A dynamical model of Jupiter’s auroral electrojet

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**Abstract.** A global simulation for the auroral electrojet on Jupiter is presented. The required sequence of models was computed using JIM (the Jovian Ionospheric Model), a time-dependent, three-dimensional model for the thermosphere and ionosphere of Jupiter, and an *a priori* model for the planet’s ionospheric electric field. We describe the plasma dynamics in the model by considering ion and electron motions at pressure levels less than 2 \(\mu\)bar, lying above Jupiter’s dynamo region, and including the region of maximum energy deposition by auroral particles.

By considering the motions of the neutral species being ‘dragged’ by the electrojet, we quantify the electrodynamic coupling between the neutral thermosphere and the auroral ionosphere. Two distinct altitude regions evolve in the model simulations, distinguished by different thermospheric flow patterns. Higher-altitude regions are subject to gas dynamic flow, while lower-altitude regions are strongly influenced by electrodynamic flow, associated with the transfer of momentum from the electrojet to the neutral gas. The electrojet models provide a basis for physical interpretation of current observational detections of ion motions in the Jovian auroral regions; as well as a means of optimizing future observations, in order to make similar detections.
1. Introduction

1.1. Background

Planetary electrojets are generally defined as localized ‘belts’ of relatively strong electric current, carried by rapidly moving particles of ionospheric plasma. The Earth’s equatorial electrojet, for example, is a locally horizontal set of rapid parallel streams of ions and electrons which occurs along the region of the dip equator, where the magnetic field lines are also horizontal. The terrestrial equatorial electrojet carries the Hall current associated with the horizontal magnetic field \( B \) and the vertical electric field \( E_z \). This latter field is augmented along the dip equator, since the Lorentz field \( u \times B \) associated with the horizontal tidal winds will be most effective at setting up vertical electrostatic fields in that region where \( B \) is horizontal. The electrojet in this case carries a current in the so-called dynamo region of the Earth’s atmosphere, which is defined by the altitudes where \( \omega_e = \nu_e \) (lower boundary) and \( \omega_i = \nu_i \) (upper boundary), with \( \nu \) and \( \omega \) representing, respectively, the collision frequency with neutrals and the magnetic gyrofrequency of electrons (subscript \( e \)) and positive ions (subscript \( i \)). In general, ions are more effectively decelerated by collisions with neutral molecules in the atmosphere than are electrons. The difference in velocity between the two types of charged particle reaches a maximum in the dynamo region, where strong electrojets are found.

The Earth has a permanent auroral electrojet whose variations in current are generally correlated with variations in the solar wind. In addition, the midnight sector of the terrestrial auroral ovals shows enhanced, oval-aligned current flow during magnetic substorms (e.g. Lopez and Baker 1994). This latter phenomenon is correlated with the direction of the interplanetary magnetic field (IMF) and is thought to be triggered by the enhancement of both ionospheric conductivity and electric fields through magnetospheric activity (field line reconnections, particle precipitation).

The connection between Jupiter’s ionosphere and magnetosphere also endows this planet, in theory, with a type of auroral electrojet. This arises from the dynamics of the planet’s magnetospheric plasma—in particular, the equatorial plasma disc, which is the source of precipitating particles that excite emissions between the planet’s main auroral ovals and the magnetic footprint of the Io orbit (Prangé et al 1998, Connerney et al 1998). This disc extends from the orbit of Io, \( \sim 6 R_J \) (Jovian radii) from the planet’s centre, to the outer reaches of the middle magnetosphere, situated at \( \sim 30 R_J \). The plasma disc is the means by which plasma is transported out to the magnetosphere from the Io plasma torus. This latter structure is the dominant original source of plasma in the Jovian magnetosphere.

Particle precipitation from the magnetosphere at high latitudes ionizes the neutral gas in Jupiter’s upper atmosphere and thereby augments the electrical conductivity associated with the ionosphere in these regions. This increase in ionospheric conductivity is also generally accompanied by an increase in the strength of the ionospheric electric field. The latter effect is a result of the increased emf induced in the outer portion of the plasma disc. This emf is a result of the significant breakdown in co-rotation between disc and planet (planetary magnetic field) which occurs at distances beyond \( \sim 20 R_J \) (Hill 1979, Vasyliunas 1994), although the precise location of significant departure from co-rotation is locally time dependent (e.g. Khurana and Kivelson 1993).

For the preliminary investigations herein, we consider a simplified representation of plasma disc dynamics. We take \( 20 R_J \) as the distance of co-rotation departure, where the disc rotation
lags behind that of the planet, and $30 \, R_J$ as the uniform boundary of the plasma disc. A potential difference $\delta V$, in this picture (in the frame co-rotating with the planet), is projected across the ionospheric region bounded by the magnetic footprints of the field lines which extend to distances $20 \, R_J < L < 30 \, R_J$. This region is approximately coincident with Jupiter’s bright auroral ovals.

In reality, a current system links the entire plasma disc to the ionosphere and the magnetic field lines connecting them. As a result, rotational kinetic energy is transmitted from the planet, which has an enormous reservoir of such energy ($\sim 5 \times 10^{34} \, J$), to the plasma disc, and partial co-rotation of the two is thereby maintained. Beyond distances of $20 \, R_J$, co-rotation between disc and planet is significantly degraded; and magnetospheric particle precipitation leads to enhanced ionospheric conductivity. The linking currents at the corresponding higher latitudes are thus greatly intensified.

