equatorial plasma sheet for comparison of all length scales (see sections 2.2 and 2.3). Values of the plasma species in the equatorial plasma sheet are indicated by the subscript "equat."

In the following three subsections, we investigate and compare the scales introduced in this subsection. In section 2.2, we begin with the scales in the magnetosphere; in section 2.3, we discuss the scales at the auroral regions; and in section 2.4, we compare the most important scales of both regions.

2.2. Properties in Jupiter’s Equatorial Magnetosphere

Now we use a very simple model of the bulk plasma and field parameters in Jupiter’s equatorial magnetosphere as a function of distance from Jupiter in order to calculate the associated plasma lengths and timescales in this region.

For the magnetic field, we use the most simple description of a nontilted spin-aligned magnetic dipole with an equatorial field strength of $B_{eq} = 4.3 \times 10^5$ nT (Connerney et al., 1993). The equatorial plasma density and ion and electron temperatures are based on Bagenal and Delamere (2011) and Scudder et al. (1981).

With these values, we can calculate electron and ion inertial length scales and electron and ion gyroradii in the equatorial plane displayed in Figure 2, where associated values are indicated by the subscript “equat.”

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Figure 3. Plasma periods (labeled with $T_p$) and gyroperiods (labeled with $T_g$) of ions and electrons in the equatorial plasma sheet and in the auroral acceleration region. Values of the plasma species in the equatorial plasma sheet are indicated by the subscript “equat.” Values from the auroral acceleration region are indicated by the subscript “aurora” (see sections 2.2 and 2.3).

In Figure 3, we display plasma and gyroperiods of the ions and electrons in the equatorial regions of Jupiter’s magnetosphere. We show the plasma periods rather than the plasma frequencies to better compare the scales with the wave lengths and wave periods of the magnetospheric Alfvén waves. We see that the gyroperiods of the oxygen ions assume the largest values with a few seconds near the Io plasma torus and more than 100 s at 40 $R_J$. Very significantly smaller are the periods assumed by the electrons where both plasma and gyroperiods are on the order of $10^{-3}$ to $10^{-6}$ s.

2.3. Properties of Jupiter’s Magnetosphere Near the Auroral Acceleration Region

The plasma properties in the auroral region are being currently explored by the Juno spacecraft. We take the following typical values for our study. We assume an electron density $n_e = 1 \times 10^4$ m$^{-3}$, a proton density $n_p = n_e$, an electron temperature $T_e = 2.5 \times 10^3$ eV similar to the work in Cowley and Bunce (2001), and a polar magnetic field strength based on a dipole model, that is, $B_{pol} \sim 10^6$ nT (Connerney et al., 1993). We assume for simplicity that the ion temperature equals the electron temperature, that is, $T_i = T_e$. Due to the strong role of the centrifugal force, the auroral ion density is dominated by the light protons, and we neglect sulfur and oxygen ions in this region even though heavy ions have been identified in this region by the Juno spacecraft (Haggerty et al., 2017). Based on these plasma parameters, we calculate the associated plasma lengths and time scales in the auroral acceleration region. In order to compare the scales in the equatorial plasma sheet with those in the auroral acceleration region, we scale the auroral scales $l_a$ to the equator applying expression (6). The physical reason behind this scaling is that we are interested at what scales...
Alfvén waves are damped and their associated electromagnetic field energy is converted into kinetic energy of the particles. The perpendicular length scales of the waves get smaller when the waves travel from the equator toward Jupiter. Thus, as an example only, if a certain plasma scale were to be equal at the equator and the acceleration region, the wave cascading from larger to smaller scales would first reach the plasma scale in the acceleration region because the waves which travel between both regions possess the smaller perpendicular length scale closer to Jupiter. Thus, the damping of the wave in this case would occur in the acceleration region.

