

1        **Evaluating the ionospheric mass source for Jupiter’s**  
2        **magnetosphere: An ionospheric outflow model for the**  
3        **auroral regions**

4        **C. J. Martin<sup>1</sup>, L. C. Ray<sup>1</sup>, D. A. Constable<sup>1</sup>, D. J. Southwood<sup>2</sup>, C. T. S.**  
5        **Lorch<sup>1</sup>, M. Felici<sup>3</sup>**

6                    <sup>1</sup>Department of Physics, Lancaster University, Bailrigg, Lancaster, UK

7                    <sup>2</sup>Blackett Laboratory, Imperial College London, UK

8                    <sup>3</sup>Centre for Space Physics, Boston University, Boston, MA, USA

9        **Key Points:**

- 10        • An ionospheric outflow model is developed for use at Jupiter’s auroral regions
- 11        • The model evaluates the effect of field-aligned currents and centrifugal forces
- 12        • A total number flux of  $1.3\text{--}1.8 \times 10^{28} \text{ s}^{-1}$  is found, which is comparable to num-
- 13        ber flux from Io

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Corresponding author: C. J. Martin, [c.martin1@lancaster.ac.uk](mailto:c.martin1@lancaster.ac.uk)

## Abstract

Ionospheric outflow is the flow of plasma initiated by a loss of equilibrium along a magnetic field line which induces an ambipolar electric field due to the separation of electrons and ions in a gravitational field and other mass dependant sources. We have developed an ionospheric outflow model using the transport equations to determine the number of particles that flow into the outer magnetosphere of Jupiter. The model ranges from 1400 km in altitude above the 1 bar level to  $2.5 R_J$  along the magnetic field line and considers  $H^+$  and  $H_3^+$  as the main ion constituents. Previously, only pressure gradients and gravitational forces were considered in modelling polar wind. However, at Jupiter we need to evaluate the affect of field-aligned currents present in the auroral regions due to the breakdown of corotation in the magnetosphere, along with the centrifugal force exerted on the particles due to the fast planetary rotation rate. The total number flux from both hemispheres is found to be  $1.3-1.8 \times 10^{28} s^{-1}$  comparable in total number flux to the Io plasma source. The mass flux is lower due to the difference in ion species. This influx of protons from the ionosphere into the inner and middle magnetosphere needs to be included in future assessments of global flux tube dynamics and composition of the magnetosphere system.

## 1 Introduction

Valek et al. (2019) reported ionospheric species at high latitudes magnetically conjugate with Jupiter's inner and middle magnetosphere using the Juno spacecraft's Jovian Auroral Distributions Experiment (JADE). In this paper, we illustrate computations of the field-aligned outflow of material from the Jovian ionosphere and the ionosphere as a source of magnetospheric plasma.

The idea of ionospheric outflow as an important element of magnetospheric physics was first theorised in the terrestrial magnetosphere as a supersonic flow of charged particles from the ionosphere in the high-latitude regions of a planet (Dungey, 1961; Axford, 1968) in analogy with the solar wind supersonic flow of charged particles from the Sun. The terrestrial polar wind, comprised of  $H^+$  and  $O^+$ , was first detected by Hoffman (1970).

Ionospheric outflow requires an imbalance of equilibrium to trigger plasma motion along the magnetic field line with low pressure at large distance. In the terrestrial case, the opening of a flux tube by reconnection at the magnetopause initiates the process and the outflow occurs on open flux tubes in the terrestrial polar cap. The first suggestion of Jovian ionospheric outflow being an important aspect of the Jovian system appears in Piddington (1969) (referenced by Kennel and Coroniti (1975)). The primary force leading to outflow was the centrifugal effect of the rapid planetary rotation on open field lines in the polar cap. However, these early predictions predate the Voyager Jupiter encounters. There is now known to be a major internal magnetospheric near-equatorial source of plasma at Io due to the moons volcanism (e.g., Hill, 1979b; Pontius Jr & Hill, 1982). Io releases  $1000 kg s^{-1}$  of  $SO_2$ , which forms a neutral torus around Jupiter at the radial distance of Io's orbit ( $5.9 R_S$ ) (Delamere & Bagenal, 2003; Delamere et al., 2005). The neutral material is ionised, predominantly by electron impact and charge exchange, picked up and accelerated to near corotation, the angular rotation velocity of the planet (Pontius Jr & Hill, 1982; Pontius, 1995). For a thorough review of these processes, see (Thomas et al., 2004).

Estimates of the total ion particle flux emanating from near Io are in the range  $(0.5-1.7) \times 10^{28} s^{-1}$  (Bagenal, 1997) or  $3 \times 10^{28} s^{-1}$  (Saur et al., 2003). Using a model of the plasma disc, Bagenal and Delamere (2011) estimate the total ion mass flux from Io to be  $260-1400 kg s^{-1}$ . The ionised iogenic material, remaining in a plasma disc near the magnetic equator, moves outwards from the inner magnetosphere in a diffusive process. The diffusion is through a flux tube interchange motion where loaded flux tubes move

65 away from the planet while depleted tubes (which have lost material at large distance)  
 66 move back in. Beyond a radial distance of  $17 R_J$ , the outward moving plasma begins to  
 67 sub-corotate, resulting in the magnetic field (McNutt Jr et al., 1979; Bagenal et al., 2016)  
 68 being bent back and the generation of field-aligned currents. Radial currents associated  
 69 with the bent back field act to maintain plasma rotation (Hill, 1979a). Field-aligned cur-  
 70 rents associated with the bent back field couple the magnetosphere to the ionosphere with  
 71 current closure occurring through Pedersen currents at the ionosphere. The rotation en-  
 72 forcement currents generate Jupiter’s quasi-steady state main auroral emission (e.g., Ray  
 73 et al., 2015).

74 The overall flux circulation providing the iogenic material diffusive transport and  
 75 loss is called the Vasyliunas cycle (see e.g., Vasyliunas, 1983). In the cycle, reconnection  
 76 takes place and plasma is lost through this process. The iogenic material is frozen to the  
 77 magnetic field as it moves outwards but somewhere the frozen-in condition must be vi-  
 78 olated as magnetic flux has to be conserved overall but steady particle transport requires  
 79 loss at large distance. The plasma loss is achieved through flux tubes undergoing mag-  
 80 netic reconnection in the magnetotail.

