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Variations of Jovian Aurora Induced by Changes in Solar Wind Dynamic Pressure

by

BIN GONG

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APPROVED, THESIS COMMITTEE

Thomas W. Hill, Professor of Physics and Astronomy, Director

Frank R. Toffoletto, Associate Professor of Physics and Astronomy

Adrian Lenardic, Assistant Professor of Geophysics

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Abstract

The jovian aurora contains a persistent main oval encircling each magnetic pole, which is associated with the upward field-aligned currents in the corotation enforcement current system. It has been suggested by two recent studies that the brightness of the main oval should become temporarily dimmer ~ 1 hr after arrival of a shock wave in the solar wind, compressing the magnetosphere abruptly, because the difference between the angular velocity of the plasma in the magnetosphere and the rigid planetary rotational speed becomes smaller. But recent observations at Jupiter and Saturn have reported the opposite: the auroral oval brightens, and moves poleward, after the arrival of a solar wind shock. In this thesis, I will quantitatively include the flywheel effect of the neutral gas in the ionosphere in the coupling current system to explain this discrepancy and show that the corotation enforcement current should reverse and strengthen after a compression, and thereby temporarily cause the main oval to become brighter and move poleward. I will also show the differences between the night side and the day side in steady state and after a compression event by applying two different magnetic field models fitted from observations, and try to qualitatively explain the dawn-dusk asymmetry by introducing a region-1 current system analogous to that at Earth, which arises from the detailed interaction between solar wind and magnetosphere. Generally, I expect the day side sector of the main oval to brighten more than the night side sector, and the dawn sector to brighten more than the dusk sector.
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1. Introduction.

Like other auroras, Jupiter's auroral emissions are excited over a broad range of wavelengths, from radio to X-ray, by the incident energetic charged particles, mainly electrons, which precipitate along the magnetic field into Jupiter's high-latitude atmosphere. The intensity of the precipitation indicates it is mainly associated with upward magnetic-field-aligned currents (FAC), which complete the system between ionospheric currents and magnetospheric field-perpendicular currents. But the Jovian aurora's structure is different from Earth-like auroras in three ways [Hill, 2001] according to observations [Clarke et al., 1998] as shown in figure 1 [Clarke et al., 2002]: a narrow, persistent, continuous oval of emission encircling the magnetic pole, located at ~ 15° magnetic colatitude; the magnetic footprints and downstream wakes of the jovian moons Io, Europa, and Ganymede, which are located in the inner magnetosphere; and time-variable and spatially-structured poleward emissions that partially fill the continuous oval, including auroral flares, dusk-dawn asymmetry, and dawn storms. To understand these distinct features, we need to investigate their origins by mapping the associated FAC into the magnetosphere.

Fueled by Jupiter’s fast rotation (its sidereal rotation period is about 10 hour while its mean equatorial radius is 11.2 times Earth's radius), Jupiter’s magnetopause location near the equatorial plane is essentially determined by a balance between the solar wind's dynamic pressure and the thermal pressure of the magnetosphere's super-hot plasma (300-400 MK), which is transported outward from the inner magnetosphere and largely concentrated near the equatorial plane by centrifugal force. These high-energy ions mainly come from the Jovian ionosphere (H⁺) and from Io's torus (mainly O²⁺ and S³⁺),
which is formed by the impact of corotating magnetospheric plasma with Io. As the plasma is transported outward, its angular velocity tends to decrease by conservation of angular momentum. Similar to the case of the Sun, this outward-moving plasma drags the frozen-in magnetic field, which is swept back as Jupiter rotates. At the feet of these corotation-lagging magnetic field lines, ion-neutral collisions in the ionosphere provide a corotation-enforcement torque to prevent the corotation of the magnetospheric plasma from breaking down completely and create a current loop to transport angular momentum from the atmosphere to the equatorial magnetospheric plasma [Hill, 1979]. The current circuit includes the ionospheric Pedersen current that provides the $\vec{J} \times \vec{B}$ force to balance the viscous force exerted by the ion-neutral collisions, the equatorial outward radial current that provides the $\vec{J} \times \vec{B}$ force to enforce partial corotation on the outward-moving plasma, and the field-aligned currents that complete the loop and provide the major source of the main auroral oval.

Because of the interaction with the solar wind, the backward sweeping becomes tailward sweeping near the magnetopause as in the case of Earth’s magnetopause. In some sense, we can say backward sweeping is driven by Jupiter’s rotation while tailward sweeping is driven by the solar wind [Vasyliunas, 1983]. In the inner and middle magnetosphere or near the equatorial plane, the backward-sweeping effect is dominant due to Jupiter’s fast rotation, while in the outer magnetosphere and away from the equatorial plane, especially in the dusk sector, we can observe the effect of tailward sweeping, which could indicate super-corotation in the dusk sector of the outer magnetosphere. This interaction with the solar wind involves another system of field-aligned currents that have been called Region-1 & 2 currents by analogy with Earth
[Kivelson et al., 2002]. The Region-1 & 2 currents overlap with Hill’s corotation-enforcement current loop and together they are responsible for the morphology of the Jovian Aurora.

The outward-moving plasma, which is energized by Jupiter’s fast rotation and concentrated near the equatorial plane, also carries a thin azimuthal current sheet, called a magnetodisk, that extends outward from Io’s torus and covers all local times like the ring current at Earth [Hill et al., 1983]. On the day side, the magnetodisk current typically peaks at about three quarters of the magnetopause distance [Cowley & Bunce, 2003]. On the night side, it merges with the current sheet of the magnetotail, which also flows azimuthally. These azimuthal currents change the configuration of the magnetospheric magnetic field and play a crucial role in mapping from the ionosphere to the equatorial plane in the magnetosphere along the field lines, which carry the FACs.

Temporal changes in the solar wind strongly affect the size and morphology of the jovian magnetosphere, and hence the jovian aurora. Two recent studies [Cowley & Bunce, 2001; Southwood & Kivelson, 2001] have argued that the jovian main auroral oval should become dimmer due to the compression of the jovian magnetosphere in response to a sudden increase in solar wind dynamic pressure. But there are observations [Baron et al., 1996; Connerney et al., 1996; Gurnett et al., 2002] reporting the opposite effect: a solar-wind compression causes the auroral oval to brighten and move poleward. Similar observations from Saturn have also been reported recently [Clarke et al., 2005; Crary et al., 2005]. In this thesis, I will address this discrepancy by including the neutral atmosphere flywheel effect [Huang and Hill, 1989; Pontius, 1995] whereby, in a steady state, the neutral atmosphere in the Pedersen conducting layer shares most of the
corotation lag of the ionospheric plasma. After a sudden magnetospheric compression
due to a solar-wind shock, the rotational velocity of the magnetospheric and ionospheric
plasma changes abruptly (~ 1 hr) due to conservation of angular momentum, but the
neutral atmosphere, because of its greater inertia, responds much more slowly. Thus, the
corotation-enforcement current circuit temporarily reverses and strengthens after the
compression, thus brightening the main auroral oval.