When we look at the auroral scales mapped to the equator in Figure 2, we find that the proton inertial length scale is the largest scale. It possesses values on the order of 1,000 km in the auroral region, but when mapped to the equator by equation (6), values of $10^5$ to $10^6$ km are reached. The next important length scale is the electron inertial length scale, which assumes values of 20 to 30 km in the auroral acceleration region. Mapping these scales to the equator leads to $10^3$ to $10^4$ km within the inner and middle magnetospheres of Jupiter. The gyro radii of the ions and electrons are very small in the acceleration region because of the strong magnetic field in the vicinity of Jupiter. Overall, we find that in the accelerator region, the inertial length scales are large due to the small plasma densities, and the gyro radii are small due to the strong magnetic field. This pattern partially reverses in the equatorial plasma sheet because the densities are large and the magnetic fields are small compared to the auroral regions.

Looking at the temporal scale in the acceleration region, we find that the proton plasma period is the largest time scale followed by the electron plasma period (Figure 3). For the comparison here, the frequencies of the Alfvén waves are assumed to not change while traveling along the field lines from the equatorial plasma sheet to the auroral region and back. The proton gyroperiods in the auroral regions are very small (see Figure 3). The electron gyroperiods are even smaller and are thus not displayed in Figure 3.

2.4. The Most Important Scales Combined

In Figure 4, we display the two most important scales from the analysis in the previous sections 2.2 and 2.3. However, we neglected the ion inertial length scale because we will show in section 3 that wave damping at the proton inertial length scale is highly inefficient, that is, is effectively not taking place. To compare the temporal with the spatial scale, we use the wave nature of the perturbations, which relates wave frequency to wave length through their dispersion relationship as shown in expression (10).

We find that outside of $L = 30$, the ion cyclotron period is the largest scale, and thus, ion cyclotron damping in the equatorial region of Jupiter’s magnetospheric plasma sheet is expected to be an important energization process due to wave-particle interaction. Inside of $L = 30$, the electron inertial length scale is the dominant scale, and thus, electron Landau damping at the high latitudes is expected to be a dominant wave-particle interaction process. This implies that heavy ions are primarily heated in the equatorial region by cyclotron damping with particular importance in the middle and outer magnetospheres. The ions in this process are dominantly accelerated in direction perpendicular to the magnetic field. Electrons in contrast are primarily accelerated at the high latitudes. A sketch of the geometrical setup indicating the regions of dissipation is shown in Figure 1.

The wave-driven processes in the auroral region lead to magnetic field-aligned electric fields and stochastically accelerated electrons parallel and antiparallel to the magnetic field (see section 3). This process will thus also populate Jupiter’s equatorial magnetospheric region with hot electrons.

2.5. Sensitivity Study of Transition Region

The L-shell value of 30 from section 2.4 where the transition of dominance from electron Landau damping to ion cyclotron damping occurs was derived under specific assumptions, which are interesting to revisit. The length scale associated with cyclotron damping given in (10) depends for $\omega = \Omega_i$ on the magnetospheric background field $B_0^{-2}$ and the total magnetospheric plasma density $\rho^{-1}$. The electron inertial length (see (4))
depends on the auroral electron density \( n_e^{-1/2} \), and its mapping to the equator in (6) depends on the magnetic field strength \( B_0^{1/2} \).

Alternatively to a dipole magnetic field, we apply the current sheet model used in Cowley and Bunce (2001) as shown in their Figure 2. It is based on a dipole plus CAN model out to 21.8 \( R_J \), and is then continued by a current sheet model after Khurana and Kivelson (1993). With this model, the transition where the dominance of the two dissipation modes changes moves from \( L = 30 \) to \( L = 24 \). A modification of the ion and electron densities in the auroral region by a factors of 2 or 1/2 makes the transition move inward by \( \Delta L = 1 \) or outward by \( \Delta L = 1.5 \), respectively. A modification of the plasma density in the plasma sheet by a factor of 2 or 1/2 leads to a shift of \( \Delta L = 3 \) outward or \( \Delta L = 2 \) inward, respectively. The magnetospheric ion temperature has no direct effect in this estimate. If we assume alternatively that the magnetosphere consists of \( S^+ \) ions, we find that the transition moves to \( L = 25 \). Finally, if we decrease the amplitude of the initial magnetic field fluctuations from \( \delta B_0 = 5 \) to 3 nT, the transition moves to \( L = 35 \), and if we decrease the perpendicular scale \( l_\perp = 1/k_\perp \) of the initial perturbation from 1 \( R_J \) to 1/2 \( R_J \), it moves to \( L = 28 \).