81 Next consider what happens to the plasma in the ionosphere in the Vasyliunas cy-  
 82 cle. Consider a tube where the cold plasma population in ionosphere and magnetosphere  
 83 are initially in equilibrium. Outward flux tube motion driven by the iogenic material near  
 84 the equator will also carry ionospheric material on the flux tube to higher invariant lat-  
 85 itude. At the same time, the volume of the tube will increase and the cold plasma pres-  
 86 sure at high altitude on the flux tube will decrease. One can thus expect ionospheric ma-  
 87 terial to move upwards to maintain equilibrium, initiating outflow. We see this as an ex-  
 88 planation of the new Juno observations (Valek et al., 2019), which are on field lines be-  
 89 tween Ios orbit and the main auroral zone (and not on open flux as one might expect  
 90 for a polar wind analogous with Earth).

91 A critical question is how far ionospheric plasma moves along the field during the  
 92 flux tube outward motion. If the ionospheric material travels far enough along the field  
 93 to participate in the reconnection, not only will some escape but the residual plasma in  
 94 the equatorial region on the depleted closed tube will be a mixture of heavy iogenic ma-  
 95 terial and light ionospheric plasma. The tube will move inwards and shrink in volume  
 96 with the iogenic material and ionospheric material gaining energy. If the ionospheric ma-  
 97 terial in the outflow induced on the outward leg of the cycle does not reach the equa-  
 98 torial region where reconnection takes place, ionospheric material will not be lost but  
 99 also the mixing will not occur.

100 The purpose of this paper is to use a simple one dimensional model to examine out-  
 101 flow using appropriate ionospheric source conditions with varying background conditions  
 102 in order to assess the nature of ionospheric flow possible on closed field lines. It is as-  
 103 sumed that the overall magnetospheric background context in the equatorial regions is  
 104 a Vasyliunas circulation system driven by diffusion of heavy material ionised in the Io  
 105 torus region, as described above.

106 As noted earlier, at Earth the dominant plasma outflow process is in the Dungey  
 107 cycle on open flux tubes. Any such process at Jupiter it is likely to be much less impor-  
 108 tant to redistributing ionospheric plasma. Cowley et al. (2003) describe it at Jupiter map-  
 109 ping to a thin slice along the dayside and dawn flank of the magnetosphere. Indeed, some  
 110 authors suggest that the Dungey-cycle does not operate at all at Jupiter (McComas et  
 111 al., 2014; Delamere et al., 2005). As our motivation is to investigate mechanisms for iono-  
 112 spheric outflow on closed flux tubes, our context needs be the Vasyliunas cycle.

113 Any ionospheric outflow introduces an electric field along the background magnetic  
 114 field. It is an ambipolar electric field and a direct consequence of the different masses  
 115 of electrons and ions in the ionosphere. However, the Vasyliunas cycle circulation induced

116 by the Io material sets up a global field-aligned current system (Vasyliunas, 1983) and  
 117 these currents will also introduce field-aligned electric fields (Ray et al., 2010), modify-  
 118 ing any outflow conditions. Moreover, this current system may also introduce heat through  
 119 Joule heating by the associated currents in the ionosphere (e.g. Smith & Aylward, 2009);  
 120 this effect could also impact the conditions for ionospheric outflow.

121 In contrast, the importance of ionospheric outflow as a source of plasma at Jupiter  
 122 is less well understood. At both of the gas giants, an ionospheric outflow is expected to  
 123 be dominated by the main ionospheric constituents,  $\text{H}^+$  and  $\text{H}_3^+$ . Bodisch et al. (2017)  
 124 discuss the relative abundance of lighter ions in Jupiter’s magnetosphere during the Voy-  
 125 ager 1 and 2 flybys. They show that protons account for up to 20% of the plasma be-  
 126 tween 5 and 30  $R_J$  and are consistent with an ionospheric source due to a high  $\text{H}^+ / \text{He}^{2+}$   
 127 ratio (Mall et al., 1993). Further evidence comes from  $\text{H}_3^+$  ions were also found during  
 128 the Ulysses flyby (Lanzerotti et al., 1993). These results are consistent with an ionospheric  
 129 particle production rate of  $2 \times 10^{28} \text{ s}^{-1}$  (Nagy et al., 1986).

130 Recently, Valek et al. (2019) observed ionospheric species at high latitudes mag-  
 131 netically conjugate with Jupiter’s inner and middle magnetosphere using the Juno space-  
 132 craft’s Jovian Auroral Distributions Experiment (JADE). The ionospheric species were  
 133 found on flux tubes mainly at latitudes below the main auroral emission but poleward  
 134 of the Io footprint location, a range approximately 10 degrees in latitude wide (Grodent  
 135 et al., 2003). No such signatures of ionospheric plasma were found at polar latitudes.

136 At Saturn, mid-latitude ionospheric outflow has also been detected. (Felici et al.,  
 137 2016) presented evidence of outflow at 36  $R_S$  ( $1 R_S = 60,268 \text{ km}$ ) in the tail region (2200  
 138 Saturn local time) using the Cassini spacecraft. The authors estimate that this outflow  
 139 event shows a number flux of between  $(6.1-2.9) \times 10^{27}$  and  $(2.9-1.4) \times 10^{28} \text{ s}^{-1}$ , correspond-  
 140 ing to a total mass source of  $(10 \pm 4)$  to  $(49 \pm 23) \text{ kg s}^{-1}$ , numbers comparable to the  
 141 mass source from the moon Enceladus ( $60-100 \text{ kg s}^{-1}$ ) (Fleshman et al., 2013).

142 These initial observations of ionospheric outflow at Jupiter and Saturn are entic-  
 143 ing, as the changes to the magnetospheric plasma composition and energy have conse-  
 144 quences for magnetospheric dynamics. A better understanding of the drivers of ionospheric  
 145 outflow at the giant planets requires modelling similar to the extensive efforts applied  
 146 at the terrestrial system (see review by Lemaire et al. (2007)). Based on Juno observa-  
 147 tions (Valek et al., 2019), ionospheric outflow may contribute to the composition of mag-  
 148 netospheric plasma near the auroral zone boundary i.e. in the middle magnetosphere.

149 The goal of this study is to describe ionospheric outflow at Jupiter, including the  
 150 effects of centrifugal forces due to the rapid planetary rotation rate and field-aligned au-  
 151 roral currents from the coupling of the magnetosphere and the ionosphere. Section 2 de-  
 152 scribes the model, which uses a hydrodynamic approach. Section 3 evaluates ionospheric  
 153 outflow at Jupiter over a range of initial conditions appropriate to the system. The im-  
 154 plications of the ionospheric contribution to Jupiter’s magnetosphere are discussed Sec-  
 155 tion 4 with a summary of our analysis presented in Section 5.