The $20 \, R_J$ and $30 \, R_J$ oval-shaped footprints are separated, at all points along their length, by a transverse distance of $d \sim 600 \, \text{km}$ (using the VIP4 model of Connerney et al. (1998)). The electric field projected onto the Jovian ionosphere (in the co-rotating frame) as a result of the sub-co-rotation described above will therefore be approximately in the range $E_c = \delta V / d \sim 0.4$–0.5 V m$^{-1}$ (using $\delta V = 0.25$–0.30 MV as estimated in section 1.2 below). The footprint separation $d$ agrees well with the observed $\sim 500 \, \text{km}$ width of the brightest parts of the main auroral ovals—although these observed emissions can sometimes be confined to a width as small as 80 km (Prangé et al. 1998). The observations also show that the brightest parts of the auroral ovals are mainly coincident with the $30 \, R_J$ magnetic footprints (in both northern and southern hemispheres) and are most likely produced by particle precipitation from the outer plasma disc. The electric field in the auroral ionosphere should therefore be large and comparable to the field $E_c$ generated by the magnetospheric emf in the co-rotating frame.

1.2. Electric field

We have made a more quantitative estimate of the magnitude and orientation of the horizontal electric field at the ionosphere as follows.

(i) Assuming a particular magnetic field model for the planet and its magnetosphere. For our example, we use the VIP4 internal model of Connerney et al. (1998) combined with the analytical magnetodisc field of Acuña et al. (1983) (the magnetodisc field strength is symmetric about the magnetic equator).

(ii) As a function of longitude, tracing the pair of field lines which connect a radially flowing current in a model plasma disc between $20 \, R_J$ and $30 \, R_J$. Locating the surface footpoints, at vector positions $r_1 (L = 20 \, R_J)$ and $r_2 (L = 30 \, R_J)$, of these field lines (the footprint positions $r_1$ and $r_2$ are dependent on longitude).

(iii) Computing the value $\delta V$ of the magnetospheric potential drop between the pair of field lines. The total emf associated with current flow in a general ionospheric-magnetospheric ‘circuit’ arises from the difference in velocity between the neutral thermosphere (velocity $u$) and the magnetospheric plasma (velocity $v$):

$$\text{emf} = \int_{r=20 \, R_J}^{30 \, R_J} (v \times B) \cdot dl - \int_{r_1}^{r_2} (u \times B) \cdot dl.$$  \hspace{1cm} (1)

The second term in (1) is implicit in the use of the ‘co-moving’ electric field $(E + u \times B)$ in computing the ionospheric current (Achilleos et al. 1998, section 1.3). The first term,
assuming radial disc current, reduces to the following equation in the frame co-rotating with the magnetic field:

\[ \delta V = \int_{r=20 R_J}^{30 R_J} -v_\phi B_\theta \, dr \]

(2)

where the integrand is the product of the azimuthal component of velocity and the meridional component of magnetic field, similar to the problem of Faraday’s disc, and the disc medium is assumed to be perfectly conducting.

(iv) Computing the orientation angle \( \xi \) of the ionospheric electric field associated with \( \delta V \). We take \( \xi \) as the angle between the vector \( r_2 - r_1 \) and a poleward direction locally perpendicular to the \( L = 20 R_J \) magnetic footprint.

Figure 1 shows the results of this mapping exercise. The magnitude \( \delta V \) of the potential difference ‘seen’ by the ionosphere, due to the plasma disc motion, varies between \( \sim 0.25 \) and \( 0.30 \) MV, for the co-rotation properties assumed—full co-rotation at \( L = 20 R_J \), linearly decreasing with \( L \) to \( 20\% \) of the planetary co-rotation rate at \( L = 30 R_J \). This profile is generally consistent with measurements of plasma flow velocity (e.g. Belcher 1983) but may overestimate the co-rotation lag of the dayside flow (by a factor of approximately two). The variation of \( \delta V \) with longitude reflects the asymmetries in the orientation and strength of the magnetic field in the plasma disc. The horizontal electric field induced at the \( L = 20 \) footprint is found to deviate by angles less than \( \sim 16^\circ \) (north) and \( \sim 10^\circ \) (south) from the horizontal normal to the footprint itself. The smallest orientation angles \( \xi \) in this geometry occur at points magnetically conjugate to regions where the planes of the plasma disc and the field line are orthogonal.

1.3. Ionospheric current

We now consider the nature of the ionospheric currents which flow in response to the large magnetospheric emf. Consider an ionospheric region with electric field \( E_\perp \), due to magnetospheric emf and other sources of electrostatic field, and intrinsic planetary magnetic field \( B \). The total drift velocity \( v_\perp \) of a charged particle in a direction perpendicular to the magnetic field is

\[ v_\perp = \left( \frac{1}{1 + \nu^2/\omega^2} \right) \left( (E \times B)/B^2 \right) \pm (\nu/\omega)(E_\perp + u \times B)/B + (\nu^2/\omega^2)u_\perp \]

(3)

where \( \nu \) represents the effective rate of collisions between the particle and the neutral gas (the ionospheric medium is weakly ionized, so these types of collisions are far more frequent); \( \omega \) represents the gyrofrequency of the particle about the magnetic field lines; and the sign preceding the second term in the final factor is positive for ions and negative for electrons.