This sensitivity study suggests that the transition of dominance from auroral electron Landau damping to equatorial ion cyclotron heating as a function of distance within the middle magnetosphere is a robust feature. It occurs around \( L = 30 \) with a variability of roughly \( \Delta L = \pm 10 \) considering the various combinations of the previous paragraph. We additionally point out that the transition does not occur as a hard switch from one mode to the other but occurs as a smooth transition where within a flux tube both processes can coexist.

### 3. Dispersion Relationship and Polarization Properties of Kinetic Alfvén Waves

Dispersion relationships for kinetic Alfvén waves have been derived under various assumptions, for example, including electron pressure and ion gyroradius effects, or in the cold plasma limit including the electron inertia (Goertz & Boswell, 1979; Hasegawa, 1976; Lysak & Lotko, 1996). In the literature, the waves in the inertial limit are sometimes referred to as inertial Alfvén waves. In this work, we will use the term kinetic Alfvén wave independently of the various possible limits similar to, for example, Lysak and Lotko (1996).

The kinetic dispersion relationship in one of its most general form arises from the set of linearized Vlasov-Maxwell equations (e.g., Stix, 1992). In this case it can be only solved numerically. In the Padé approximation for the plasma dispersion function \( Z \), a numerical solver for the dispersion relationship of kinetic Alfvén waves is available as the WHAMP code (Rönmark, 1982). We use here a numerical solver for the general hot dispersion relationship, which considers the full plasma dispersion function. Details of the solver are described in the appendix of Schreiner and Saur (2017).

Lysak and Lotko (1996) and Lysak (2008) provide a dispersion relationship for kinetic Alfvén waves including the full kinetic effects for the electrons and ions. It is based on the set of linearized Vlasov-Maxwell equations but neglects the fast mode branch in the limit of small electron plasma beta. Maintaining the effects of the displacement currents and finite Debye length effects, the dispersion relation is given in Lysak (2008) as

\[
\left( \frac{\omega}{k_i \nu_A} \right)^2 = \frac{1}{(\nu_A/c)^2 + \left(1 - \Gamma_0(\mu_i)/\mu_i \right)} + \frac{k_i^2 \rho_i^2}{\Gamma_0(\mu_i)(1 + \xi Z(\xi)) + k_i^2 \lambda_0^2},
\]

with \( c \) the speed of light, the Alfvén velocity \( v_A = B/\sqrt{\mu_0 \rho_i \nu_A} = k_i^2 \rho_i^2 \), with \( \rho_i \), the electron and ion gyroradii, \( \rho_i^2 = (T_e/T_i)^{1/2} \) the ion acoustic gyroradius, \( v_A^2 = k_0 T_e/m_e = c_s^2/2 \) the electron thermal speed, \( \xi = \omega/k_i \lambda_0 \), and the Debye length \( \lambda_0 \), \( \Gamma_0 \) is the modified Bessel function and \( Z \) the plasma dispersion function. The relativistic correction due to the displacement current is included in (11) through the term \( (\nu_A/c)^2 \).

In the inertial limit, that is, for cold electrons, parallel wavelength much larger than the Debye length, and small ion gyroradius, we can simplify the relationship in (11) to

\[
\left( \frac{\omega}{k_i \nu_A} \right)^2 = \frac{1}{\left(\frac{\nu_A}{c}\right)^2 + 1} \left(\frac{1}{1 + k_i^2 \lambda_0^2} \right).
\]

We will see in subsequent sections that (12) captures several properties of the waves in the auroral region.