## 156 2 Model

157 The outflow model described here is a hydrodynamic, multi-fluid, 1-D model. The  
 158 spatial dimension is along the magnetic field, which has a cross-sectional area,  $A$ , that  
 159 increases as the reciprocal of the field strength. The model introduces contributions from  
 160 gravitational forces, centrifugal forces, pressure gradients and forces associated with the  
 161 ambipolar electric field. As we are expanding the model to a number of planetary radii,  
 162 the JRM09 magnetic field model (Connerney et al., 2018) is implemented to estimate  
 163 the flux tube cross-section.

164 The two major ion species,  $H^+$  and  $H_3^+$ , are evaluated through use of the five-moment  
 165 gyrotropic transport equations (Banks & Kockarts, 1973) which are based on the con-  
 166 tinuity of mass (equation 1), momentum (equation 2) and energy (equation 3) in a sys-  
 167 tem. The equations also include the centrifugal acceleration term ( $\omega^2 r$ ), where  $\omega$  is the  
 168 angular velocity due to corotation and  $r$  is cylindrical distance from the rotational axis  
 169 resolved along the field line. Only rigid corotation is evaluated.

$$\frac{\partial}{\partial t}(A\rho_i) = -\frac{\partial}{\partial r}(A\rho_i u_i) + AS_i \quad (1)$$

$$\frac{\partial}{\partial t}(A\rho_i u_i) = -\frac{\partial}{\partial r}(A\rho_i u_i^2) - A\frac{\partial P_i}{\partial r} + A\rho_i\left(\frac{e}{m_i}E_{\parallel} - g + \omega^2 r\right) + \frac{DM_i}{Dt} + Au_i S_i \quad (2)$$

$$\begin{aligned} \frac{\partial}{\partial t}\left(\frac{1}{2}A\rho_i u_i^2 + AP_i\frac{1}{\gamma_i - 1}\right) = & -\frac{\partial}{\partial r}\left(\frac{1}{2}A\rho_i u_i^3 - Au_i P_i\frac{\gamma_i}{\gamma_i - 1}\right) + Au_i \rho_i\left(\frac{e}{m_i}E_{\parallel} - g + \omega^2 r\right) \\ & + \frac{\partial}{\partial r}\left(A\kappa_i\frac{\partial T_i}{\partial r}\right) + \frac{DM_i}{Dt} + \frac{DE_i}{Dt} + \frac{1}{2}Au_i^2 S_i \quad (3) \end{aligned}$$

172 A subscript of ' $i$ ' denotes this is done for each ionic species separately,  $\rho$  is mass  
 173 density,  $u$  is velocity,  $S$  is the mass production rate,  $P$  is pressure,  $e$  is electron charge,  
 174  $m$  is the mass of the ion species,  $g$  is the gravitational acceleration,  $\kappa$  is the thermal con-  
 175 ductivity,  $T$  is temperature, and  $\gamma$  is the specific heat ratio.  $\frac{DM_i}{Dt}$  is the rate of momen-  
 176 tum exchange and  $\frac{DE_i}{Dt}$  is the rate of energy exchange.

177 We assume  $\kappa_i = 4.6 \times 10^6 \frac{m_i}{m_p}^{-0.5} T^{5/2} e \text{ Jm}^{-1} \text{ s}^{-1} \text{ K}^{-1}$  and  $\kappa_e = 1.8 \times 10^8 T^{5/2} e \text{ Jm}^{-1} \text{ s}^{-1} \text{ K}^{-1}$   
 178 (Banks & Kockarts, 1973), where  $m_p$  is the proton mass.  $\frac{\partial}{\partial r}(A\kappa_i\frac{\partial T_i}{\partial r})$  is considered neg-  
 179 ligible in this formulation. This is determined by magnitude analysis at the first itera-  
 180 tions ( $<0.5\%$  magnitude compared to the largest terms in equation 3). The full term is  
 181 removed to improve computational efficiency.

182 The magnetic-field-aligned components of the gravitational and centrifugal accel-  
 183 eration terms are evaluated along the field line. The parallel electric field,  $E_{\parallel}$ , produced  
 184 by the net charge separation is given by:

$$E_{\parallel} = -\frac{1}{en_e}\left(\frac{\partial}{\partial r}(P_e - \rho_e u_e^2) + \frac{dA}{dr}\rho_e u_e^2\right) + \frac{1}{en_e}\frac{\partial}{\partial r}\left(\sum_i \frac{m_e}{m_i}\left((u_e - u_i)S_i - \frac{DM_i}{Dt}\right) + \frac{DM_e}{Dt}\right) \quad (4)$$

185 A subscript of ' $e$ ' denotes the quantity for an electron and  $n$  is the number den-  
 186 sity. The remaining unknowns are  $\frac{DM_i}{Dt}$  (rate of momentum exchange) and  $\frac{DE_i}{Dt}$  (rate of  
 187 energy exchange) which are given by:

$$\frac{DM_i}{Dt} = -\sum_y \rho_i \nu_{iy}(u_i - u_y) \quad (5)$$

$$\frac{DE_i}{Dt} = \sum_y \frac{\rho_i \nu_{iy}}{m_i + m_y} (3k_b(T_y - T_i) + m_j(u_i - u_y)^2) \quad (6)$$

188 A subscript of ' $y$ ' denotes the different neutral species,  $\nu_{iy}$  is the collision frequency  
 189 between the ionic species and neutral species,  $k_b$  is the Boltzmann constant. We assume  
 190 the neutral atmosphere is at rest ( $u_y = 0$ ). The momentum exchange rate for electrons  
 191  $\frac{\delta M_e}{\delta t}$  is considered negligible compared to the dominant electron pressure gradient in equa-  
 192 tion 4.