The current density \( j \) associated with the complete motion of the charged species in the auroral ionosphere is determined by the mobility \( \sigma \) of that species through the ambient neutral gas (which depends on the relative sizes of \( \nu \) and \( \omega \)), the electric field \( E \) and the magnetic field \( B \):

\[ j = \sigma_o E_\parallel + \sigma_p E_\perp - \sigma_h E' \times B/B \]

(4)

where \( \sigma_o \), \( \sigma_p \) and \( \sigma_h \) are, respectively, the direct, Pedersen and Hall mobilities of the ion or electron and \( E' = E + u \times B \), with \( u \) being the velocity of the neutral gas. The components of \( E' \) parallel and perpendicular to \( B \) are factors in the respective first and second terms of the right-hand side of equation (4).
Figure 1. Profiles in the co-rotating frame (see text) for the northern (full curves) and southern (dashed curves) $L = 20 R_J$ magnetic footprints. (a) The magnetospheric EMF induced for radial disc current between $20 R_J$ and $30 R_J$ in the plasma disc as a function of longitude of the magnetically conjugate point in the plasma disc. (b) Orientation angle $\xi$ of the horizontal electric field induced at the footprint (positive $\xi$ indicates a field oriented closer to the footprint direction of decreasing System III (S III) longitude). (c) Latitude and (d) longitude along the footprint as a function of longitude of the magnetically conjugate point in the plasma disc.

In higher-pressure regions ($\gtrsim 1 \mu \text{bar}$) (see figure 2), the collision rates become comparable to the gyrofrequencies of the particles in the ionospheric plasma, and the final two terms in equation (3) become significant. The third term in the equation is an indication of the momentum transferred from the neutral gas to the plasma through collisions; while the second term is associated with the Pedersen current and represents the momentum acquired from electric and magnetic forces on collisional time scales. Because the second term carries opposite signs according to the sign of the particle’s charge, the emf associated with it may possibly lead to charge separation and the establishment of polarization electric fields. This type of behaviour is generally associated with the dynamo region of Jupiter’s atmosphere, which lies below the lower boundary of our thermosphere model and is not considered further in this paper.

We now consider equation (3) in the limit of negligible collision rates ($\nu/\omega \ll 1$). This is a good approximation over most of Jupiter’s thermosphere (pressure $\ll 1 \mu \text{bar}$), and the surviving term approaches $(\mathbf{E} \times \mathbf{B})/B^2$, the classical Hall drift velocity driven by the combination of electric and magnetic fields. No charge separation can occur since the ions and electrons drift together at the same limiting velocity. However, the electrons drift at higher velocities than the
Figure 2. Ratio of particle-neutral frequency to gyrofrequency for electrons and H$_3^+$ ions as a function of pressure level. The computations assume a magnetic field strength of 10 G and a thermospheric profile taken from the subsolar point of the global model by Achilleos et al (1998). Collision frequencies were computed as in that study.

ions at lower altitudes (pressure ∼1 µbar), since the ratio $\nu/\omega$ for electrons remains much less than unity throughout the thermospheric region (see figure 2).

An electric current arises when the electrons and ions move with different velocities. While the difference in electron and ion velocity increases with pressure in this region, the magnitude of the current also depends on the density of these charge carriers. In the auroral ionosphere, the density of ions and electrons is strongly peaked at around the 0.1 µbar pressure level, where the precipitating particles are observed to deposit most of their energy (e.g. Prangé et al 1998). The region of maximum current, as a result, also lies close to this pressure level. The Joule heating associated with the electric current flowing in the ionosphere is an important source of heating for the thermospheric region, rivalling that associated with auroral energy deposition. A detailed study of heating mechanisms and electric currents in the thermosphere will form a follow-up study to the present investigation of dynamics.

Clearly, any ionospheric region with large electric fields will also have high-velocity ion flows. We may estimate the maximum velocity of ionospheric plasma in the auroral region, where we expect the $E$ field to be strongest. The speed of the plasma particles, in the limit of high altitudes and low $\nu/\omega$, will be $E_c/B \sim 400$ m s$^{-1}$ (in the limit of no collisions), using the electric field $E_c$ derived in section 1.1 and a value of 10 G for the (radially directed) magnetic field in the auroral region. Depending on the level of magnetospheric ‘forcing’ on the ionosphere, as represented by the field $E_c$, it is conceivable that the auroral electrojet on Jupiter may reach speeds of the order of 1 km s$^{-1}$.

In fact, recent observations of the infrared spectral lines of auroral H$_3^+$ ions have shown Doppler shifts, near the limit of detection, which are indicative of speeds of around 2 km s$^{-1}$ for these ions (Rego et al 1999). The spatial variation of the observed velocity shifts may be indicative of electrojets which are strongly aligned with the auroral ovals. These data are therefore also a potential diagnostic of the electric currents in the auroral ionosphere. More observations at a wider range in central meridian longitude (CML) are required, however, to confirm or invalidate this scenario. The mapping done in section 1.2 indicates that the auroral electrojet should be largely aligned with the ovals, since: (i) the ovals themselves closely follow
the \( L = 30 R_J \) magnetic footprints; and (ii) the horizontal normal to these footprints is separated from the induced electric field by angles \( \sim 15^\circ \) (for our picture with a rigid disc boundary and radial disc currents).

The high ion velocities observed by Rego et al (1999) were associated with an unusual auroral event, lasting about 1 h; or a longer-lived event confined to the range in CML seen by these observers (260° \( \leq \lambda_{III} \leq 290° \)). The highest ion velocities observed (\( \sim 3 \text{ km s}^{-1} \)) correspond to electric fields of the order \( E \approx vB = 3 \text{ V m}^{-1} \), using \( B = 10 \text{ G} \) for the auroral regions. Such a large electric field suggests that the dynamics and heating of the neutral thermosphere may be significantly influenced by the electrodynamic (\( J \times B \)) forces and Joule heating associated with the ionospheric current system. It is the dynamics associated with the Jovian auroral electrojet that is the subject of this study. In the next section, we describe a global model of the electrojet which we use for: (i) determination of a more accurate relation between electric field and ion velocity at the ionization peak, by including ion–neutral collisions and a self-consistent neutral wind system; (ii) studying the effect of electrodynamic forces on global neutral winds and the link between ion and neutral velocities; and (iii) studying the effect of sudden increases in the potential drop \( \delta V \) across the auroral oval by simulating the effects of such an event on the polar neutral and ion velocity distributions.