In Figure 5, we display the real part of the dispersion relationship in the magnetospheric plasma sheet at various distances from Jupiter. Here we use the full hot dispersion relationship (Schreiner & Saur, 2017; Stix, 1992) to include finite gyrofrequency effects. In accordance with our plasma scale study in section 2.2, we see that the dominant dissipation scale in the magnetosphere is the gyroperiod of the oxygen ion. Figure 5
Figure 5. Wave frequency of kinetic Alfvén waves in the plasma sheet as a function of perpendicular wave number at four different radial distances. This shows that the kinetic Alfvén waves start to become dispersive around the ion gyroradius but experience a singularity at the cyclotron resonance $\Omega_i$ and are heavily damped. At an equatorial distance of $10 R_J$, damping at larger scales than the gyroperiod and its associated length scales are already important, but these are not expected to play an important role in the damping within a whole flux tube because the damping at auroral scales is dominant.

In Figure 6, we show the real part of the wave frequency $Re[\omega]/k_\parallel v_A$ in the acceleration region above Jupiter’s ionosphere normalized to the wave frequency of the nondispersive shear Alfvén mode. It is calculated with (11) as a function of perpendicular wave number for four different electron temperatures. On the right-hand side of the figure, we show the phase velocity of the Alfvén waves. We see that the phase velocity of the wave never exceeds the speed of light even though $v_A = B/\sqrt{\mu_0 \rho}$ exceeds the speed of light by more than a factor of 10. This demonstrates the importance to include the displacement current in the calculation of the dispersion relationship, that is, the correction terms of the form $(v_A/c)^2$ in (11) and (12). Figure 6 also shows that the normalized wave frequency and the phase velocity decrease with increasing perpendicular wave number, which is, with stronger filamentation of the waves perpendicular to the magnetic field. We also see that increasing electron temperatures increase the phase velocity of the waves. The approximate and simple relationship (12) is shown as dashed line in Figure 6. It captures basic properties of the waves fairly well in particular for the smaller electron temperatures.

In Figure 7, we display the damping rate of the kinetic Alfvén waves in the acceleration region, which is represented by the imaginary part of $\omega$, that is, $\gamma = -Im[\omega]$ normalized to $Re[\omega]$. Averaged over several wave periods/wave lengths, the damping of the wave is proportional to $2P(k_\parallel)\gamma(k_\parallel)$ with the wave spectral power density $P(k)$ (e.g., Howes et al., 2008; Schreiner & Saur, 2017). We see that damping sets in around the electron inertial length scale. In Figure 7, we display the damping for four different values of the electron temperature and find that only temperatures significantly larger than 1 keV lead to a significant damping in the vicinity of the electron inertial length scale.

Now we revisit the claim raised in section 2.4 that dissipation of kinetic Alfvén waves at length scales of the ion inertial length is effectively not taking place. Inspection of Figure 7 demonstrates that at $l_i = \lambda_e$ (see left vertical dotted line), the imaginary part of the wave frequency is negligibly small.

We note that for the larger electron temperatures, the relativistic correction in the electron momentum needs to be considered in the distribution function and the dispersion relationship, which is however outside the scope of this work. The reason is that electrons with energies of $\sim 0.2 \text{MeV}$ approach the speed of light, which is also the approximate wave velocity in the region of the auroral particle acceleration.