193 We use charge neutrality for singly ionised species (7) and a steady state electron  
 194 velocity assumption (8) to solve for the density and velocity of the electrons. To solve  
 195 for the energy of the electrons we use an energy equation (9).

$$n_e = \sum_i n_i \quad (7)$$

$$u_e = \frac{1}{n_e} \left( \sum_i n_i u_i - \frac{j}{e} \right) \quad (8)$$

$$\begin{aligned} \rho_e \frac{\partial T_e}{\partial t} = & -\rho_e u_e \frac{\partial T_e}{\partial r} - T_e \left( S_e + \frac{\gamma_e - 1}{A} \rho_e \frac{\partial}{\partial r} (A u_e) \right) \\ & + (\gamma_e - 1) \frac{m_e}{k_b} \frac{D E_e}{D t} + (\gamma_e - 1) \frac{m_e}{k_b A} \frac{\partial}{\partial r} \left( A \kappa_e \frac{\partial T_e}{\partial r} \right) \end{aligned} \quad (9)$$

196  $\frac{D E_e}{D t}$  and  $\frac{\partial}{\partial r} (A \kappa_e \frac{\partial T_e}{\partial r})$  are negligible compared to the other terms so the final two  
 197 terms are not used.  $j$  is current density of field-aligned currents which is scaled using  
 198 the flux tube cross-section  $j = j_0 A_0 / A$  where  $j_0$  is the current density at a reference  
 199 altitude  $A_0$ . The current density profile as a function of latitude (Ray et al., 2015) is ap-  
 200 plied at a height of 1000 km, coincident with the peak in ionospheric electron density.

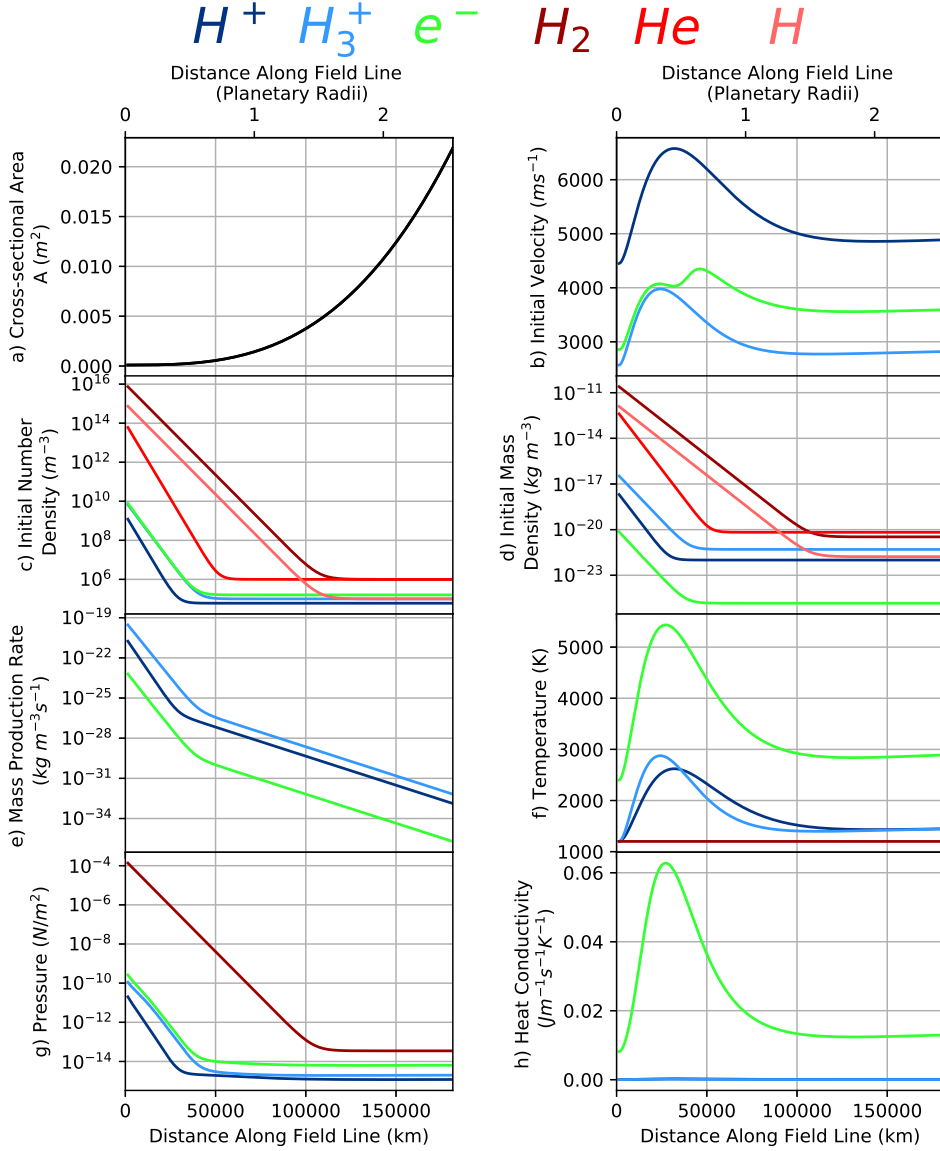
201 The temporal resolution is 0.01 s. The field line is split into 75 km wide spatial grid  
 202 points, which relates to 2400 grid points for a field line of length  $2.5 R_J$  over which the  
 203 spatial derivatives are estimated using central difference Euler for first order derivatives.  
 204 This method is used as the terms are not stiff when using a time step of 0.01 s or less.  
 205 We note that the results are robust for smaller spatial grid sizes (down to 20 km) and  
 206 as such we use 75 km for efficiency in computing.

207 Initial distributions are specified along the entire spatial domain, and are derived  
 208 from either the initial temperature distribution or the initial density distribution using  
 209 the following formulations. Velocity is found from equating the thermal energy to the  
 210 kinetic energy,  $u_i = \sqrt{\frac{2k_b T_i}{m_i}}$ . Mass production is estimated as a 1% fraction of the mass  
 211 density, and the results are robust against a 2 order of magnitude change in this value.  
 212 Pressure is calculated from the plasma pressure equation,  $P_i = n_i k_b T_i$ .