2. The model

The three-dimensional, time-dependent model of Jupiter’s thermosphere and ionosphere described by Achilleos et al (1998) (hereafter A98) forms the basis of our electrojet models. This global model is known as JIM (the Jovian Ionospheric Model), and uses time-stepping to solve transport equations of momentum, energy and density of ions and neutral species. We augment the numerical solution to the transport equations for ion and neutral densities in the vicinity of the auroral regions, where high ionization and velocity gradients develop, by using the ‘upwind’ differencing scheme described by Press et al (1986) (this scheme uses information only from points upstream in the flow to evolve the density at a given point). JIM uses a spherical coordinate grid with 91 latitude points, 40 longitude points and 30 logarithmically spaced pressure levels (the range in pressure is 0.02 nbar–2 \( \mu \)bar).

Because the latitudinal resolution of JIM is 2°, or \( \sim 2400 \text{ km} \), we are unable to simulate electrojet flow over dimensions corresponding to the width of the main auroral oval (\( \sim 80–500 \text{ km} \)). However, it is possible to resolve a region in our model which includes the main oval and the ‘belt’ of low-level particle precipitation (\( \sim 10 \text{ ergs cm}^{-2} \text{s}^{-1} \)), which is observed to extend over \( \sim 5000 \text{ km} \) from the oval to the magnetic footprint of Io’s orbit (Prangé et al 1998). Following A98, we include a simplified belt of uniform field-aligned precipitation between ovals which are the footprints of a simple dipole field. These bounding ovals in the model are approximately congruent (to within 2° in latitude) to the \( 6 R_J \) and \( 30 R_J \) footprints of more accurate magnetic field models. We kept the precipitation flux at 8 ergs cm\(^{-2}\) s\(^{-1}\) (delivered by 10 keV electrons) as used by A98 in order to simulate a ‘weak’ aurora.

The electric potential in our model is the sum of two components.

(i) Solar wind component. To include the interaction of the Jovian magnetosphere with the solar wind in our model potential, we follow A98 and adapt the analytical potential, originally developed for terrestrial plasma observations, by Spiro et al (1978). The associated parameters for this potential in our study are identical to those used by A98. Our polar
cap potential is arbitrarily set at 100 kV (a factor of ≥3 higher than that associated with the Earth); and the angular diameter of the polar cap boundary (i.e. where direction of plasma drift reverses) is assigned a value of 10° (taken to be smaller than that of the Earth, in view of Jupiter’s larger plasmasphere (Engel 1994 Private communication)).

(ii) Disc component. The electric field associated with the breakdown in co-rotation between plasma in the disc and the planet’s magnetic field has been described above (section 1). As a result of these co-rotation properties, a large electric field arises in the main auroral ovals. We have estimated in section 1 the potential drop $\delta V$ across these narrow (~500 km wide) main ovals, which are magnetically conjugate to the equatorial magnetospheric region extending between 20 $R_J$ and 30 $R_J$ from the planet. Such a narrow oval, however, is beyond our current JIM grid resolution. We have therefore chosen to model an enhanced electric field structure throughout the wider precipitation belt. This field is varied through a parameter $\Delta V$, which represents a uniform potential drop across the width of the model auroral oval (the model ovals are assumed to be contours of equal projected disc potential). The potential difference $\Delta V$ is projected across a belt which spans two to three latitude grid points. While our model thus overestimates the size of the electrojet region, we are nevertheless able to make quantitative estimates of the influence on the polar thermosphere of a high-velocity belt of plasma whose width is small in comparison with the radius of the enclosed polar cap. The influence of a more realistic, narrower electrojet region on our results is considered in the following sections.

In the absence of a detailed model for field-aligned currents linking the ionosphere and magnetosphere, we adopt the assumptions of A98 and assume: (i) a condition of zero vertical current to compute the horizontal ion velocities; and (ii) divergences in the horizontal ion current system are closed by vertical electron currents connected to a perfectly conducting magnetosphere. This is a reasonable first approximation since the field-aligned mobility of the electrons greatly exceeds that of the (far more massive) ions. We aim to compute the ionospheric current system in a self-consistent manner in future studies by making use of a more realistic magnetospheric current model.

3. Results

3.1. Polar distribution of ion and neutral velocities

We consider firstly the distribution of velocity in the vicinity of the northern auroral belt in our model. Figure 3 shows the distribution of $H_3^+$ number density (coloured contours) over the 0.1 $\mu$bar pressure surface in this region. This pressure level samples the auroral ionization peak over most of the model auroral belt (the location of the ionization peak varies between ~0.07 $\mu$bar and 0.3 $\mu$bar around the auroral belt due to change in magnetic field orientation, which controls the atmospheric angle of incidence of the precipitating particles (A98)). As we expect, the $H_3^+$ ion density is enhanced by about an order of magnitude inside the auroral belt due to the additional ionization of $H_2$ by precipitating electrons ($H_2$ is the dominant species, ≥90% by number, at the plotted pressure level).