2. Review of Steady-State Models

The divergence-free magnetic field can be expressed in terms of Euler potentials \( f \)
and \( g \) [Goertz et al., 1976; Khurana, 1997] as:

\[
\vec{B} = \nabla f \times \nabla g
\]  

(1)

Since \( \vec{B} \cdot \nabla f = 0 \) and \( \vec{B} \cdot \nabla g = 0 \), we can track a field line from the equatorial plane
to the ionosphere by finding constant Euler potentials \( f \) and \( g \). In the magnetosphere, I
will ignore \( B_\phi \) and consider an axisymmetric model because \( B_\phi \) does not affect the radial
distance at which a field line crosses the equatorial plane. A rotational-axis-aligned
dipole field model is used in this paper to represent the internal planetary field for
simplicity, and none of the magnetic field models I consider account for the
magnetopause currents that cause local time asymmetry. In cylindrical coordinates, we
can assign \( g = \phi \) (the azimuthal angle) so that

\[
B_\phi = 0, \quad B_z = \frac{1}{\rho} \frac{\partial \rho}{\partial \rho} f, \quad B_\rho = -\frac{1}{\rho} \frac{\partial}{\partial \rho} f
\]  

(2)
Cowley et al. [2001] called $f$ the flux function and derived it from the vector potential $A$ by assuming $A_\rho, A_z = 0$ and $f = \rho A_\phi$. The flux function is constant along an L-shell in axis-symmetric magnetic field models.

When mapping a field line from the ionosphere to the equatorial plane, if no global 3-D magnetic field model is available, we need two separate 2-D magnetic field models to calculate the flux function separately, one for the ionosphere and one for the equatorial plane, and we set the arbitrary constant in the flux function at certain locations both on the equatorial plane and in ionosphere, where we can assume they map to each other through the same field line. There are two sets of locations for us to utilize: the intersection of the equatorial plane with the ionosphere, and the moon Io’s orbit and its flux tube footprint in the ionosphere.

2.1 Hill’s corotation enforcement current system

As illustrated in figure 2, if we assume axial symmetry and that the angular velocity of the plasma in the equatorial plane equals that of the ions at the footprint of the same flux tube in the ionosphere, the equatorward height-integrated ionospheric Pedersen current that is generated by ion-neutral collisions in the ionosphere has height-integrated current density per unit length:

$$i_p = \Sigma_p B_i p_i \left( \Omega_i - \omega(\theta_i) \right)$$

(3)

where $\Sigma_p$ is the height-integrated Pedersen conductivity, $B_i \approx 2B_j$ is the strength of the ionospheric magnetic field that is assumed to be radial and approximated in strength by its polar value, $p_i = R_i \sin(\theta_i)$ is the distance from the magnetic axis, $p_i \left( \Omega_i - \omega \right)$ is the
azimuthal velocity of the ions relative to the neutrals (westward when \( \omega < \Omega_j^* \)), and \( \Omega_j^* \) is the angular velocity of the neutrals, which also lags behind planetary rigid corotation due to the effect of ion-neutral collisions, and is given by [Huang and Hill, 1989]:

\[
\Omega_j^*(\theta, (\rho_e)) = (1 - k)\Omega_j + k\omega_{\text{steady}}(\rho_e)
\]  

(4)

where \( \Omega_j = 1.76 \times 10^{-4} \text{ rad s}^{-1} \) is the planetary rigid-corotation angular velocity, \( k \approx 0.9 \) is the slippage ratio [Huang and Hill, 1989; Pontius, 1995], and \( \omega_{\text{steady}} \) is the plasma angular velocity when the magnetosphere is in a steady state. When considering a time-variable event in the magnetosphere, I will assume \( \Omega_j^* \) does not change because of the huge mass of the Jovian atmosphere, which acts like a running flywheel that can not be stopped suddenly by a small torque. Huang and Hill [1989] called this the flywheel effect. So from equation (4), in a magnetospheric event, \( \Omega_j^* \) is related to the initial state of the plasma partial corotation profile. In a steady state, after assuming an axis-aligned dipole field model in the ionosphere and substituting Eq. (4) into Eq. (3):

\[
i_p(\theta, (\rho_e)) = 2\Sigma_p^* B_j R_j \sqrt{\frac{F_e(\rho_e)}{B_j R_j}} (\Omega_j - \omega(\rho_e))
\]  

(5)

where \( \Sigma_p^* = (1 - k)\Sigma_p \sim 0.25\text{mho} \) is an effective height-integrated Pedersen conductivity.

From the condition of current continuity in Hill’s corotation enforcement current circuit and the simplification of axial-symmetry and north-south symmetry, as shown in figure 2, we have [Cowley and Bunce, 2001]:

\[
2\pi \rho_i i_p = 2(2\pi \rho_i) i_p
\]

\[
\frac{j_{\theta i}}{2B_j} = \frac{j_{\phi i}}{B_i} = \frac{j_{\phi}}{B_{se}}
\]

\[
2j_{se} \cdot (2\pi \rho_e d\rho_e) = -2\pi d(\rho_i i_p)
\]  

(6)
where \( i_p \) is the radial equatorial corotation enforcement current (CEC) intensity per unit length, \( j_{\parallel i} \), \( j_{\perp} \) are the field aligned current (FAC) density (per unit area) at the foot of the same flux tube in the ionosphere and at the equatorial plane. Substitute Eq. (5) into Eq. (6):

\[
j_{\parallel i} = -\frac{4B_j}{\rho_e B_{ze}} \frac{d}{d\rho_e} \left( F_e \sum \left( \Omega_j - \omega \right) \right) = -4 \sum B_j \left[ \frac{F_e}{\rho_e |B_{ze}|} \frac{d\omega}{d\rho_e} + (\Omega_j - \omega) \right]
\]  

(7)

If we assume that plasma moves slowly radial outward while ions are confined to the equatorial plane, the electromagnetic torque \( dT_z \) exerted by the CEC in an equatorial annular disc between radial distances \( \rho_e \) and \( \rho_e + d\rho_e \) is:

\[
dT_z = |r \times (j \times B)| 2\pi \rho_e d\rho_e = 2\pi \rho_e^2 i_p |B_{ze}| d\rho_e = 4\pi \rho_e \rho_i p_i |B_{ze}| d\rho_e
\]  

(8)

From Newton’s second law, this equals the radial differential of the flux of angular momentum:

\[
\frac{dT_z}{d\rho_e} = \frac{d}{d\rho_e} \left( M \rho_e^2 \omega(\rho_e) \right)
\]  

(9)

where \( M \approx 1 \text{ ton s}^{-1} \) is the azimuthally integrated plasma radial outward mass transport rate. In a steady state, after substituting Eq. (8), (5) into Eq. (9), we get Hill’s [1979] corotation enforcement equation:

\[
\frac{d\omega}{d\rho_e} = \left[ 4R_H^4 \frac{F_e}{B_j R_j^2} \frac{|B_{ze}|}{B_j} (\Omega_j - \omega) - 2\omega \right] / \rho_e
\]  

(10)

where \( R_H/R_j = \left( \frac{2\pi \sum B_j^2 R_j^2}{M} \right)^{1/4} \) is the Hill scale. Our boundary condition for Eq. (10), following Cowley et al [2002], is to assume rigid corotation at \( \rho_e = 7.5R_j \). After
substituting into Eq. (7) the solution for the steady-state angular velocity profile from Eq. (10), and using a magnetic field model to map from the equatorial plane to the ionosphere, we will get the distribution of the FACs in the ionosphere as a function of colatitude.