213 The neutral species evaluated within the model are  $H_2$ , He and H. Each species is  
 214 used to calculate the mass and energy exchange rates which require a collision frequency  
 215 which is calculated using:

$$\nu_{iy} = 2.21 \pi \frac{\rho_y}{m_i + m_y} \frac{\lambda_y e^2}{\frac{m_i m_y}{m_i + m_y}}, \quad (10)$$

216 where  $\lambda_y$  is the neutral gas polarisability which are  $0.82 \times 10^{-30} \text{ m}^3$ ,  $0.21 \times 10^{-30} \text{ m}^3$   
 217 and  $0.67 \times 10^{-30} \text{ m}^3$  for  $H_2$ , He and H respectively (Schunk & Nagy, 2000). Initial val-  
 218 ues of density of the ionic and neutral species are extrapolated with an exponential de-  
 219 cay, with appropriate scale height, from 1400 km in ‘JIM’- the Jovian Ionospheric Model  
 220 (Achilleos et al., 1998). An initial distribution of temperature is also retrieved from the  
 221 Jovian Ionospheric Model which increases as an exponential to  $0.5 R_J$  and then is esti-  
 222 mated by a logarithmic decay to a base value. Evaluation and robustness of these val-  
 223 ues is discussed later. All initial value are shown in figure 1, along with the flux tube cross-  
 224 sectional area,  $A$ . The model is run until quasi-steady-state is reached, or until the dif-  
 225 ference between two iterations is negligible (difference between outputs of two iterations  
 226 is  $< 0.1\%$  for 1 second in simulation time, or 100 time steps). Number flux along a sin-  
 227 gle flux rope is calculated as  $n_e u_e$  multiplied by the cross-sectional area  $A$ . This can also  
 228 be calculated for each ionic species.



**Figure 1.** Initial conditions a) cross-sectional area of flux rope, b) velocity of ions and electrons. Neutral velocity is  $0 \text{ km s}^{-1}$ , c) number density of ions, electrons and neutrals, d) mass density of ions, electrons and neutrals, e) mass production rate of ions and electrons, f) temperature profile of ions, electrons and neutrals (neutrals all have the same temperature), g) pressure of ions, electrons and neutrals (neutrals all have the same pressure), h) thermal conductivity of ions and electrons, for the ionospheric outflow model along a field line from 1400 km to  $2.5 R_J$  from the 1 bar level. Ions are shown in blue, electrons in green and neutrals in red. The key to the different colours is at the top of the figure.

### 3 Results

Figure 2 displays the quasi-steady-state parallel electric field, the acceleration terms (gravitational, centrifugal, electric field), and electron and ion fluxes, corresponding to an initial values described as ‘run 1’ in table 1. The electric field (figure 2a) peaks around 10000 km along the field line, which is the position at which the separation of the electrons and ions is largest due to the corresponding densities and temperatures. The electric field then reduces to a steady value. This pattern is followed by the acceleration due to the electric field in both the  $H^+$  and  $H_3^+$  ions (dark blue and light blue solid curves in 2b).

Additionally, we see the gravitational acceleration decreases with radial distance along the field line, whilst the centrifugal force increases (dashed teal and dashed purple in figure 2b). At around  $2R_J$  the centrifugal acceleration becomes dominant over the gravitational acceleration. A density depletion is expected to occur in this region.

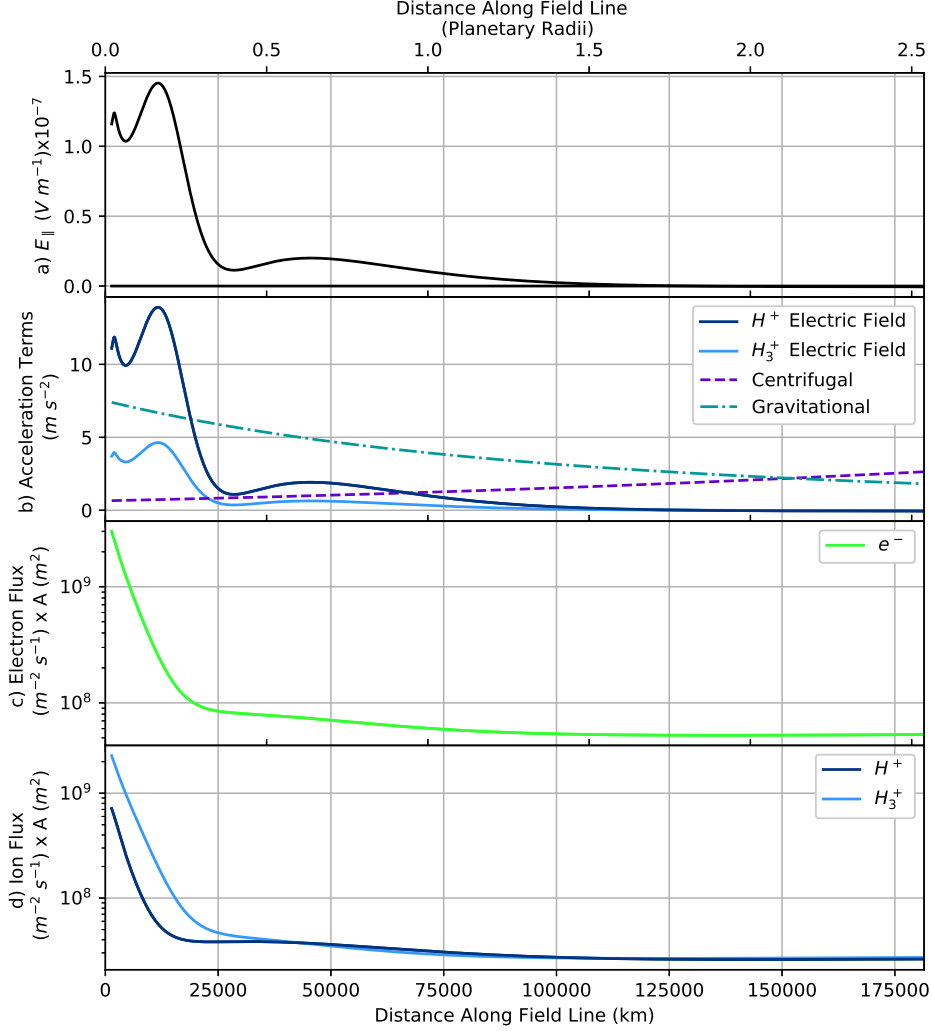
The total particle source from the auroral oval can be estimated by multiplying the number flux of particles with the area of a  $2^\circ$  wide oval at  $75^\circ$ – $77^\circ$  latitude around the planet, and then multiplying by 2 to give a value for both hemispheres. This is done at an altitude of 25,000 km, where the number flux becomes approximately constant. The initial conditions described for figure 2, and the total particle and mass sources (calculated by taking the relative proportions of electrons,  $H^+$  and  $H_3^+$ ) are shown by ‘run 1’ in table 1. A field-aligned current function (Ray et al., 2015) is used where the largest magnitude current used is  $3 \times 10^{-6} \text{ Am}^{-2}$  scaled from the bottom of the ionosphere.