At Jupiter’s polar region, we also expect nonresonant wave-particle interaction to play an important role. In case of a homogeneous plasma and field background, the nonresonant interaction is not expected to lead to an effective wave-particle interaction because nonresonant particles are accelerated during one half of the wave phase and decelerated during the other half approximately equally strong. However, in a strongly inhomogeneous medium such as along the flux tubes of Jupiter’s magnetosphere, the particles can be accelerated during one phase of the wave and can escape the acceleration region before they are accelerated in the opposite direction during the other phase of the wave. This effect has been discussed, for example, for the acceleration along the satellite flux tubes by Hess et al. (2011).
We can also use the dispersion relationship (11) from Lysak (2008) to calculate the associate polarization relations, for example, similar to Lysak and Song (2003) but including the semirelativistic effects due to the displacement current. Assuming a wave amplitude for the magnetic field \( \delta B_y \) where the y direction is in arbitrary direction perpendicular to the background magnetic field, then the associated wave electric fields perpendicular to the background magnetic field in the x direction are given by

\[
\frac{\delta E_x}{\delta B_y} = k_x \frac{c^2}{\omega} \varepsilon_{xx},
\]

(13)

based on Faraday's law of induction with the parallel wave vector \( k_z = k_j \) and the \( \varepsilon_{xx} \) component of the dielectric tensor from Lysak (2008)

\[
\varepsilon_{xx} = 1 + \left( \frac{c}{v_A} \right)^2 \frac{1 - \Gamma_0(\mu_i)}{\mu_i}.
\]

(14)

The relationship for the electric field amplitude \( \delta E_z \) parallel to the background magnetic field reads

\[
\frac{\delta E_z}{\delta B_y} = k_z \frac{c^2}{\omega} \frac{\omega}{k_x}.
\]

(15)

In case of small ion gyroradii, the polarization relationships can be reduced to simple algebraic expressions

\[
\frac{\delta E_x}{\delta B_y} = k_x \left( \frac{c^2}{1 + (c/v_A)^2} \right),
\]

(16)

\[
\frac{\delta E_z}{\delta B_y} = k_z \left( \frac{c^2k_z/k_x}{1 + (c/v_A)^2} \right) - \frac{\omega}{k_x}.
\]

(17)

In Figure 8, we show the ratio of the perpendicular wave amplitudes in the top panel and the ratio of the parallel electric field to the perpendicular magnetic field component in the bottom panel. In nondispersive low-frequency Alfvén waves, the ratio of the perpendicular electric to magnetic field components is the Alfvén velocity. In the region of Jupiter's auroral particle acceleration, the Alfvén velocity equals approximately the speed of light. We find that for small perpendicular wave numbers, the kinetic Alfvén waves show a ratio equal to the speed of light. For perpendicular length scales smaller than \( \lambda_e \), the ratio grows and can reach values approximately 10 times the speed of light (top panel). This is important because identifications of the wave modes in plasma wave data need to consider this effect. In the bottom panel, we show the parallel electric field in units of the perpendicular wave amplitude. For a magnetic field amplitude of 1 nT, the resultant perpendicular electric field is on the order of 0.3 to 2 V/m for perpendicular wave vectors in the range of 0.3 to 10 in units of \( 1/\lambda_e \). The resultant parallel electric fields are in the range of 10\(^{-3}\) mV/m to 0.03 V/m for the same perpendicular length scale range. As an order of magnitude estimate only, if we assume a length scale of the order of 1 R\(_J\) along a magnetic field line where the plasma density is the lowest and strong parallel electric fields are driven (Bagenal, Adriani, et al., 2017; Hess et al., 2011), then a parallel electric field of 0.01 V/m would lead to a net gain of electron energy of 0.7 MeV. The significant parallel electric fields driven by kinetic Alfvén waves are consistent with the highly field-aligned electron beams observed by the JEDI and JADE instruments of the Juno spacecraft.
4. Properties of Stochastic Acceleration in Auroral Region

In this section we discuss various properties of stochastic acceleration mostly related to its energetics.