2.2 Magnetic field models

Connerney’s VIP4 3-D internal field model [Connerney et al., 1998] successfully maps Io’s orbit to its observed auroral footprint, and fits the in situ magnetic field measurements throughout the inner magnetosphere ($r<30R_J$). This model is obtained from the summation of the internal planetary field, which is represented by a degree and order 4 spherical harmonic expansion, and the magnetic field generated from a model of the magnetodisc, which extends from 5 $R_J$ to 50 $R_J$, has a half thickness of 2.5 $R_J$, and bears an azimuthal current whose density falls inversely with distance from the dipole-field axis. As stated before, for simplification, I will ignore the tilt angle (9.6°) between the magnetic dipole moment and the planet’s rotational axis and substitute a spin-aligned dipole field for the internal planetary field since the dipole field is dominant in the inner magnetosphere. Following Cowley et al.’s paper [2001], I will call this simplified model the CAN model. With the CAN model we can use a dipole field model in the ionosphere since the effect of the magnetodisc is ignorable there. Following Cowley et al. [2001], the ionospheric value of the flux function is set to be zero on the magnetic axis that maps to infinite radial distance on the equatorial plane in a 3-D dipole field model. So the modeled flux function in the ionosphere is

$$F_i = B_J R_J^2 \sin^2 \theta_i$$  \hspace{1cm} (11)
where $B_j$ is the jovian equatorial magnetic field strength (taken as $4.28 \times 10^5$ nT in conformity with the VIP4 model), $R_j$ is Jupiter's radius (taken as 71,373 km), $\theta_i$ is the magnetic colatitude, and I am assuming that the ionosphere is a thin spherical surface at a radial distance of $R_j$.

From equation (11), we can get the relation between the colatitude of the field line's footprint in the ionosphere and the value of the flux function in the equatorial plane by setting $F_r(\rho_e) = F_r(\theta_i)$:

$$\theta_i(\rho_e) = \sin^{-1} \left( \frac{F_r(\rho_e)}{B_j R_j^2} \right)$$  \hspace{1cm} (12)

This is the equation used by Cowley & Bunce [2001] to map field lines from the equatorial plane to the ionosphere.

The corresponding approximate analytical solution for the modeled flux function in the equatorial plane, for $5R_j < r < 30R_j$, is [Edwards et al., 2000; Cowley & Bunce, 2001]

$$F_e(\rho_e) = \frac{B_j R_j^2}{\rho_e} + \frac{\mu_0 I_0}{2} \left\{ D \sqrt{\rho_e^2 + D^2} + \frac{\rho_e^2}{2} \log \left[ \sqrt{\rho_e^2 + D^2} \right] \right\}$$

$$- \rho_e^2 \log \left[ \frac{\sqrt{R_i^2 + D^2} + D}{\sqrt{R_i^2 + D^2} - D} \right] - \frac{R_0 D}{2 \sqrt{\rho_e^2 + D^2}} - D^2$$ \hspace{1cm} (13)

where $R_0 = 5R_j$ and $R_i = 50R_j$ are the inner and outer radii of the magnetodisc, $D = 2.5R_j$ is the half-thickness of the magnetodisc, $\rho_e$ is the radial distance from the magnetic axis on the equatorial plane, and $\frac{1}{2} \mu_0 I_0 = 225nT$ is the current intensity parameter of the magnetodisc.
Because of the strong internal field of Jupiter, the magnetic field strength changes vastly from $\sim 10^5$ nT at Jupiter's ionosphere to $\sim$ several nT near the magnetopause in the magnetosphere. The VIP4 field model that fits the observations in the inner magnetosphere usually does not fit the data in the middle and outer magnetosphere because the relative error becomes larger while the absolute field strength becomes smaller as the influence of the planetary internal field weakens with radial distance, and because the model does not consider the shielding effect of the magnetopause current and the detailed distribution of the azimuthal current density in the magnetodisc. Thus we need to find a 2-D equatorial magnetic field model that fits the observations in the middle and outer magnetosphere. Since $B_\rho, B_\varphi = 0$ in the equatorial plane, the flux function can be obtained by integration of Eq. (2):

$$ F_\varphi(\rho) = F_\varphi(\rho_0) + \int_{\rho_0}^{\rho} \rho' B_{\varphi}(\rho')d\rho' $$

(14)

where $\rho_0$ is the radial distance at which the magnetic field strength computed from the model equals that of the CAN model within 30 R$_J$, and $F_\varphi(\rho_0)$ is calculated from the CAN model.

Goertz et al. [1976] built an azimuthally symmetric Harris sheet field model coupled with the dipole field. The model also includes the observed data on the sweeping back of the field lines. From Khurana (1997), the field produced by the Harris sheet is fitted as:
\[ B_\rho = \frac{b_0 \tanh(Z/D)}{r^a} - B_Z \frac{Z}{\rho} \]
\[ B_\varphi = -6.12 \times 10^{-3} B_\rho \rho e^{\frac{\rho}{500}} \tag{15} \]
\[ B_Z = \frac{ab_0}{r^{a+2}} \left[ \ln \left( \cosh \frac{Z}{D} \right) + C \right] \]

where D is the half-thickness of the Harris sheet, \( \rho, r, Z \) are in units of \( R_J \), and \( r^2 = \rho^2 + Z^2 \) here. From equation (15), in the equatorial plane where \( Z = 0 \), coupled with the dipole field, \( B_Z \) is then of the form:

\[ B_Z = -\frac{M_J}{\rho^5} + \frac{K}{\rho^{a+2}} \tag{16} \]

where \( M_J = 4 \times 10^5 nTR_J^3 \) is the dipole moment, and \( K = ab_0 C \). When fitted to the observations in logarithmic scale, if \(|a - 1| < 0.4\), the modeled curve can be approximated by a linear curve in the region \( 10R_J < \rho < 100R_J \):

\[ B_z = -\frac{A}{\rho^m} \tag{17} \]

Khurana and Kivelson (1993) fitted this formula to the data in the middle and outer magnetosphere from Voyager 1 and got \( A = 5.4 \times 10^4 nT, m = 2.71 \), which correspond approximately to \( K = 5 \times 10^5 nT, a = 1.18 \) in equation (16). Cowley [2001] called this simple power law model the KK model.