However, we note that the density and temperature in the ionosphere may vary significantly, and the upward field-aligned currents alone may range from  $1\text{--}7 \mu\text{Am}^{-2}$  (Ray et al., 2009). As such, we vary the field-aligned currents, temperature, and number densities of  $n_{H^+}$  and  $n_{H_3^+}$  to present a range of total particle and mass source rates. The extremes of these ranges are presented in table 1 as ‘run 2’ and ‘run 3’, where ‘run 3’ represents a more auroral-like ionosphere, and ‘run 2’ represents a more non-auroral ionosphere. This results in a range for the total particle source of  $2.4 - 4.9 \times 10^{27} \text{ s}^{-1}$ , and a range in the total mass source of  $4.3 - 8.5 \text{ kg s}^{-1}$ . As the ranges of number density and temperature used to evaluate an uncertainty are large, we assume this is the largest source of uncertainty in the model and do not evaluate the intrinsic errors involved with the numerical methods used.

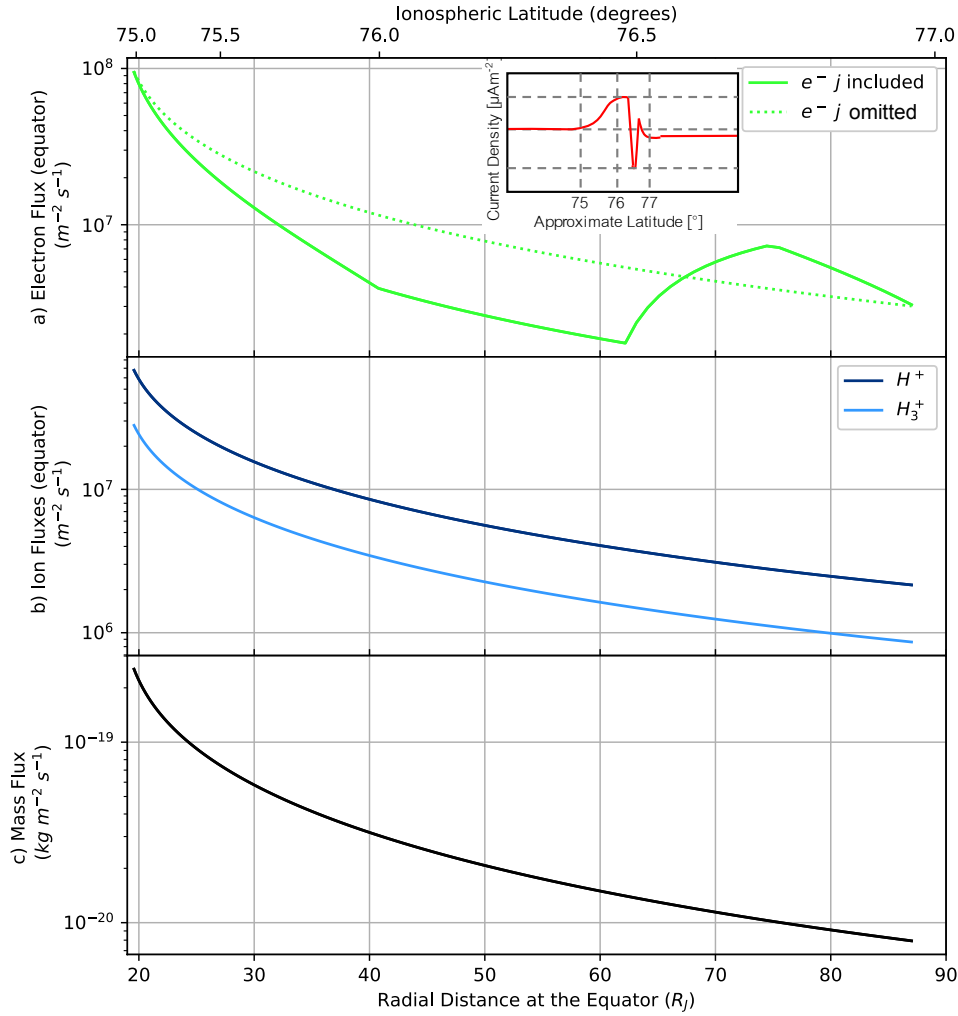
By mapping the ionosphere out to the magnetically conjugate area in the equatorial region (Vogt et al., 2011), the particle and mass flux that reaches the equatorial region can be quantified. We use flux equivalence,  $A_I F_I = A_E F_E$ , where  $A_I$  is the area in the ionosphere, and  $F_I$  is the flux through this area.  $A_E$  is the area in the equatorial region that the ionospheric area maps to, and  $F_E$  is the flux through the equatorial area. We then run the model over the auroral region at  $75^\circ$  to  $77^\circ$  in steps of  $0.02^\circ$ , where a upward current is present between  $75^\circ$  -  $76^\circ$  and a downward current is present between  $76^\circ$  to  $77^\circ$ . The strength and direction of the field-aligned currents in this region follow the model in figure 9f of Ray et al. (2015). Figure 3 shows the electron, ion and mass flux scaled to the equator from a height of 25,000 km. The electron flux is highly modified by the field-aligned currents present, where it is enhanced by a downward current and retarded by an upward current in the auroral regions. Electron flux resulting from the inclusion of FACs is shown as the solid green curve, the dotted green curve shows electron flux with FACs omitted.

We extend figure 3 to include the equator-ward range of latitudes of  $65\text{--}75^\circ$  using a dipole field to map the field lines to the equator between  $5\text{--}15R_J$ , shown in figure 4. This is the region bounded by the Io footprint and the auroral oval described by Valek et al. (2019). The model implements no field-aligned currents in this area, and a gen-





**Figure 2.** Results for ‘run 1’ of the ionospheric outflow model, where initial values are  $T = 700$  K,  $n_{H^+} = 2 \times 10^9 \text{ m}^{-3}$  and  $n_{H_3^+} = 1 \times 10^{10} \text{ m}^{-3}$  for the ionospheric end of the flux tube. a) Shows the electric field from 1400 km to  $2.5 R_J$  in altitude, b) shows the magnitude of the acceleration terms, where solid dark blue is due to the electric field acting on the  $H^+$  ions, solid pale blue is due to the electric field acting on the  $H_3^+$  ions, the purple dashed line is the centrifugal acceleration, and the dot-dash teal line is the gravitational acceleration, c) shows the electron flux, scaled to the cross sectional-area and d) shows the ion fluxes scaled to the cross sectional-area, where dark blue is  $H^+$  ions and pale blue is  $H_3^+$  ions.