The arrows superposed on the $H_3^+$ density maps show the direction and magnitude (arrow length) of ion ($H_3^+$) and neutral velocity in the model’s northern polar region. The ion convection pattern is mainly determined by our choice of ionospheric potential. The ‘two-cell’ flow seen on the polar cap (i.e. within the high-latitude boundary of the auroral belt) is an Earth-like signature.
of the interaction between the solar wind and high-latitude magnetic field. These two cells meet at a 'bar-like' region, running from magnetic noon to midnight, of antisunward ion convection in the model (corresponding to a northward IMF condition). Recent UV images suggest that this 'bar' region may be situated close to a transpolar emission feature seen in Jupiter’s northern polar cap, which also appears to approximately follow magnetic noon as the planet rotates (Prangé et al 1998).

The ion convection inside the auroral belt itself is dominated by the large potential drop of $\Delta V = 2 \times 10^6$ V across the belt’s transverse width (higher potential at higher latitude). The resulting horizontal electric field ($\sim 0.4$ V m$^{-1}$) is locally perpendicular to the auroral belt. Combined with the approximately radial magnetic field in this region, it drives $H^+_3$ ions at velocities of up to $\sim 480$ m s$^{-1}$. The resulting direction of motion of the ions is approximately parallel to the auroral belt itself, being dominated by the Hall-type drift associated with the electric and magnetic fields there. The ion velocity is directed against the direction of rotation of the planet in both northern and southern auroral belts. Similar properties apply to the electron velocity distribution, although it is worth emphasizing that it is the difference between electron and ion velocities that gives rise to the electrojet current (see section 3.2).

If we now look at the neutral gas in the same polar region, we see that the flow inside the auroral belt is largely aligned with this belt, although to a lesser degree than the ion velocities.
3.10

Table 1. Dynamical properties of model auroral belts (RMS speeds are calculated using density (of neutral gas or ions, as appropriate) as a weighting factor). \( \Delta V = 2 \times 10^6 \) V.

|                          | North          | South          |
|--------------------------|----------------|----------------|
| Neutral kinetic energy   | \( 7.09 \times 10^{15} \) J | \( 8.54 \times 10^{15} \) J |
| \( \text{H}_3^+ \) kinetic energy | \( 9.78 \times 10^9 \) J | \( 1.11 \times 10^{10} \) J |
| Neutral RMS, maximum speed | 106 m s\(^{-1}\), 257 m s\(^{-1}\) | 113 m s\(^{-1}\), 228 m s\(^{-1}\) |
| \( \text{H}_3^+ \) RMS, maximum speed | 270 m s\(^{-1}\), 476 m s\(^{-1}\) | 282 m s\(^{-1}\), 457 m s\(^{-1}\) |

This alignment comes about via an electrodynamic acceleration—the collisional transfer of momentum from ions to neutrals, which is strongest in the direction locally parallel to the auroral oval. We see that the neutrals at this pressure level have, in general, a velocity component perpendicular to the auroral belt which is comparable to the parallel velocity. This is a signature of the presence of gas dynamic forces in addition to the electrodynamic acceleration (section 3.2). The maximum speed of the neutrals in the auroral belt region is \( \sim 250 \) m s\(^{-1}\).

In addition, there is a region of flow reversal surrounding the auroral belt, of latitudinal width 5–10° (6000–12 000 km), where the neutrals are accelerated from the co-rotational, gas dynamic flow characteristic of the sub-polar regions of the model planet to the strongly auroral belt-aligned, anti-co-rotational flow described above. This ‘reversal region’ is caused by the transport of momentum through advection and viscous forces (section 3.2).

The relatively rapid flow of ionospheric plasma in the auroral belts, and its associated current form the auroral electrojet. The model thus predicts the development of a strong ‘circumpolar neutral jet’ in response to the auroral electrojet.

Table 1 shows the kinetic energies contained in the model auroral belts in a region enclosing the ionization peak due to precipitation. These numbers should be reduced by an order of magnitude if we wish to determine the kinetic energy in a more realistic, narrower model jet of width \( \sim 600 \) km. If this latter narrow region were resolvable by the model grid, it would subtend a magnetospheric potential drop of \( \delta V_{\text{mod}} = 80 \) kV (which is \( \sim 4\% \) of the potential drop \( \Delta V \) assumed for the wider auroral belt). This is lower than the minimum value of \( \delta V_{\text{est}} \) estimated for a ‘quiescent’ narrow oval in section 1.2, by a factor of \( \sim 3 \). If \( \Delta V \) in the model were increased by a similar factor (in order to make \( \delta V_{\text{mod}} \) agree with \( \delta V_{\text{est}} \)) the ion kinetic energy in the narrow ‘main’ auroral ovals would actually become similar to that enclosed in the current model’s wider auroral belt region, as listed in Table 1. While our chosen model thus underestimates the electric field in the auroral region, it encloses an ion kinetic energy in its auroral belt which is comparable to that contained in the main auroral oval of the real planet.

Whether we consider the relatively wide auroral belt of our model or a narrower oval region, the corresponding kinetic energies are clearly enormous. This naturally raises the question of the role played by viscous dissipation of kinetic energy in polar regions close to the auroral belts. It is beyond the scope of our current modelling to explore this question. However, we aim to include viscous dissipation in our model and investigate this matter in a future study.

Another remarkable feature of the dynamical properties of the model auroral belts is the contrast between the ion and neutral kinetic energies. About six orders of magnitude separate...
Figure 4. Projected \( \text{H}_3^+ \) velocity. The maximum projected velocities are shown as a function of S III longitude for the northern (red curve) and southern (blue curve) auroral belts in the model. The projection is along the line of sight of an observer whose CML is coincident with the longitude at a particular point in the plot.