Another model available for the middle and outer magnetosphere was developed by Khurana (1997), which is also derived from Goertz’s [1976] model but also includes the effects of hinging and rotational delay of the current sheet with radial distance. In the equatorial plane where \( Z = 0 \), from equations (20) & (25) of Khurana’s [1997] paper, the magnetic field produced by the Harris sheet is
\[ B_z = C_2 \left[ \tanh \left( \frac{\rho_{02}}{\rho} \right) \right]^{a_2} + C_3 \left[ \tanh \left( \frac{\rho_{03}}{\rho} \right) \right]^{a_3} + C_4 \]  

where \( C_2 = 916.4nT \), \( C_3 = 70.6nT \), \( C_4 = -1.3nT \), \( \rho_{02} = 1.78R_J \), \( \rho_{03} = 27.9R_J \), \( a_2 = 1.62 \), \( a_3 = 9.56 \) when the model is fit to Voyager 1 data. The planetary internal field model used by Khurana is the GSFC O6 model. For the same reason stated above in connection with the VIP4 model, we will replace O6 by the dipole field model and call the resulting model the K97 model. As noted by Khurana, this model only fits the data in the nightside low-latitude magnetosphere, and its parameters change greatly among different data sets since it also does not include the magnetopause currents.

3. Time-Dependent Model

Since I am considering an axisymmetric model in this thesis, which means the detailed interactions between the solar wind and magnetosphere are ignored, the only time-dependent events induced by the solar wind that I can investigate in this model are the expansions and compressions of the magnetosphere caused by solar wind dynamic pressure variations. Cowley and Bunce [2003] estimate that the time scale for a magnetospheric compression caused by a sharp increase in the solar wind dynamic pressure is \( \tau_{MP} \sim 2 \) hour, the time scale for communication between the equatorial plane and the ionosphere along a flux tube is \( \tau_{\lambda}(\rho_e) \sim \left( 30 \right) \left( \frac{\rho_e}{20R_J} \right)^{2.7} \), and the time scale for equatorial plasma acceleration due to the \( j \times B \) force provided by the CEC is \( \tau_{Mi}(\rho_e) \sim \left( 5 \right) \left( \frac{\rho_e}{20R_J} \right)^{4.7} \left( -\frac{\rho_e}{13R_J} \right). \) I will assume that the magnetosphere gets
suddenly compressed or expanded by a sharp variation in the solar wind; thus modeling the event on a time scale larger than $\tau_{MP}$, which is $\sim 2$ hour. Since $\tau_A \ll \tau_{MP}$, I will assume there are no variations of the plasma angular velocity along a flux tube between the ionosphere and equatorial plane during the magnetospheric event. During a sudden compression or expansion of the magnetosphere, I also ignore the effect of the $j \times B$ force provided by the CEC on the plasma angular velocities in the middle magnetospheric equatorial plane since $\tau_{MF} \gg \tau_{MP}$ in the middle magnetosphere, which means the angular momentum of the plasma is approximately conserved during the sudden compression or expansion of the magnetosphere. Thus the angular velocity of a flux tube after the compression is

$$\omega'(\theta') = \omega'(\rho') = \left(\frac{\rho'}{\rho}\right)^2 \omega(\rho)$$

(19)

where $\rho$ and $\rho'$ are the equatorial radial distances of the same flux tube before and after the compression, and $\omega(\rho)$ is the steady-state angular velocity computed from Eq. (10).

The change in the magnetic field after a sudden magnetospheric compression induced by the solar wind is modeled by adding a constant $\Delta B_{ze}$ (negative in compression) to the steady-state equatorial magnetic field model [Cowley and Bunce, 2003]. This is certainly a rough approximation to represent the fact that the displacement of the field lines becomes smaller for smaller radial jovicentric distance and becomes negligible in the inner magnetosphere where $\Delta B_{ze}$ is much weaker than the original field. But I argue that this assumption is approximately valid based on the paradigm of a dipole field confined inside a spherical magnetopause, where the shielding magnetic field
produced by magnetopause currents is constant. To investigate the spatial variation of $\Delta B_{ze}$ we would need to introduce the detailed shape of the magnetopause and break the simplification of axisymmetry. So the equatorial magnetic field after the compression of the magnetosphere is assumed to be:

$$B'_{ze}(\rho') = B_{ze}(\rho') + \Delta B_{ze}$$  \hspace{1cm} (20)

where $\rho'$ is the plasma equatorial radial distance after the compression, and $B_{ze}(\rho')$ is computed from the steady-state magnetic field model before compression. Using Eq. (14) and assuming that the value of the flux function for a given flux tube does not change during the compression since the ionospheric foot of the flux tube hardly changes during the compression ($\theta' = \theta$), we can find the relationship between $\rho$ and $\rho'$, the equatorial radial distances of the flux tube before and after the compression,

$$F_e(\rho) = F'_e(\rho') = F_e(\rho') + \frac{1}{2} \Delta B_{ze} \rho'^2$$  \hspace{1cm} (21)

where $F_e(\rho)$ and $F'_e(\rho')$ are computed from the steady-state magnetic field model with Eq. (14). Differentiating both sides of Eq. (21) by $\rho$ and using Eq. (2), we have:

$$\frac{d\rho}{d\rho'} = \frac{\rho'}{\rho} \cdot \frac{B_{ze}(\rho') + \Delta B_{ze}}{B_{ze}(\rho)}$$  \hspace{1cm} (22)

3.1. Neutral Atmosphere Flywheel Effect

After the sudden compression or expansion, we need to consider the flywheel effect of the neutral atmosphere that appears in Eq.(3) and Eq.(7) in the form of $\Omega_j^*$. The ionospheric Pederssen current is now proportional to $\Sigma_p(\Omega_j^* - \omega')$, because $\Omega_j^*$ changes on a much longer time scale than $\omega$. It is proportional to the true conductance $\Sigma_p$ rather
than the effective conductance $\Sigma^*_p$ that applies to the prior steady state. However $\Sigma^*_p$ is better constrained by observations than $\Sigma_p$ itself, so I define an "effective" angular velocity $\omega_{f_0}$ such that $\omega_{f_0}(\rho') = \frac{\Sigma^*_p}{\Sigma_p} \left( \Omega_j'(\triangledown' \theta' - \rho'(\rho')) \right)$. With Eq. (4), we have

$$\omega_{f_0}(\rho') = \frac{1}{1-k} \left[ (\Omega_j - \omega(\rho')) - k(\Omega_j - \omega(\rho')) \right]$$ (23)

where $\omega(\rho')$ and $\omega'(\rho')$ can be computed from Eq. (10) and (19). After we normalize all the angular velocities in units of $\Omega_j$, radial distance in units of $R_j$, magnetic field in units of $B_j$, and flux function in units of $B_j R_j^2$, with Eq. (14), Eq. (5) and (7) change to:

