Planetary and Space Science 58 (2010) 351–364

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Jovian magnetosphere–ionosphere current system characterized by diurnal variation of ionospheric conductance

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ARTICLE INFO

Article history:
Received 22 June 2009
Received in revised form
19 October 2009
Accepted 20 October 2009
Available online 3 November 2009

Keywords:
Jupiter
Magnetosphere–ionosphere coupling
Field-aligned current
Aurora
Solar EUV response

ABSTRACT

We developed a new numerical model of the Jovian magnetosphere–ionosphere coupling current system in order to investigate the effects of diurnal variation of ionospheric conductance. The conductance is determined by ion chemical processes that include the generation of hydrogen and hydrocarbon ions by solar EUV radiation and auroral electrons precipitation. The model solves the torque equations for magnetospheric plasma accelerated by the radial currents flowing along the magnetospheric equator. The conductance and magnetospheric plasma then change the field-aligned currents (FACs) and the intensity of the electric field projected onto the ionosphere. Because of the positive feedback of the ionospheric conductance on the FAC, the FAC is the maximum on the dayside and minimum just before sunrise. The power transferred from the planetary rotation is mainly consumed in the upper atmosphere on the dayside, while it is used for magnetospheric plasma acceleration in other local time (LT) sectors. Further, our simulations show that the magnetospheric plasma density and mass flux affect the temporal variation in the peak FAC density. The enhancement of the solar EUV flux by a factor of 2.4 increases the FAC density by 30%. The maximum density of the FAC is determined not only by the relationship between the precipitating electron flux and ionospheric conductance, but also by the system inertia, i.e., the inertia of the magnetospheric plasma. A theoretical analysis and numerical simulations reveal that the FAC density is in proportion to the planetary angular velocity on the dayside and to the square of the planetary angular velocity on the nightside. When the radial current at the outer boundary is fixed at values above 30 MA, as assumed in previous model studies, the peak FAC density determined at latitude 73°–74° is larger than the diurnal variable component. This result suggests large effects of this assumed radial current at the outer boundary on the system.

1. Introduction

In the Jovian magnetosphere, plasma in a vast region rotates around the planet. The fact that the plasma production of $\sim$1000 kg/s from the Moon Io and its outward transport requires a net torque transferring angular momentum outward from Jupiter's atmosphere to the magnetospheric plasma through electromagnetic coupling (e.g., Hill, 1979). The coupling processes are summarized as follows. Assuming conservation of angular momentum, a parcel of plasma which is initially in near-corotation with the planet will develop a lag in angular velocity behind corotation as it is transported radially outward from the Io torus. In the reference frame which corotates with the planet, an electric field is induced at high latitudes in the ionosphere. This electric field is equatorially directed. The Pedersen current flows in the same direction. As a result of current closure in the steady state, downward and upward field-aligned currents (FACs) are established as we move from higher (subcorotating magnetosphere) to lower ionospheric latitudes (corotating magnetosphere). The upward FAC is principally carried by downward-precipitating electrons. This region corresponds to the main auroral oval (Cowley and Bunce, 2001; Hill, 2001; Khurana, 2001; Southwood and Kivelson, 2001). In the magnetospheric equatorial plane, the radially outward current accelerates the lagging plasma towards corotation through the $\vec{J} \times \vec{B}$ force. In fact, the observed angular velocity of plasmas (e.g., McNutt et al., 1981) does not significantly lag behind corotation within radial distances of $\sim 20\,R_J$. The main auroral oval therefore reflects the angular momentum transfer process in this system.

High resolution images observed with space telescopes have revealed auroral structures along the main auroral oval that depend on local time (LT); for example, "dawn storms" are enhancements of the auroral emissions along the main oval over several MR in a confined longitude region extending from the

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doi:10.1016/j.pss.2009.10.005

dawn limb (Clarke et al., 1998; Gustin et al., 2006). “Multiple dawn arcs” are parallel bright arcs located at the poleward edge of the dawn-side main oval (Grodent et al., 2003). “Discontinuity” is an emission drop in the main oval reaching less than one-tenth of the maximum emission, as observed in 0700–1300 LT (Radioti et al., 2008). The solar wind is thought to be responsible for the discontinuity in the main oval. The dawn storms are as yet unexplained, and might be internally driven processes. On the other hand, the effects of LT asymmetry in the ionosphere on the FAC and the main oval are unknown. These effects have not been explored well, even though the ionosphere is an important region for the angular momentum transfer in the coupling system.