The model’s maximum projected \( \text{H}_3^+ \) velocity in the region of the auroral ionization peak at 0.07–0.3 \( \mu \)bar (observed infrared spectral lines of auroral \( \text{H}_3^+ \) are dominated by emission from the ionization peak). The projection is taken along the line of sight of an observer at 0°N latitude who views the planet at the CML shown on the horizontal axis. The predicted velocity measurements are shown for both northern and southern auroral belts. We see that the northern auroral belt in the model yields maximum ‘observed’ velocities of magnitude \( \sim 400 \) m s\(^{-1}\) at CMLs of 80° and 280°. For the southern belt, the corresponding maxima occur at CMLs 160° and 340° and have magnitudes \( \sim 200 \) m s\(^{-1}\).

Neglecting vertical flow in the model changes these numbers by \( \lesssim 20 \) m s\(^{-1}\). However, the general projected velocity profile may be significantly changed for auroral regions in which: (i) hydrostatic equilibrium in the vertical direction is not maintained and velocities with comparable vertical and horizontal components exist; and/or (ii) the ion convection at the auroral ionization peak deviates strongly from auroral belt-aligned flow, due to non-orthogonality of the auroral belt and ionospheric electric field (section 1.2).
3.12

Figure 5. Velocity profiles for electrons, H$_3^+$ ions and neutrals are shown as a function of pressure for a point inside the model’s northern auroral belt, at the Jovigraphic coordinates shown. The density profile of H$_3^+$ is shown in the left panel for comparison (on an arbitrary scale).

It is evident that determinations of quiescent H$_3^+$ velocity need to be made, over a wide range of CML, before we can make detailed comparisons with the model predictions. In the case of the observations by Rego et al (1999), which were indicative of H$_3^+$ velocities $\lesssim 3$ km s$^{-1}$, comparison is not useful. This is due to the fact that, during these observations, the auroral region was not quiescent, but in an unusually active phase, with the corresponding ionospheric electric field possibly enhanced by factors of up to $\sim 10$.

3.2. Vertical profiles of velocity and acceleration

We now consider the behaviour of velocity with altitude as predicted by our model. We begin by looking at a point inside the northern auroral belt (85°N latitude, 0° longitude (SIII)) of the model studied in section 3.1, with $\Delta V = 2 \times 10^6$ V. Plots of velocity versus pressure level for ions, electrons and neutral gas at this location are shown in figure 5 (we use pressure level in order to avoid having to choose a zero point for altitude, several of which are currently in use).

Several features of importance are immediately apparent in these auroral velocity profiles. First, the ion and electron horizontal velocities approach equal values of $\sim 300$ m s$^{-1}$ (their Hall drift velocity) at high altitudes. Our point is thus not the site of the maximum ion velocity for the entire auroral belt (476 m s$^{-1}$ from table 1)—this latter site is at 86°N latitude and 306° longitude (SIII), $\sim 5100$ km from the point under current consideration.

The direction of the horizontal ion and electron motions seen in figure 5 at high altitude is azimuthal, which is locally parallel to the auroral belt at our chosen point (motivation for our choice of grid point). The electron velocity never exceeds the ion acoustic velocity ($\sim 3$ km s$^{-1}$)
Figure 6. Acceleration profiles for neutrals are shown as a function of pressure for a point inside the model’s northern auroral belt, at the Jovigraphic coordinates shown. The legend identifies the accelerative processes by the colour of the corresponding curves. For clarity, the red (‘$J \times B$’) curve in the left panel has been ‘compressed’ in the horizontal direction by a factor of five.

in our model, and the plasma flow we consider would thus not be subject to type I (‘two-stream’) instability (Farley 1963). The ions and electrons begin to stream with significant (>10 m s$^{-1}$) velocity difference once pressure exceeds $\sim 0.3$ µbar. The resulting decrease of azimuthal (Hall) ion velocity, due to increasing collision rate, is apparent. The electrons (less massive, higher gyrofrequency) experience negligible deceleration in comparison. The meridional plasma velocities in this low-altitude region show that the ions are the dominant carriers of the Pedersen current. For the point under scrutiny, the Pedersen current is approximately horizontal, locally perpendicular to the auroral belt and stronger than the Hall current at all altitudes.

The second important feature of the velocity profiles in figure 5 is the behaviour of the neutral gas dynamics. The most prominent feature is the presence of a velocity peak situated at $\sim 0.3$ µbar, just below the auroral ionization peak. This peak arises in the azimuthal (belt-aligned) direction as a result of the electrodynamic (‘$J \times B$’) acceleration. This latter process may be interpreted equivalently as: (i) the forcing of the neutral medium by the flow of the Pedersen current; or (ii) the transfer of momentum in the belt-aligned direction from ions (and, to a lesser degree, electrons) to neutral particles through collisions. The corresponding acceleration profiles associated with the input processes in the model are shown in figure 6. The dominant acceleration at low altitude (pressure $> 0.1$ µbar) is the electrodynamic one. At higher altitudes (pressure $< 1$ nbar), it is mainly the Coriolis force and gas dynamic forces—pressure gradients, and, to a lesser degree, viscous force—which control the velocity evolution.

Figure 5 also shows a velocity peak in the meridional direction at the same altitude as that in the azimuthal direction. The accelerative processes responsible for this peak are seen in the
corresponding acceleration profile in figure 6. The low-altitude (pressure >0.1 \(\mu\)bar) meridional velocity peak is formed by competition between the Coriolis and electrodynamic forces (note that the latter force is weaker in the meridional direction since it is produced by the weaker Hall current). The acceleration due to pressure gradient is also significant in this region, and arises from the deposition of energy by auroral particle precipitation, and the subsequent transport of this energy outwards from the auroral belt (A98). The approach of the model further towards thermal equilibrium could conceivably increase the meridional pressure gradients, although such an outcome could only be confirmed by further calculations.