$$i'_{e}(\theta'(\rho')) = 2 j_0 R_j \omega_{f_0}(\rho') \sqrt{F'(\rho')}$$

$$j'_{e, \theta}(\rho') = -\frac{4 j_0 F'(\rho')}{\rho'B_e'(\rho')} \frac{d}{d\rho'} \left[ \omega_{f_0}(\rho') \right] - 4 j_0 \omega_{f_0}(\rho')$$ (24)

where $j_0 = \Sigma_p B_j \Omega_j$, $B_e'(\rho')$ and $F'(\rho')$ can be obtained from Eq. (20) and (21), and from Eq. (23), we have:

$$\frac{d\omega_{f_0}(\rho')}{d\rho'} = \frac{1}{1-k} \left[ -\frac{d\omega(\rho')}{d\rho'} + k \frac{d\omega(\rho')}{d\rho'} \right]$$ (25)

where $d\omega(\rho')/d\rho'$ can be derived from Eq. (10) with numerical interpolation. From Eq. (19), we have:

$$\frac{d\omega'(\rho')}{d\rho'} = \left( \frac{\rho}{\rho'} \right)^2 \frac{d\omega(\rho)}{d\rho} \cdot \frac{d\rho}{d\rho'} + 2\omega(\rho) \frac{\rho}{\rho'} \left( \frac{d\rho}{d\rho'} - \frac{\rho}{\rho'} \right)$$ (26)

where $\frac{d\omega(\rho)}{d\rho}$ and $\frac{d\rho}{d\rho'}$ can be derived from Eq. (10) and (22).
3.2. Response to Sudden Solar-Wind Pressure Variations

Cowley and Bunce [2003] summarized the empirical relationship of the distance of the outer boundary of the magnetodisk on the noon side, \( R_{eb} \), and the solar wind dynamic pressure \( P \) as

\[
R_{eb} \approx \frac{26.6}{P^{0.22}}
\]  

(27)

where \( P \) is in units of nPa, typically \( \sim 0.06 \) nPa, and in the range of \( 0.01 - 1 \) nPa for Voyager 1 (Cowley and Bunce, 2003), and \( R_{eb} \) is in units of \( R_J \), typically at \( \sim 50 \) \( R_J \), and the corresponding range is \( \sim 30 \) to \( 70 \) \( R_J \). In this thesis, \( R_{eb} \) is also regarded as the distance where the return current begins. If the solar wind dynamic pressure changes on a time scale of \( \sim 2 \) h or shorter, from Eq. (21) we can calculate the induced \( \Delta B_{ze} \) as

\[
\Delta B_{ze} = 2[F_e(R_{eb}) - F_e(R'_{eb})] / R_{eb}^2
\]  

(28)

where \( R_{eb} \) and \( R'_{eb} \) are the distance where the return current begins on the noon side (in this thesis, this means the KK model) before and after the change, and \( F_e(R_{eb}) \) and \( F_e(R'_{eb}) \) are computed from the steady-state magnetic field model on the noon side. The computed \( \Delta B_{ze} \) is applied both to the noon side (KK model) and midnight side (K97 model) from Eq. (20) and (21) to model the magnetic field after the change, and then to calculate the plasma angular velocity profile after the change from Eq. (19) and (22). With this modeled angular velocity profile, we can then compute the FAC density in the ionosphere from Eq. (24) and the resulting UV auroral brightness.
4. Results and Discussion

4.1 Steady State Models

Figure 3 shows modeled $B_z$ profiles as functions of the equatorial distance from the magnetic axis in log-linear format. The CAN model has an artifact of an up-turn outside of 30 $R_J$. This is mainly due to the fact that the systematic error of the analytical simplification in this model becomes non-negligible beyond 30 $R_J$. The CAN model is based on data within 30 $R_J$ and is intended for use only in that range. The KK and K97 models include observational data from the middle and outer magnetosphere. The KK model is a power law curve simplified from a Harris sheet model, while the K97 model includes the effects of hinging and rotational delay of the current sheet with radial distance. K97 exhibits a slight increase of $|B_z|$ with distance outside of 70 $R_J$. In this thesis, I adopted a numerical finder to find the intersection of the KK or K97 model with the CAN model inside 30 $R_J$, using KK and K97 to represent the magnetosphere outside the intersections and the CAN model inside the intersections. The dashed line shows the planetary dipole field alone for comparison.

Figure 4 shows the flux function profile as a function of equatorial distance and the corresponding colatitude mapping function $\theta_c(\rho_c)$ from Eq. (12). The KK and K97 models both indicate that the flux function is nearly constant beyond 20-30 $R_J$, as is the colatitude range of the ionospheric mapping: for radial distances from 30 $R_J$ to 100 $R_J$ the ionospheric colatitude varies only in the range of $16.2^\circ \pm 0.5^\circ$ with the KK model and $16.65^\circ \pm 0.5^\circ$ with the K97 model (in a dipole field, this small range of magnetic colatitude maps to a narrow band of field lines in the equatorial plane centered near ~12 $R_J$ as noted
by Cowley and Bunce (2003)). This suggests that phenomena occurring in the middle magnetosphere are all being mapped to a very narrow region in the ionosphere along magnetic field lines, which explains the brightness of the main auroral oval. It also implies that the KK and K97 models do not cover the region poleward of the main auroral oval since the field lines in these models are closed field lines while part of the polar region is linked by open field lines.

Figure 5 shows plasma angular velocity profiles based on Eq. (10) with different magnetic field models. Eq. (10) was solved with a standard fourth-order [or whatever order it was] Runge-Kutta method. The dashed line based on the axis-aligned dipole field model is plotted to verify the validity of the numerical method by comparing it to the analytical result, which is basically identical. If $|B_{ze}|$ falls monotonically with radial distance, which is true for all models except K97 beyond 70 R$_J$ (and CAN outside its region of validity < 30 R$_J$), The corotation-enforcement component on the right hand side of Eq.(10) decreases to such a negligible level that the asymptote of the angular velocity curve outside of 70 R$_J$ becomes $\rho^{-2}$, which implies conservation of angular momentum as the plasma travels outward. The reported observations vary greatly. As shown by Cowley and Bunce [2001], the K97 model conforms approximately to the data from the post-midnight pass of Voyager 2 in which $\omega/\Omega_j \approx 0.5$ at ~50R$_J$, falling to ~0.3 at ~120 R$_J$, while the KK model behaves similarly to the pre-noon Ulysses data where $\omega/\Omega_j \approx 0.2$ at ~50-70R$_J$. This variety arises mainly from the interaction between the backward sweeping driven by planetary rotation and the tailward sweeping driven by the solar wind. The tailward sweeping will enhance sub-corotation in the dawn sector while diminishing it or even driving it to super-corotation in the dusk sector as illustrated in
figure 6. In this thesis, I will use K97 to represent the post-midnight sector data and KK to represent the pre-noon sector. Because of the tailward sweeping produced by the solar wind impact, we should expect mapping differences at different local time sectors at the same equatorial distance. The mapping distance for a given colatitude should be larger in the midnight sector than in the noon sector, as shown in Figure 4 where the KK curve is distinctively lower than the K97 curve.