**Figure 3.** An example of results for the mapping of the ionospheric outflow to the equator, where initial values in this example are  $T = 700$  K,  $n_{H^+} = 2 \times 10^{10} \text{ m}^{-3}$  and  $n_{H_3^+} = 1 \times 10^9 \text{ m}^{-3}$  for the ionospheric end of the flux tube, a) shows the electron flux, solid green is with field-aligned currents, dotted green is without field-aligned currents for reference, where the insert in a) shows the shape of the field-aligned currents. b) Shows the ion fluxes, where solid dark blue is  $H^+$  ions, solid pale blue is  $H_3^+$  ions, c) shows the mass flux. This example is for auroral field lines which are mapped to the equator using the Vogt et al. (2011) mapping.

**Table 1.** Comparison of five model runs over an area of specified ‘oval size’ in degrees wide to show the large variation in particle and mass source rates. Run 3 has auroral-like values with high temperature and low densities at the ionospheric end of the field line, run 2 has non-auroral region values with low temperatures and high densities at the ionospheric end of the field line. Values for run 1 correspond to the results presented in figure 2, run 4 shows an example of the same initial conditions as run 1 but excluding both field-aligned currents and centrifugal force. Run 5 shows an example of a run for the sub-auroral regions.

Input Variables at Ionosphere	Run 1 Figure 2	Run 2 Non Auroral	Run 3 Auroral	Run 4 Exc. FAC	Run 5 Sub Auroral
$n_{H^+}$ [ $m^{-3}$ ]	$2 \times 10^9$	$5 \times 10^8$	$1 \times 10^{10}$	$2 \times 10^9$	$2 \times 10^9$
$n_{H_3^+}$ [ $m^{-3}$ ]	$1 \times 10^{10}$	$1 \times 10^9$	$5 \times 10^{10}$	$1 \times 10^{10}$	$1 \times 10^{10}$
T [K]	700	200	2000	700	200
j (peak value) [ $\mu A m^{-2}$ ]	3	0	7	0	0
Oval size ( $^\circ$ )	2	2	2	2	10
Output Variables					
Total particle source rate [ $s^{-1}$ ]	$3.2 \times 10^{27}$	$2.4 \times 10^{27}$	$4.9 \times 10^{27}$	$1.9 \times 10^{27}$	$1.2 \times 10^{28}$
Total mass source rate [ $kg s^{-1}$ ]	7.4	4.3	8.5	3.9	18.4

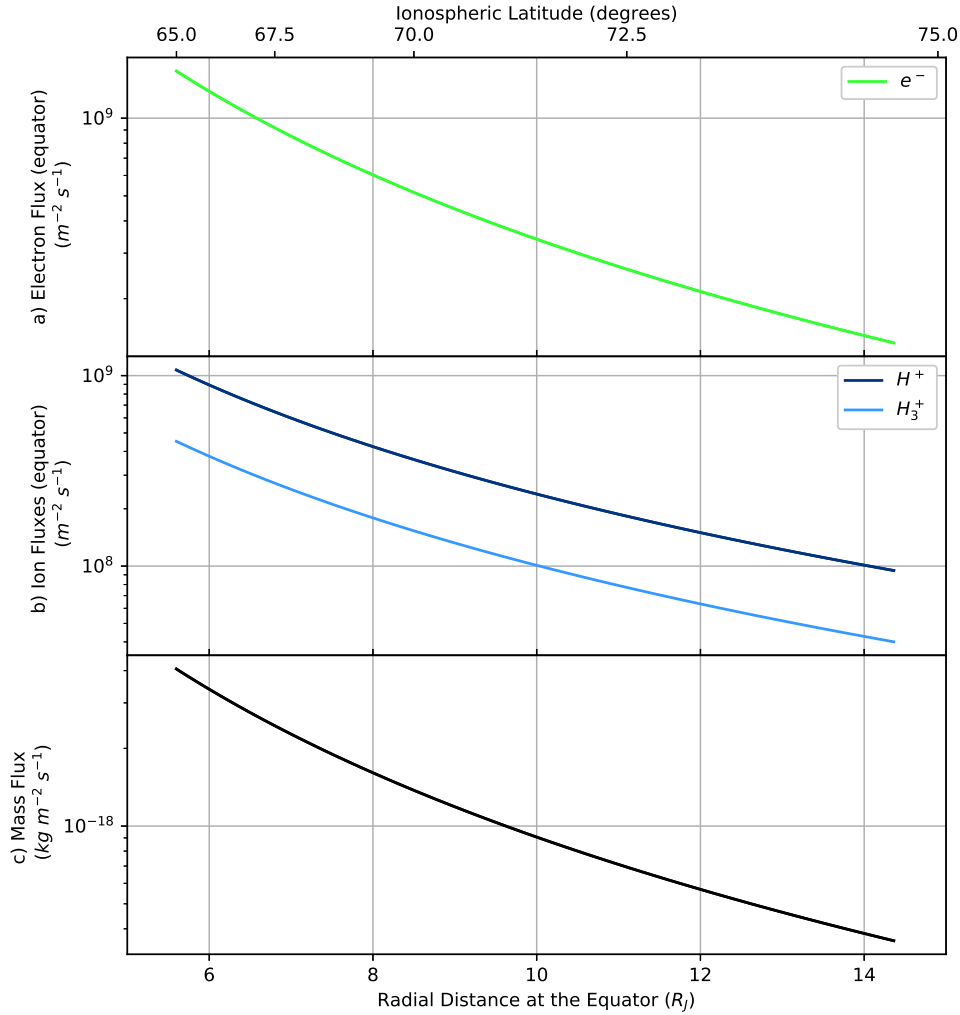
279 eral trend of decreasing particle flux is found due to the increasing area of which each  
 280 ionospheric area maps out to the equator.

281 Combined with the  $2^\circ$  wide auroral region we discussed above, a total particle source  
 282 from polar wind at Jupiter would be between  $1.3-1.8 \times 10^{28} s^{-1}$  and a mass source of  
 283  $18.7 - 31.7 kg s^{-1}$ . This is a comparable number source, but a much smaller mass source  
 284 than that of Io. This total mass source is also within the range of total mass sources from  
 285 the solar wind discussed earlier (20 and  $150 kg s^{-1}$ ).