In order to understand characteristics of the coupling system, it is necessary to know the temporal and spatial distributions of the ionospheric Pedersen conductance (Nichols and Cowley, 2004). It depends on ionospheric plasma density (e.g., Achilleos et al., 1998; Millward et al., 2002). The ionization processes governing the plasma density in this region are mainly due to auroral electron precipitation and solar EUV radiation. Nichols and Cowley (2004) showed that both magnitude and distribution of the FAC were affected by the Pedersen conductance which depends on the auroral electron flux. However, neither theoretical studies nor restricted observations have enough to understand the effects of solar EUV on the coupling system so far.

In this study, we investigate the magnetosphere–ionosphere coupling system under the condition of diurnal variation of solar EUV radiation. In Section 2, a numerical model used in this study is outlined. In Section 3 we describe the variations of the FAC and energy transfer. In Section 4 we discuss their dependence on solar EUV flux and several system parameters, i.e., the magnetospheric plasma mass flux and density, electron energy spectrum, and planetary rotation velocity. Our results are summarized in Section 5.

2. Model

A model applied to this study calculates the ionospheric conductance, the FAC, and azimuthal velocity of the magnetospheric plasma assuming an empirical magnetic field, plasma density, and plasma mass flux from the Io torus. Our model is essentially similar to the model by Nichols and Cowley (2004), except for the estimation method for the conductance and inclusion of the magnetospheric plasma inertia. This model is based on the one presented by Tao et al. (2009) while we include diurnal variation of solar EUV radiation without calculating thermospheric wind in this study.

Solar EUV radiation and precipitating auroral electrons ionize the upper atmosphere. For the solar EUV flux at the top layer of the atmosphere, we use the EUVAC model (Richards et al., 1994), which is based on the reference spectra derived from sounding rocket observations. This model spectrum provides the solar EUV flux with wavelengths of 5–105 nm as a function of the F10.7 index and its 80-day average. We assume low solar activity conditions ($F10.7=80\times10^{-22}\,\mathrm{W/m^2\,Hz}$) in this study. Because this model gives the solar flux at the Earth, namely, at a distance of 1 AU from the Sun, the flux value is divided by a factor 5.2^2 for the case of Jupiter (Jupiter is located at 5.2 AU from the Sun). The photo-ionization rates for H_2^+, CH_4^+, and $C_2H_2^+$ from H_2, CH_4, and C_2H_2 are calculated using appropriate ionization cross sections (Schunk and Nagy, 2000; after Kim and Fox, 1994).

We use the distribution function of auroral electrons presented by Nichols and Cowley (2004). The energy distribution of auroral electrons is assumed to be isotropic over the downward-going hemisphere and to be represented as a function of electron velocity v as follows (Nichols and Cowley, 2004):

$$f(v)=\frac{f_0}{(v/v_0)^{\alpha}+(v/v_0)^{\beta}}\,(\mathrm{s^3/m^6}),\tag{1}$$

where f_0 is a normalization constant described later; constants α and β represent spectral slopes for $v<v_0$ and $v>v_0$, respectively. The characteristic velocity v_0 is given by

$$v_0=\sqrt{\frac{2q\Phi}{m_{\mathrm{ele}}}}=\sqrt{\frac{2W_{\mathrm{th}}}{m_{\mathrm{ele}}}\left(\frac{j_{//\mathrm{i}}}{j_{//\mathrm{i0}}}-1\right)},\tag{2}$$

where q is the charge; Φ the field-aligned voltage; m_{ele} the mass of electrons; $W_{\mathrm{th}}=2.5\,\mathrm{keV}$ a thermal energy of the magnetospheric electrons; $j_{//\mathrm{i}}$ the FAC density in the ionosphere; and $j_{//\mathrm{i0}}=0.0134\,\mu\mathrm{A/m^2}$ the current density which would be without the electrons' acceleration. The total electron flux is scaled to the value $j_{//\mathrm{i}}/q$, where $j_{//\mathrm{i}}$ is calculated in the model (see below), setting the factor f_0 as follows,

$$f_0=\frac{j_{//\mathrm{i}}}{\pi q}\Bigg/\int_0^{\infty}\frac{v^3}{(v/v_0)^{\alpha}+(v/v_0)^{\beta}}\,dv.\tag{3}$$

We apply the case with $\alpha=2$ and $\beta=8$ in this study as Nichols and Cowley (2004). We include electrons with energy of 5–504 keV as a carrier of the current. The altitude distribution of the ionization rate in a H_2 atmosphere caused by electron precipitation is obtained using a parameterized equation provided by Hiraki and Tao (2008). Sensitivities of the coupling system to the assumed solar EUV flux and energy spectrum of auroral electron are discussed in Sections 4.2 and 4.3, respectively.