Figure 7 shows the upward field-aligned current density $j_{\parallel i}$ computed from Eq. (7) in the ionosphere versus colatitude (top panel) and versus the corresponding mapped equatorial jovicentric distance (bottom panel). The upward peak value of $j_{\parallel i}$ is directly related to the auroral precipitated energy flux $E_f$ and hence to auroral brightness. Assuming that the ratio of the magnetic field strength in the ionosphere $B_i$ to that at the top of the voltage drop $B_\odot$ is $R_B = B_i / B_\odot \gg 1$ which is valid in the middle magnetosphere (figure 3), we have:

$$\frac{E_f}{E_{f0}} = \frac{1}{2} \left[ \left( \frac{j_{\parallel i}}{j_{\parallel i0}} \right)^2 + 1 \right]$$

[Knight, 1973; Cowley and Bunce, 2001]

where $j_{\parallel i0} = 0.013 \mu A \ m^{-2}$ is the maximum field aligned current density in the absence of a field-aligned voltage, and $E_{f0} \approx 0.07 \ mW \ m^{-2}$ is the maximum energy flux without field-aligned acceleration, corresponding to a UV auroral brightness $\sim 0.8 \ kR$ with the assumption of 20% conversion efficiency. From figure 7, the pre-noon sector auroral brightness predicted by the KK model peaks at $\sim 15.9^\circ$ colatitude, mapping to 70.5 R$_i$. The peak value of $j_{\parallel i}$ is $0.38 \ \mu A \ m^{-2}$, corresponding to brightness of 340 kR. The kink at
~17.1° colatitude and ~ 21 R_J is an artifact due to the transition between the CAN model and the KK model. The post-midnight sector prediction from the K97 model peaks at ~17.15° colatitude, mapping to 30.5 R_J. The peak value of $j_{||}$ is 0.78 μA m$^{-2}$, corresponding to a brightness ~1.44 MR. Note that the FAC density at the ionosphere in pre-noon sector (KK model) peaks beyond 70 R_J although, as mentioned above, the angular velocity of plasma beyond that location falls nearly as $\rho_e^{-2}$ as it travels outward, which implies that the torque provided by the CEC is negligible. The most likely explanation for this is that in Eq. (6) the ratio of the FAC density in the magnetospheric equatorial plane to that at the ionosphere is proportional to the ratio of magnetic field strength. Since the magnetic field strength in the equatorial plane in the pre-noon sector falls roughly in proportion to $\rho^{-2.7}$ from Eq. (17), the FAC density in the equatorial plane peaks far inside 70 R_J (it peaks at 21.7 R_J as calculated from Eq. (6)). In fact, most of the $\vec{J} \times \vec{B}$ torque transferred from the ionosphere by FAC is within 30 R_J for both the KK and K97 models, which means that the torque provided by Hill's corotation enforcement current system is mainly applied around 20-30 R_J where the CAN model is valid and is not much affected by solar wind impact although the FAC density in the ionosphere varies significantly as a function of local time.

4.2. Time-Dependent Results

Figure 8 and figure 9 show the equatorial magnetic field strength, the mapped magnetic colatitude, the plasma angular velocity profile, and the FAC density in the ionosphere before (marked 50 R_J) and after a sudden change in solar wind dynamic pressure for the pre-noon side using the KK model. Most of the FAC is confined to a
small range of magnetic colatitude, from 16.2° to 18° (with mapped equatorial distance from $R_{eB}$ to $\sim 15$ $R_J$). The colatitude does not vary during the compression/expansion event by assumption in Eq. (21). In the plot of angular velocity profile, the dashed line is the angular velocity of the neutrals modeled from Eq. (4), which is also assumed to be constant during the event because of the flywheel effect [Huang and Hill, 1989; Pontius, 1995]. For cases of expansion induced by a decrease in solar wind dynamic pressure, the plasma in the magnetosphere lags more behind the rotation speed of the neutrals, causing the FAC density to increase, and hence the brightness of the jovian main auroral oval. From Eq. (29), the bottom panel of figure 9 shows that the main oval will become 10-fold brighter if $R_{eB}$ expands from 50 $R_J$ to 60 $R_J$, corresponding to the solar wind dynamic pressure dropping to 0.025 nPa from Eq. (27).

During most events of compression, the plasma in the magnetosphere may temporarily become super-corotational relative to the neutrals in the planetary ionosphere as its angular momentum is conserved during the events, as shown in the cases marked as “45” and “40” in the top panel of figure 9, or even become super-corotational relative to the planetary rigid-cototation angular velocity, as shown in the cases marked “35” and “30”. This will reverse the ‘effective’ angular velocity $\omega_{\text{rot}}$ of ions relative to the neutrals in the ionosphere in Eq. (23) in most compression events, which means the neutrals will slow down the ions during these events and reverse the Pedersen currents in the ionosphere and hence the whole corotation enforcement current system as indicated in Eq. (24). Since the FAC in the ionosphere is reversed in most compression events (its density distribution is shown in the bottom panel of figure 9; note that the bulges in the curves are magnetic field modeling artifacts due to transiting from the CAN model to the KK
model), the return current becomes upward after the compression to complete the current system, and the main auroral oval is now associated with the return current mapping to the outer magnetosphere rather than to the middle magnetosphere as before the compression. As we do not have a detailed magnetic field model of the outer magnetosphere, we cannot model the detailed distribution of the return current. But we can infer that the main oval is now 'contracted' and lies poleward of its quiet time location, and we can calculate the total magnitude of the return current density per unit azimuthal distance, which is associated with the average brightness of the main oval. In this thesis, we will assume the return current flows at the last closed field line outside $R_{eq}$ and its magnitude equals the ionospheric Pedersen current $i_p$ per unit length that maps to this location, because of the continuity of current. Figure 10 shows the total return current density versus the compressed (or expanded) $R_{eq}$. The return current density crosses zero at 47 $R_J$ and its magnitude becomes larger than the quiet time value starting at 45 $R_J$ (equivalent to 0.09 nPa of solar wind dynamic pressure from eq. (27)), indicating that the jovian main auroral oval becomes brighter (from eq. (29)). So we expect that the jovian main auroral oval becomes contracted and brighter when the solar wind dynamic pressure increases beyond 0.09 nPa from 0.06 nPa within a 2-hour time scale. From Eq. (29), it becomes more than 10-fold brighter than steady state if the pressure increases to 0.13 nPa (corresponding to $R_{eq} \sim 42$ $R_J$) and 100-fold brighter if it increases to 0.29 nPa (corresponding to $R_{eq} \sim 35$ $R_J$).