4.1. Energy Flux Versus Average Electron Energy Characteristics

The Juno spacecraft observes particles and fields in the auroral acceleration region to constrain and resolve the nature of the acceleration processes. One of the properties of the acceleration process is its energy characteristic, that is, the energy flux as a function of characteristic electron energy. Clark et al. (2018) extracted such characteristic relationship from a large set of Juno/JEDI data to constrain the underlying acceleration mechanisms. For a comparison with these observations, we derive a characteristic relationship based on the idea that the acceleration of the electrons is stochastic and energetically fed by stochastic, that is, turbulent Alfvén waves. The derivation is based on Poynting’s theorem for the evolution of electromagnetic energy $W_{EM}$

$$\frac{\partial}{\partial t} W_{EM} + \nabla \cdot \mathbf{S} = -\mathbf{j} \cdot \mathbf{E}. \quad (18)$$

with the electric current density $\mathbf{j}$ and $\mathbf{S}$ being the Poynting flux. For small-amplitude Alfvén waves, the Poynting flux along the background magnetic field can be written as

$$\mathbf{S} = \frac{\delta B^2}{\mu_0} \mathbf{v}_A. \quad (19)$$

We assume that the magnetosphere is overall in a quasi-steady state such that the temporal averages $< \ldots >$ of the high-frequency and small-scale waves do not evolve in time. Integrating (18) over the cross-sectional region of a magnetic flux tube with unit width and parallel length scale $L_0$, where we assume the dissipation to occur, we find that the Poynting flux per unit area directed into the volume can be written as

$$< S > = \int_{L_0} ds < \mathbf{j} \cdot \mathbf{E} >$$

$$= \int_{L_0} ds < j_0 \cdot \mathbf{E}_0 + \delta j \cdot \delta \mathbf{E} >$$

$$= j_0 \Phi_0 + \int_{L_0} ds < \delta j \cdot \delta \mathbf{E} >. \quad (20)$$

In (20), we split up the term $\mathbf{j} \cdot \mathbf{E}$ into $j_0 \cdot \mathbf{E}_0$ related to large-scale steady-state electric current systems $j_0$ (Cowley & Bunce, 2001; Hill, 2001) and into a fluctuating part due to the small-scale turbulent fluctuations $\delta j \cdot \delta \mathbf{E}$, where we used $\mathbf{j} = j_0 + \delta j$ and $\mathbf{E} = \mathbf{E}_0 + \delta \mathbf{E}$ with $< \delta j > = 0$ and $< \delta \mathbf{E} > = 0$ due to the wave nature of the fluctuations. The steady-state contribution can be integrated along the field lines assuming for simplicity that $j_0$ is approximately constant in the dissipation region. The time constant part leads to $j_0 \Phi_0$ with the potential drop $\Phi_0$. In equation (20), the second term $< \delta j \cdot \delta \mathbf{E} >$ describes the dissipation of electromagnetic wave energy into stochastic acceleration. In Saur et al. (2003), we discussed the generation of a potential drop at the presence of a net field-aligned current of $j_0 = 2 \times 10^{-12} \text{ A/m}^2$ derived in the plasma sheet at an L-shell of 21 (Khurana, 2001). However, as pointed out by Saur et al. (2003) and Mauk and Saur (2007), the stochastic component of the electric current is estimated to be on average approximately a factor of 10 larger than the steady-state current, that is, $|\delta j|/j_0 \approx 10$. Neglecting thus the steady-state current in (20), we can derive a simple order of magnitude scaling relationship between the characteristic energy and average energy flux for the plain stochastic case. Using Ampère’s law, the stochastic currents can be approximated by

$$< |\delta j| > = \left< \frac{|\delta B|}{\mu_0} \right> = \left< \frac{|\delta \Phi|}{l_0 \mu_0} \right>. \quad (21)$$

Now we approximate $\int_{L_0} < \delta j \cdot \delta \mathbf{E} > ds$ through $< |\delta j| > < |\delta \Phi| >$ with the characteristic potential $< |\delta \Phi| >$ along $L_0$ and approximate $< |\delta B| >^2$ with $< \delta \Phi^2 >$. Using (20) in the stochastic limit, (19), and (21), we find that the stochastic energy flux is related to a characteristic potential through

$$< S_{stoch} > = \frac{1}{\mu_0} \left( \frac{\lambda_e}{v_A} \right)^2 \left< |\delta \Phi| >. \quad (22)$$