The orientation of the auroral belt exerts a strong influence on the velocity profiles. At the point we have examined, the low-altitude meridional (perpendicular to auroral belt) flow is subject to a combination of accelerative processes. This is in strong contrast with the azimuthal (parallel to auroral belt) flow, which is clearly electrodynamically dominated at low altitude. The electrodynamic force diminishes with distance from the ionization peak, due to generally decreasing conductivity (ion density) and current density. These results are generally true for all points in the auroral belts. In the high-altitude region (pressure <1 nbar), the meridional acceleration profile in figure 6 shows strongest contributions from pressure gradients, followed by the Coriolis and viscous forces.

We now consider a location outside the auroral belt region, in order to investigate regions where the electrodynamic force is negligible in comparison with other accelerative mechanisms. Figure 7 shows the run of neutral velocity with altitude at a point situated at 66°N latitude and 180° longitude (SIII). An inspection of figure 3 shows that this location is outside the northern auroral belt, and \(\sim 5°\) in latitude (\(\sim 12000\) km) poleward of the high-latitude boundary of the belt. The meridional direction at our chosen point is, as in the previous example, perpendicular

**Figure 7.** Velocity profiles for neutrals are shown as a function of pressure for a point inside outside the model’s northern auroral belt, at the Jovigraphic coordinates shown. The density profile of \(H_3^+\) is also shown for comparison (on an arbitrary scale).
3.15

Figure 8. Acceleration profiles for neutrals are shown as a function of pressure for a point outside the model’s northern auroral belt, at the Jovigraphic coordinates shown. The legend identifies the accelerative processes by the colour of the corresponding curves. For clarity, the dark blue (‘Coriolis’) curve in the left panel has been ‘compressed’ in the horizontal direction by a factor of ten.

to the direction of the auroral belt.

We see from the corresponding profile of ion (H$^+$) density that there is no correlation between velocity and maximum ionization, as found for the points inside the auroral region (figure 5). This is due to the lack of electrodynamic acceleration, which is a consequence of the absence of strong electric fields and the relatively low ion column density in the non-auroral ionosphere (non-auroral H$^+$ has a lower column density than that in the auroral region by an order of magnitude or more, according to both observations and models (A98, Majeed and McConnell 1991, Miller et al 1997)).

The neutral velocities seen at the pressure levels previously associated with the auroral ionization peak (0.07–0.3 µbar) are smaller than those inside the auroral belt (figure 5) by factors of $\leq$10.

The corresponding acceleration profiles are shown in figure 8. The evolution of azimuthal (parallel to auroral belt) velocity at pressures of $\sim$0.1 µbar is controlled by a balance between the Coriolis force, pressure gradient and momentum advection. The first two forces are associated with geostrophic balance, but this has been modified due to advection of momentum from the nearby circumpolar neutral jet. At higher altitudes (pressure $\sim$1 nbar), away from the peak velocities of the circumpolar jet, the ‘third force’ in this competition is viscous force rather than advective. Momentum advected from the circumpolar neutral jet is transported to the high-latitude regions enclosed by the auroral belt, towards which the jet velocity is directed. Similar comments apply to the analogous southern region. In regions which are also close to the auroral belts but equatorward of their low-latitude boundaries, advection is less effective and the viscous

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force is also significant in the low-altitude (∼0.1 μbar) region (section 3.3). The meridional acceleration profiles shown in figure 8 indicate that, at the point we are considering, pressure gradients and Coriolis forces are the two principal accelerators which govern velocity in this direction.

3.3. A simulated electrodynamic acceleration event

The illustrative model which was the subject of the dynamical studies of sections 3.1 and 3.2 is the end result of a time-dependent simulation which we computed in order to monitor the effect of an increase in the auroral potential drop ΔV on the neutral velocity distribution in the model’s north polar regions. This simulation was the result of:

(i) starting with the model of A98, which has ΔV = 10⁴ V and represents 3.84 simulated Jovian days (d_J) of evolution;
(ii) changing ΔV to 10⁵ V and running the model until t = 4.277 d_J (noon meridian longitude 100° (SIII));
(iii) changing ΔV to 10⁶ V and running the model until t = 4.727 d_J (noon meridian longitude 262° (SIII));
(iv) changing ΔV to 2 × 10⁶ V and running the model until t = 5.00 d_J (noon meridian longitude 0° (SIII)).

We concentrate on the evolution of neutral velocity during stage (ii) above, since this shows most clearly the principal accelerative processes at work in the auroral and sub-auroral regions. A time sequence of model output plots (similar in format to figure 3), covering this acceleration event, is shown in the animation in figure 9. In each frame, we also show: a histogram representation of the auroral belt’s plotted velocity distribution (over that part of the 0.1 μbar surface lying inside the belt); the RMS velocity of this distribution; and the central velocity of the occupied bin of maximum kinetic energy in the histogram.

If we consider firstly the effect of the increase in ΔV on the flow inside the belt, we see that the velocity in general is increased in magnitude and also rotated polewards in orientation as the simulation proceeds. This is a result of: (i) the increased electrodynamic (’J × B’) force which accompanies the intensification of the ionospheric electric field; and (ii) the increase of the Coriolis force which accompanies the initial increase in velocity. It is the balance between these two major forces that determines the direction of the velocity flow inside the belt (section 3.2). At intermediate altitudes (pressure 1 nbar–0.07 μbar), the electrodynamic force weakens significantly, due to decreased conductivity, and a geostrophic balance between pressure gradients and Coriolis force is approached. At higher altitudes (pressure ≈ 1 nbar), gas dynamic outflow from the auroral belt results (A98, section 3.2).