4.3. Discussion
As the main auroral oval is now temporarily mapped to the outer magnetosphere during most cases, we need to consider the effect of another field-aligned current in that region: Region-1 currents. As shown in figure 11, the solar-wind-driven region-1 currents flow downward in the dusk sector and upward in the dawn sector. In steady state, their effect on the jovian aurora is diminished by the overlapping downward return current of the CEC system, while the detailed distributions of these currents are not known yet. In the cases of inverted return currents, we expect some dawn-dusk asymmetry induced by the overlapping region-1 currents, in which the contracted main oval is brighter on the dawn side than the dusk side. If the solar wind dynamic pressure increases only modestly, the main oval could become smaller but not necessarily dimmer since the overlapping region-1 current density varies strongly with changes in the solar wind as we know from the case of the Earth.

Figures 12, 13, and 14 show the changes in the post-midnight sector with the K97 model during a sudden change in solar wind dynamic pressure. The induced $\Delta B_{se}$ is calculated from the pre-midnight sector using the KK model. Note that, when we apply the same $\Delta B_{se}$ to both the pre-midnight sector and the mid-night sector, the flux tubes with the same equatorial radial distance in both sectors are compressed/expanded to approximately the same equatorial radial distance after the sudden change. In other words, if a flux tube in the pre-midnight sector with an equatorial radial distance of 50 $R_J$ in steady state is compressed to 30 $R_J$, a flux tube in the post-midnight sector at 50 $R_J$ will also be compressed to 30 $R_J$. This is mainly due to the fact that the curves of the flux function of the KK model and the K97 model are almost parallel to each other between 30 $R_J$ and 70 $R_J$ as we can see from the top panel of figure 4, and that, from eq. (28), the parallel curves
of flux function with the same \( R_{eB} \) and \( R'_{eB} \) will introduce the same \( \Delta B_{eB} \). So in the post-
midnight sector, we marked the curves the same as in the pre-noon sector to model the
same changes in the solar wind.

The bottom panel of figure 13 shows that most of the FAC in the post-midnight
sector also lies in a small range of magnetic colatitude, from 16.9° to 18°. The main oval
in the midnight sector will become about 9-fold brighter if \( R_{eB} \) expands from 50 to 60 \( R_J \),
corresponding to the solar wind dynamic pressure dropping from 0.06 to 0.025 nPa (the
pre-noon sector is 10-fold brighter in this case). During compression events, plasma in
the magnetotail becomes temporarily super-corotational relative to the neutrals in the
planetary atmosphere in the cases marked from "45" to "30" in the top panel of figure
13, but its angular velocity increases less than in the pre-noon sector as we can conclude
from comparison of figures 9 and 13. Figure 14 shows the total return current density in
the post-midnight sector versus \( R_{eB} \). The return current density crosses zero at around
46.3 \( R_J \) and its magnitude becomes larger than quiet time below 44 \( R_J \). So we expect that
the jovian main auroral oval in the post-midnight sector becomes contracted and brighter
when the solar wind dynamic pressure increases beyond 0.1 nPa within a 2-hour time
scale. Also it becomes more than 10-fold brighter than steady state if the pressure
increases to 0.22 nPa (corresponding to \( R_{eB} \sim 37 \ R_J \)). Overall, we expect a pattern of
change in the post-midnight sector similar to its pre-noon counterpart, but the magnitude
of the change is less than that of the pre-noon sector. In other words, the sector mapping
to the magnetotail is less affected by solar wind dynamic pressure than the sector
mapping near the sub-solar point.
5. Summary and Conclusions

Discrete auroral features are mainly related to upward field-aligned currents (FAC), especially in the UV and visible regions of the spectrum. The current continuity equation requires that the upward FAC density equals the negative divergence of the height-integrated Pedersen current in the ionosphere, which results from $\mathbf{E} \times \mathbf{B}$ convection of plasma in the magnetosphere. Such a divergence can result, for example, from solar-wind-driven convection as in Earth's magnetosphere, or from sub-corotation in the magnetospheres of Jupiter and Saturn. The maximum upward FAC density in the absence of a field-aligned potential drop is the magnetospheric thermal current density

$$J_0 = eN \sqrt{\frac{W_{th}}{2\pi m_e}}$$  [Knight, 1973], which assumes a full electron loss cone all along the field line. This value is much less than the magnitude required to excite observed auroral brightness features. With a potential drop, the maximum upward FAC density becomes

$$J_{max} = J_0 \left( \frac{B_i}{B_{eq}} \right)$$

which assumes continuity of electrical current along a flux tube (where $B_i$ and $B_{eq}$ are the field strengths at the ionosphere and at the equatorial crossing point of a field line). In a steady state, the Jovian auroral main oval is related to the upward FAC in the corotation-enforcement current (CEC) circuit [Hill, 1979; 2001], which transports angular momentum from the ionosphere to the outward traveling plasma near the magnetospheric equatorial plane through ionospheric collisions between neutrals and charged particles.

To map the equatorial plane to the ionosphere along field lines, in the present work I utilized the flux function, which is constant along a field line. (Note that by using this mapping method we can not track the open field lines that have only one end on Jupiter.) I have applied a 2-D spin-aligned dipole field model to the ionosphere, and a simplified
VIP4 model to the inner magnetosphere (following Cowley and Bunce [2001]). I have applied two different empirical magnetic field models to different local time sectors in the middle magnetosphere, the KK model to the pre-noon sector and the K97 model to the post-midnight sector, to examine the effect of the solar wind on different local time sectors of the main auroral oval. Both models map the magnetosphere at radial distances from 30 Rₗ to 100 Rₗ to a narrow band in the ionosphere with a small range (~1°) of magnetic latitude. However outside 60 Rₗ the magnitude of the equatorial magnetic field in the day side middle magnetosphere model (KK) is larger than in the night side model (K97), causing the distribution of the upward FAC mapping to move significantly outward on the night side compared to the day side. The mapped equatorial distance of a given magnetic colatitude is also larger on the night side than on the day side.

Both models produce plasma angular velocity profiles from Hill's [1979] equation that are consistent with observations. In a steady state, the computed peak value of auroral brightness in the post-midnight sector is much larger than that in the pre-noon sector because of the different magnetic field configurations induced by the tailward sweeping caused by the solar wind. The dusk sector may be the brightest sector because the plasma in that sector, especially in the low-latitude boundary layer, could become super-corotational relative to the rigid planetary rotational angular velocity, in association with the enhanced tailward sweeping in this sector.

In this thesis, although the modeled peak brightness of the main auroral oval varies significantly and maps to different radial distances in the equatorial plane in different local time sectors, most of the modeled J×B torque transferred from the ionosphere occurs within 30 Rₗ for both models, consistent with my assumption that the angular
momentum of the plasma is approximately conserved during a sudden compression or expansion of the magnetosphere in response to a sudden change in the solar wind impact pressure.

Following Cowley and Bunce [2003], I modeled a sudden change in solar wind dynamic pressure by adding a uniform $\Delta B_{ze}$ at the magnetospheric equatorial plane, consistent with the simplifying assumption of axisymmetry. I assumed that during a sudden compression/expansion event there is no variation of angular velocity along a given flux tube, because the ionosphere-magnetosphere coupling time scale is much shorter than the compression/expansion time scale, and that the angular momentum of the plasma is conserved because the plasma acceleration time scale is much longer than the compression/expansion time scale. I included the flywheel effect of the neutral particles in the ionosphere [Huang and Hill, 1989; Pontius, 1995] and assumed that the neutral’s rotational speed does not change during a compression/expansion event because of the huge inertia of the neutral atmosphere, acting like a running flywheel.