Under the assumption that the dissipation occurs close to the electron inertial length scale $\lambda_e$ and introducing an effective Alfvén conductance $\Sigma_A = 1/(\mu_0 v_A)$, we finally find

$$< S_{stoch} > = \frac{\Sigma_A}{\lambda_e} \left< |\delta \Phi| >. \quad (23)$$
4.2. Magnetic Fields Associated With Stochastic Acceleration

Assuming that the electric current connecting Jupiter’s ionosphere and its magnetosphere are composed of steady-state and fluctuating currents, that is, \( j = j_0 + \delta j \), we discuss its associated magnetic field perturbations. The temporally and/or spatially highly structured fluctuations will lead to very small large-scale magnetic field perturbations, while the time-steady currents \( j_0 \) lead to significant large-scale magnetic field perturbations (e.g., Cowley et al., 2017). The large-scale current system introduced in Hill (2001) and Cowley and Bunce (2001) is required to exist due to the magnetic stresses between Jupiter’s ionosphere and magnetosphere caused by the radial transport of mass in its rotating magnetosphere. These global magnetic stresses control the amplitudes of the associated steady-state electric currents. We note that both the steady-state and the time-variable components are however not independent. Further aspects of the relationship between the steady-state and time-variable components and their possible relationship to aurora is being discussed in section 5.

4.3. Energetics of Acceleration

Now we look at the overall energetics of stochastic acceleration. A magnetic perturbation of 5 nT at an equatorial distance of 20 \( R_J \) as, for example, seen in Galileo spacecraft measurements (e.g., Saur et al., 2002; Tao et al., 2015) and an Alfvén velocity of 300 km/s leads to a Poynting flux of \( 6 \times 10^{-6} \) W/m². This corresponds to an energy flux of 0.1 W/m² at Jupiter. This flux is on the order of typical energy fluxes observed by the JEDI instrument (Mauk et al., 2017b) but smaller than the maximum observed fluxes up to 3 W/m² (Mauk et al., 2018). Fluctuations of 5 nT could, for example, however generate fluxes of 0.6 W/m² when launched further outside in the magnetosphere where the Jovian background magnetic field is down to 10 nT. Important to further constrain the acceleration mechanism and its energetics will be measurements of the amplitudes and directions of magnetic fluctuations outside of the equatorial plasma sheet. Based on typical values of fluctuations of 5 nT in the equatorial magnetospheric regions, we conclude that not all of the accelerated electrons might be due to stochastic Alfvén waves but related to other effects of Jupiter’s magnetosphere-ionosphere coupling system.

5. Discussion

In this work we investigate important plasma scales where wave-particle interaction can occur in Jupiter’s magnetosphere. We work with the hypothesis that Alfvén waves play an important role in Jupiter’s magnetosphere-ionosphere coupling. Counterpropagating Alfvén waves in Jupiter’s magnetosphere interact nonlinearly and break up to smaller and smaller scales. This causes a cascade of waves from large to small scales. When the scales of the waves are close to the scales of the plasma, electromagnetic energy in the wave can be converted into particle acceleration and heating. Thus, the largest plasma scale that the Alfvén wave cascade encounters will play an important role in the acceleration and heating of magnetospheric particles. We find that for Alfvén waves inward of \( L = 30 \) with a possible variability of approximately \( \pm 10 \), the electron inertial length scale at the auroral acceleration region is the largest relevant plasma scale. This scale and the associated electron Landau damping of kinetic Alfvén waves is expected to contribute to the energetic electron population that causes Jupiter’s main auroral oval and to contribute to the energetic electron distribution in the magnetosphere. Outside of \( L = 30 \) (with a possible variability of \( \pm 10 \)), we find that the ion gyroperiod of the heavy ions, in particular \( O^+ \), in the equatorial plasma sheet is the dominant scale. Thus, we expect the magnetospheric ions to be significantly heated by ion-cyclotron damping of Alfvén waves in the middle and outer magnetosphere.