## 286 4 Discussion

287 While our model is spatially 1D, compounding where and under what conditions  
 288 the model is run, we can describe the behaviour of ionospheric outflow in Jupiter’s po-  
 289 lar regions by applying it for a range of latitudes and auroral current conditions. Fig-  
 290 ure 3 displays the results of 100 runs of the model along one line of longitude ( $\sim 0300$   
 291 local time) between latitudes of  $75-77^\circ$ . This is done to estimate the effects of field-aligned  
 292 currents on the flux that will reach the equator along each of these field lines, assum-  
 293 ing that this latitude region is where the auroral oval at Jupiter is found. The current-  
 294 latitude relationship from Ray et al. (2015) is used, and it is clear that an inverse rela-  
 295 tion is present between current and electron flux at the equator.

296 The latitudinal structure of the auroral currents has consequences for the total iono-  
 297 spheric outflow. The region of upward current causes the electron flux (solid green curve)  
 298 to reduce in this area, and the region of downward current causes the electron flux to  
 299 increase. This effect is due to the fact that electrons are already moving along the field  
 300 line in either the opposite (upward current) direction, and as such decreases the num-  
 301 ber of electrons moving outward, or outward along the field line (downward current) and  
 302 as such increases the number of electrons moving outward. The dotted green curve shows  
 303 the relation without field-aligned currents. This relationship is dominated by the gen-



**Figure 4.** An example of results for the mapping of the ionospheric outflow to the equator, where initial values in this example are  $T = 700$  K,  $n_{H^+} = 2 \times 10^{10} m^{-3}$  and  $n_{H_3^+} = 1 \times 10^9 m^{-3}$  for the ionospheric end of the flux tube. a) Shows the electron flux, b) shows the ion fluxes, where solid dark blue is  $H^+$  ions, solid pale blue is  $H_3^+$  ions, and c) shows the mass flux. This example is for sub-auroral field lines which are mapped to the equator using a dipole field model.

304 eral decrease with increasing latitude which is due to the area that each latitude is map-  
 305 ping out to increases at the equator.

306 We note that very little effect is seen in the ion flux and the mass flux due to the  
 307 much smaller mass of the electrons. Hence, downward field-aligned currents increase the  
 308 overall ionospheric outflow and upward field-aligned currents decrease the overall iono-  
 309 spheric outflow. Spatial and temporal changes in field-aligned currents are not investi-  
 310 gated at this time. However, discussion of their effects with regard to Saturn can be found  
 311 in the companion manuscript, Martin et al. (Accepted).

312 In addition to the field-aligned currents, this model also takes into account the ef-  
 313 fects of centrifugal acceleration. As shown in figure 2b, the centrifugal acceleration (pur-  
 314 ple dashed line) increases in magnitude along the spatial domain of the model, where  
 315 at around 150,000 km it becomes dominant over the gravitational acceleration. However,  
 316 it has a non-zero contribution to the velocity of the particles flowing from the ionosphere.  
 317 Run 4 in table 1 excludes both the centrifugal force and field-aligned currents. As a re-  
 318 sult, the total particle source over a  $2^\circ$  oval at the polar region is reduced by a near fac-  
 319 tor of 2 from the range of values given when the centrifugal force is included. Thus, we  
 320 conclude that the centrifugal force acts to enhance the flux of particles from the iono-  
 321 sphere at the giant planets.

322 The results from Valek et al. (2019) show an increased value of ionospheric out-  
 323 flow between the Io footprint and the auroral oval on average. If we assume that iono-  
 324 spheric outflow occurs only at latitudes between the Io footprint and the auroral oval,  
 325 which is approximately  $10^\circ$  in latitude wide (Grodent et al., 2003), we find a total par-  
 326 ticle source of  $1.3-1.8 \times 10^{28} \text{ s}^{-1}$  which equates to a total mass source of  $14.4 - 23.2 \text{ kg s}^{-1}$ ,  
 327 an example of which is shown in ‘run 5’ of table 1. This range is calculated using the same  
 328 ranges of input values for runs 1 and 2, with no field-aligned currents as described for  
 329 this region by Ray et al. (2015). Changes in ionospheric density over this region could  
 330 be included in future development of this model to give a more accurate representation  
 331 of the flux reaching the equator along the field lines. For the time being, a constant den-  
 332 sity is used which leads to the smooth decrease in the fluxes. Valek et al. (2019) also showed  
 333 that very little ionospheric plasma is found on polar cap field lines. This may indicate  
 334 that the Dungey cycle does not efficiently drive ionospheric outflow at Jupiter, if the cy-  
 335 cle is present at all.

336 A complete picture of the sources of Jovian magnetospheric plasma will also requires  
 337 eventual understanding of the entry and assimilation of solar wind material as the es-  
 338 timates based on incident flux by (Hill et al., 1983) and (Bagenal & Delamere, 2011) make  
 339 clear.

## 340 5 Summary

341 An ionospheric outflow model was developed to model the outflow at the auroral  
 342 regions of Jupiter. The model uses the 5-moment gyrotopic transport equations, along  
 343 with the assumption of quasi-neutrality and a steady state electron velocity. The effects  
 344 of field-aligned currents in the auroral region and the centrifugal acceleration experienced  
 345 by the particles are included. The main conclusions of the study are:

- 346 1. A total particle source for both hemispheres is found to be  $1.3 - 1.8 \times 10^{28} \text{ s}^{-1}$   
 347 when considering the auroral and sub-auroral source regions.
- 348 2. This corresponds to a total mass source of  $18.7 - 31.7 \text{ kg s}^{-1}$ .
- 349 3. These values are comparable to studies of Io as a source (Bagenal, 1997; Saur et  
 350 al., 2003) and is close to estimates of ionospheric particle production rate by Nagy  
 351 et al. (1986).

- 352 4. The total ionic mass source from Io is far larger than the ionic mass source of the  
 353 ionosphere found in this study, where at Io the major ion is assumed to be  $\text{SO}_2^+$   
 354 compared to the ionospheric  $\text{H}^+$  and  $\text{H}_3^+$  ions.
- 355 5. Centrifugal force and downward field-aligned currents act to increase the flow of  
 356 electrons from the polar regions, whereas upward field-aligned currents act to de-  
 357 crease the flow of electrons from the ionosphere.
- 358 6. Mapping the flux from the auroral region to the equator, we find a radially de-  
 359 pendent mass flux with a near exponential decrease from the middle magnetosphere  
 360 to the outer, with a electron flux which is highly modulated by the field-aligned  
 361 currents present.

362 Constraints on initial conditions to improve a future model and give local time and  
 363 latitudinal variation may be possible with the Juno spacecraft now in a position to mea-  
 364 sure ionospheric outflow and plasma properties in the high latitudes at Jupiter.

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