During an expansion event, the brightness of the main oval is found to be correlated positively with the degree of expansion, and the changes on the day side are found to be larger than on the night side. During most compression events, the plasma becomes super-corotational relative to the neutrals, causing the “effective angular velocity” to be inverted, and thus also the direction of the Pedersen current and the polarity of the whole CEC circuit. The absolute value of the inverted FAC density is also larger than the steady state value, and the steady state return current becomes the upward field-aligned current related to the main oval, indicating that the main oval will jump poleward and brighten. Thus I draw the conclusion that any sudden change in solar wind pressure, positive or
negative, should produce a general brightening of the aurora. (Of course, sudden positive changes of solar wind pressure are much more likely than sudden negative changes because solar-wind compressions tend to develop into shocks, while rarefactions do not.) After a sudden positive change in solar wind pressure, the CEC system is generally inverted and strengthened temporarily, thus causing the main auroral oval to contract and brighten. Existing observations [Baron et al., 1996; Connerney et al., 1996; Gurnett et al., 2002] verify the general contraction and brightening of the auroral oval in response to a solar-wind shock. And there is recent evidence from Saturn [Clarke et al., 2005; Crary et al., 2005] also supporting this conclusion.

I also expect there are local-time variations of the brightness changes of the main auroral oval in response to a sudden change in solar wind pressure, as shown qualitatively in figure 15. Based on a comparison of the KK and K97 models, I infer that the brightness changes on the noon side are substantially larger than on the night side. By including an overlapping region-1 current system analogous to that at Earth [Kivelson et al., 2002] and considering the inverted CEC system after a sudden solar-wind shock, I also expect the dawn side of the contracted main oval to become temporarily brighter than the dusk side after the compression. These expectations remain to be tested by future observations, and could be tested by Cassini UVIS data from Saturn.

Future improvements to the present model could include the magnetopause boundary conditions, allowing us to model different local time sectors together and obtain the detailed distribution of the return currents in the CEC system and the variable $\Delta B_{se}$ induced by changes of the size of the magnetosphere. Another important extension would be to model the much slower recovery toward a new steady-state configuration...
after a solar-wind compression event. This would require explicit consideration of the ion-neutral momentum exchange in the ionosphere as well as the plasma acceleration in the magnetosphere, both of which have much longer time scales than the compression itself. In the absence of such a more detailed model, one can only speculate that the auroral oval should dim after its initial brightening, going through a minimum brightness before recovering to a new steady-state brightness level at a new, more equatorward, location.
References


Figure 1. Ultraviolet image of Jupiter taken with the Hubble Space Telescope Imaging Spectrograph (HST STIS) on 26 November 1998 [Clarke, 2002].
Figure 2. Schematic plot of Hill's corotation enforcement current circuit. The distances are in units of $R_J$. $i_p$ denotes the radial equatorial corotation enforcement current (CEC), $j_{||}, j_{ze}$ are the field aligned current (FAC) at the foot of the same flux tube in the ionosphere and the equatorial plane, $i_p$ is the equatorward height-integrated ionospheric Pedersen current. The field lines are computed from the CAN magnetic field model [Edwards et al., 2000].
Figure 3. Log-linear plot of the southward component of the equatorial field $B_{ze}$ in different magnetic field models as functions of jovicentric equatorial distance. DP denotes the dipole field. The CAN model is intended only for use within 30 $R_J$. 
**Figure 4.** Plot of the flux function normalized to planetary units versus jovianentric equatorial distance (upper panel) and corresponding mapping colatitude profile calculated from eq. (12) (bottom panel).
Figure 5. Plot of the plasma angular velocity profile normalized to the planetary angular velocity $\omega/\Omega_p$ versus jovicentric equatorial distance based on different magnetic field models used in this thesis. DP denotes a simple dipole field model.

Figure 6. Schematic configuration of field lines in different types of magnetosphere [Khurana, 2001].
Figure 7. Distribution of azimuthally averaged field aligned current (FAC) density in units of A m\(^{-2}\) in the ionosphere versus colatitude (top panel) and versus the corresponding equatorial distance (bottom panel).
Figure 8. For various $R_{\odot}$ due to sudden changes in solar wind dynamic pressure, (top panel) log-linear plot of the southward component of the equatorial field $B_{\phi}$ on the pre-noon side computed from the KK magnetic field model, and (bottom panel) the corresponding mapping colatitude, versus jovicentric equatorial distance. The line marked ‘50’ is for the initial model.
Figure 9. For various $R_{ab}$ due to sudden changes in solar wind dynamic pressure, (top panel) the plasma angular velocity profile on the pre-noon side (KK model) versus joviancentric equatorial distance, and (bottom panel) the FAC density in the ionosphere versus colatitude. The dashed line shows the angular velocity profile of the neutrals representing the flywheel effect, and the line marked ‘50’ is for the initial model.
**Figure 10.** Plot of the total return current density on the pre-noon side (KK model) versus different $R_{eB}$ induced by a sudden change in solar wind dynamic pressure. The point marked at 50 $R_J$ is the steady state value.

**Figure 11.** Schematic representation of the corotation enforcement current and region 1 current [Kivelson et al., 2002]
Figure 12. For various $R_{sh}$ due to sudden changes in the solar wind dynamic pressure, (top panel) log-linear plot of the southward component of equatorial field $B_{se}$ in the post-midnight sector computed from the K97 magnetic field model, and (bottom panel) the corresponding ionospheric colatitude, versus jovicentric equatorial distance. The line marked ‘50’ is for the initial model.
Figure 13. For various $R_{eB}$ due to sudden changes in the solar wind dynamic pressure, (top panel) the plasma angular velocity profile in the post-midnight sector (K97 model) versus the equatorial distance, and (bottom panel) the FAC density in the ionosphere versus colatitude. The dashed line shows the angular velocity profile of the neutrals representing the flywheel effect, and the line marked ‘50’ is for the initial model.
Figure 14. Plot of the total return current density in the post-midnight sector (K97 model) versus $R_{eB}$ induced by a sudden change in solar wind dynamic pressure. The point marked at 50 $R_j$ is the steady state value.
Figure 15. Sketches of the main oval before and after a solar wind compression, with the two ovals separated in time by about 2 hr. Brighter blue color means more intense upward FAC. The contracted oval after the compression is expected to be related to the return current in the CEC system. The indentation appearing in the oval is drawn to denote the kink in Clark’s [1998] HST image, which probably results from the localized magnetic field anomaly, because it is observed to corotate with Jupiter's 10-hr rotation period. The dotted lines here are shown as the magnetic latitudes, which are 1° apart from each other.