Overall, we showed that wave-particle interaction and stochastic acceleration due to kinetic Alfvén waves can contribute to acceleration of auroral electrons and the energization processes in Jupiter’s magnetosphere; however, we expect also other energization processes to play an important role. For example, Mauk et al. (2017a), Clark et al. (2017), and Mauk et al. (2018) observed inverted V structures and potential drops in the auroral acceleration regions, which may be related to steady-state, that is, nonwave-related, processes.

Several general arguments speak for the importance of Alfvénic acceleration in contributing to the auroral emission of Jupiter. These are in particular the observed bidirectional and broadband nature of the electron distribution (Mauk et al., 2017b), which is consistent with stochastic acceleration in comparison with a plain potential drop acceleration.

Similar broadband bidirectional electron distribution as above Jupiter’s main auroral oval and its polar regions have also been observed at Earth (Marklund et al., 2001), at Saturn (Carbary et al., 2011; Mitchell et al., 2009; Saur et al., 2006), and at the moons of Jupiter and Saturn (Bonfond et al., 2008; Clarke et al., 2002;
Hess et al., 2011; Pryor et al., 2011; Williams et al., 1996). The acceleration of electrons generating the footprints of the moons has its root cause in the Alfvén waves generated by the interaction of the magnetospheric plasma with the moons of Jupiter as demonstrated by a series of in situ spacecraft flybys at the moons and associated theoretical studies (e.g., Acuña et al., 1981; Kivelson et al., 2004; Neubauer, 1980; Saur et al., 2013). In the case of the moons, the auroral emission of the main spots and the footprint tails are caused by electron distributions, which are broadband and bidirectional (e.g., Bonfond et al., 2008, Bonfond, Grodent, et al., 2017; Bonfond, Saur, et al., 2017; Hess et al., 2011). Thus, in analogy with the similarities of the observed distributions above the main oval and the Alfvén wings at the moons, Alfvénic processes might similarly contribute to Jupiter’s main aurora. A comparison of the acceleration processes related to the moons might be of particular value because in this case, the nature of the source, that is, the plasma interaction at the moons, is spatially well constrained and observationally much better understood as the generator processes of Jupiter’s main auroral oval.

We like to end with a discussion why broadband bidirectional electron distribution probably caused by stochastic acceleration and peaked distributions probably caused by field-aligned potential drops are observed at Jupiter often spatially located at close distance. One possible reason could be that on field lines where Jupiter’s magnetosphere-ionosphere coupling has reached approximately steady state, that is, is in stress balance, we find potentials as expected in a quasi-steady state current loop when magnetosphere and ionosphere are in force balance (e.g., Cowley & Bunce, 2001; Hill, 2001). On other field lines where such a force balance is not given, Alfvén waves will transfer momentum between the magnetosphere and the ionosphere to establish this force balance, and thus, the wave nature of this process will lead to stochastic acceleration. Jupiter’s magnetosphere is constantly perturbed due to radial transport of mass in a rotating system. The transport occurs via flux tube interchange which is a noncontinuous process and renders the magnetosphere locally out of force balance. Earth’s magnetosphere in contrast does not have an internal mass source similar to Io and is much less rotationally dominated. This could be a reason why Alfvénic processes play a significantly larger role for Jupiter’s aurora compared to Earth. Another possible reason is that the quasi-steady state current system, which generates peaked distributions due to field-aligned potential drops, turns unstable, for example, because threshold currents are reached and the potentials cannot be maintained anymore (Mauk et al., 2018). This instability will lead to small-scale, high-frequency waves, which give rise to wave-particle interaction and associated stochastic acceleration. This process might operate independently from the acceleration due to Alfvénic processes. Statistical studies of the spatial scales and the temporal variability of the electron populations will help to distinguish these scenarios and to more clearly identify the acceleration mechanisms at work in Jupiter’s magnetosphere.

References