The RMS velocity inside the belt reaches a peak value of ∼18 m s⁻¹ at a time of ∼2 h (0.22 d_J) after the change in ΔV. The corresponding peak in the maximum velocity is ∼45 m s⁻¹, as shown in figure 10. As dynamical balance begins to be established once again at this pressure, the velocities of belt material decrease to lower values. Apart from its effect on the Coriolis force, the velocity of the neutral flow also regulates the electrodynamic acceleration. Equation (3) indicates that as the velocity parallel to the belt (Hall drift direction in our model) approaches E⊥/B, the magnitude of the Hall drift velocity (in the limit of no collisions), the rate of momentum transfer from ions (and electrons) to neutrals decreases. We have seen that the
Figure 9. An animation showing the evolution of the northern polar region of the JIM model in response to an instantaneous change in trans-auroral potential from $\Delta V = 10^5$ V to $10^6$ V at simulation time $t = 4.277$ Jovian days (see text). The northern polar region is shown on a rotating planetary surface (local noon meridian is vertically downwards). As in figure 3, the colour scale represents the logarithmic density of $H_3^+$ ions on the 0.1 µbar surface. The arrows represent direction and magnitude of neutral velocity on the 0.1 µbar pressure surface. The mixed linear/logarithmic velocity scale bar maps the length of each arrow to the speed it represents, and optimally displays the full dynamic range of the velocity distribution. A histogram representing the evolving distribution of speeds inside the auroral belt is also shown. The time-dependent read-outs include: the potential drop $\Delta V$; the RMS speed of the belt velocity distribution; and the central velocity value of the occupied bin of maximum speed in the histogram. The depicted acceleration event is maintained for just under half a planetary rotation (0.45 Jovian days) (see figure 10).

Neutral speeds can be a large fraction ($\approx 60\%$) of the ion speeds at the auroral ionization peak (section 3.1). The ‘self-regulating’ nature of electrodynamic acceleration, combined with the mitigating effects of Coriolis force and losses in kinetic energy due to gas dynamic processes (advection, viscosity), generally prevent velocity synchronization of the neutral gas and the ionospheric plasma.
If we now consider the flow across the polar cap (inside the high-latitude bounding oval of the auroral belt) during the acceleration event, we see that it initially attains a higher belt-aligned velocity, followed by a rotation towards the north pole. While the Coriolis force is responsible for the latter adjustment in the flow direction, the initial acceleration is provided by advection of momentum from the high-velocity flow inside the auroral belt itself (the belt flow is generally rotated poleward from the direction parallel to the belt). This process affects nearly the entire polar cap region.

It is viscosity rather than advection which provides the initial deceleration, parallel to the belt, of the flow in the ‘reversal’ region extending for \(\sim 5^\circ\) equatorward of the auroral belt’s low-latitude boundary. For our simulation, the pressure gradient in the reversal region drives gas towards the auroral belt. This is a signature of flow occurring between belt-aligned regions of higher pressure in the ‘wave-like’ pattern of energy outflow from the auroral regions (A98). Changes in our model’s pressure structure in the approach to thermal equilibrium, however, could have significant effects on the flow perpendicular to the auroral belt in this ‘reversal’ region.

4. Conclusions

We have developed a dynamical model for the ion, electron and neutral velocity distributions in the vicinity of Jupiter’s auroral belts. An auroral electrojet develops in this model region, within the belts themselves, in response to magnetospheric forcing. The current associated with the model electrojet peaks near the location of the ionization peak due to particle precipitation inside the belts.

Concentrating on the north polar region, we examined the global patterns of ion (\(\text{H}_3^+\))
convection and neutral gas flow. Ion convection was mainly controlled by the Hall drift associated with our model ionospheric electric field. Inside the auroral belt, the direction of this drift was aligned with the belt itself. However, the true degree of this alignment is dependent on the actual angle between the auroral oval and the induced electric field (which we assumed to be orthogonal).

The circumpolar neutral jet which develops inside the auroral belt, in response to the electrodynamic forcing by the electrojet, is strongly coupled to it, showing velocities up to \(\sim 60\%\) of the ion velocities at the same location.

Investigation of the altitude dependence of neutral velocity showed the following:

(i) At pressure levels close to the ionization peak in the auroral belts (0.07–0.3 \(\mu\)bar), the flow is mainly controlled by the electrodynamic and Coriolis forces. At higher altitudes (lower pressures), the electrodynamic force weakens considerably and the combination of gas dynamic forces (pressure gradients, viscosity, advection) and Coriolis force control the flow.

(ii) The flow across the polar cap, at pressure levels coincident with the velocity maximum near the auroral ionization peak, is strongly influenced by advection of momentum from within the auroral belt.

(iii) The flow in a narrow region, extending \(\sim 5^\circ\) (6000 km) equatorward of the auroral belt (at the same pressure level) experiences strong acceleration in the direction of the electrojet due to viscous momentum transport.

The auroral electrojet therefore has a potentially enormous impact on the dynamics of Jupiter’s auroral and polar regions. There is strong electrodynamic coupling between ion and neutral velocity distributions inside the belts themselves. Our model provides a means by which neutral thermospheric velocities may be deduced using observed ion (\(\text{H}_3^+\)) velocity measurements, such as those of Rego et al (1999). More observations of this nature, combined with further modelling, will undoubtedly help build the most detailed picture to date of the dynamics of the Jovian ionosphere and thermosphere. Such studies of auroral velocity distributions will also be of value in understanding this electrodynamic interface in the coupling between the ionosphere and magnetosphere.

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