We solve ion composition equations using the implicit method, considering a simplified set of neutral-ion chemical reactions (Table 1) for nine ions—H_2^+, H_3^+, CH_4^+, CH_5^+, $C_2H_2^+$, $C_2H_3^+$, $C_2H_5^+$, $C_3H_n^+$, and $C_4H_n^+$, where the latter two ions represent

Table 1
Ion–neutral reactions and rates used in this study.

Reactions	Rates	References
$H_2+e^{-*}\rightarrow H_2^+ + e^- + e^{-*}$		1
$H_2+h\nu\rightarrow H_2^+ + e^-$		2
$CH_4+h\nu\rightarrow H_2^+ + e^- +$ products		2
$CH_4+h\nu\rightarrow CH_3^+ + e^- +$ products		3
$CH_4+h\nu\rightarrow CH_4^+ + e^-$		3
$C_2H_2+h\nu\rightarrow C_2H_2^+ + e^-$		3
$H_2^+ + H_2\rightarrow H_3^+ + H$	2×10^{-9}	4
$H_3^+ + CH_4\rightarrow CH_5^+ + H_2$	2.4×10^{-9}	4
$CH_3^+ + CH_4\rightarrow C_2H_5^+ + H_2$	1.20×10^{-9}	3
$CH_4^+ + H_2\rightarrow CH_5^+ + H$	3×10^{-11}	4
$CH_5^+ + C_2H_2\rightarrow C_2H_3^+ + CH_4$	1.56×10^{-9}	3
$C_2H_2^+ + H_2\rightarrow C_2H_3^+ + H$	1.8×10^{-12}	After 4
$C_2H_3^+ + CH_4\rightarrow C_3H_5^+ + H_2$	2.00×10^{-10}	3
$C_2H_3^+ + C_2H_2\rightarrow C_4H_3^+ + H_2$	2.16×10^{-10}	3
$C_2H_3^+ + C_2H_4\rightarrow C_2H_5^+ + C_2H_2$	9.30×10^{-10}	3
$C_2H_5^+ + C_2H_2\rightarrow C_3H_3^+ + CH_4$	6.84×10^{-11}	3
$\rightarrow C_4H_5^+ + H_2$	1.22×10^{-10}	3
$H_3^+ + e^-\rightarrow$ products	$1.15\times10^{-7}\,(300/T_e)^{0.65}$	4
$CH_3^+ + e^-\rightarrow$ products	$3.5\times10^{-7}\,(300/T_e)^{0.5}$	3
$CH_4^+ + e^-\rightarrow$ products	$3.5\times10^{-7}\,(300/T_e)^{0.5}$	3
$CH_5^+ + e^-\rightarrow$ products	$2.78\times10^{-7}\,(300/T_e)^{0.52}$	4
$C_2H_2^+ + e^-\rightarrow$ products	$2.71\times10^{-7}\,(300/T_e)^{0.5}$	4
$C_2H_3^+ + e^-\rightarrow$ products	$4.6\times10^{-7}\,(300/T_e)^{0.5}$	4
$C_2H_5^+ + e^-\rightarrow$ products	$7.4\times10^{-7}\,(300/T_e)^{0.5}$	3
$C_3H_n^+ + e^-\rightarrow$ products	$7.5\times10^{-7}\,(300/T_e)^{0.5}$	4
$C_4H_n^+ + e^-\rightarrow$ products	$7.5\times10^{-7}\,(300/T_e)^{0.5}$	4

*References: 1, Hiraki and Tao (2008); 2, Schunk and Nagy (2000); 3, Kim and Fox (1994); and 4, Perry et al. (1999). T_e denotes the electron temperature. Unit of measurement for the rate is $\mathrm{cm^3/s}$.