

Kinetic e⁻ Polar Wind Outflow Model **(KePWOM)**

A. Glocer G. Khazanov, K. Garcia-Sage, M. Liemohn, G. Toth, J. Bell, T. Gombosi

Outline

- **Ionospheric plasma has system wide consequences for** the magnetosphere.
- Particle and electrodynamic energy inputs are critical to generating ionospheric outflows.
- We have developed a new model that simulates how these inputs drive outflows.
- **S** The ionospheric outflow occurs at planets other than Earth.

Mext steps

Ionospheric Plasma has System Wide Effects

Ionospheric Plasma has System Wide Effects

O+ and Convection

- Two types of inputs drive outflow: Electromagnetic and Particle **BO**
- The first principles channels through which these inputs operate are still 汤 not fully understood.

$SEs = e^-$ with Energy $>> T_e$

Stephane Three types of SEs:

- Photoelectrons from photoionization of the neutral atmosphere.
- Primary Electrons auroral precipitation, diffuse precipitation, and polar rain.
- Secondary Electrons generated by impact

Superthermal Electrons (SEs)

Mechanisms by which SEs affect outflow

- Formation of the self-consistent ambipolar electric field
- Coulomb collisions between the superthermal and thermal electrons raising Te.

A New Model

To model the effect of SEs, three things are required

- 1. A treatment of the SEs (typically kinetic)
- 2. A treatment of the thermal plasma (typically fluid)
- 3. Self-consistent interaction between the two populations through the E_{\parallel} and and collisional interactions.

We have developed just such a model.

Modeling Effect of Photoelectrons

● Steady state solution of stationary field line. **[●]Solution with photoelectrons increases O+/H+ crossover alt.**

Modeling Effects of a Soft et **Precipitation Event**

- Secondaries contribute much more to the number flux than the primaries.
- Photoelectrons from real conditions of illumination.

Modeling Effects of a Soft e-Precipitation Event

[●]Strongest response is seen in the O+ where densities at high altitudes increase by orders of magnitude.

Scaling of O+ flux with precipitation

- [●]Holding E₀=400eV we increase the intensity of the precipitation in each run.
- **S** The peak O+ flux at each altitude increases with the precipitating number flux.

Glocer et al., [2015]

Including the Effect of Waves

Assume wave with E=50 mV/m
 $F_p = -\frac{1}{8} \frac{E_{wave}^2}{B_o^2} \frac{\rho_o}{\rho^{1.5}} \frac{\partial \rho}{\partial r}$

relating the fitted gaussian curves. Errors in the EPAC data, as given in table 1, are the data are smoothed and fitted with a multigaussian fit. The ratios calculated for e single gaussian curves.

Next Steps

[●] Recent development will be published (papers in preparation).

³ Planetary applications such as Jupiter, Saturn, exoplanets are being pursued.

S KePWOM will soon be updated in SWMF.

S KePWOM made available through CCMC this year.

Thank You

Ionospheric Outflow at Saturn the nonlinear dependence on the neutral temperature. The lowest neutral temperature case in Figure 6 corresponds to the lowest peak ion temperature, but the highest neutral temperature case does not correspond to the highest peak

 ~ 108 m⁻² \sim 1 at 10 000 km **8 Glocer et al.** [2006]: Fluxes ~10⁸cm⁻²s⁻¹ at 10,000km

A consequence of the low-altitude heating and high-altitude

. The flux is the largest considered in these studies but

Figure 4. The plot demonstrates the ambipolar electric

 ϵ at this time. Hence, we interpret this event as interpret this event as ionospheric outflow via a polar wind. *Felici et al.* [2016]: Fluxes ~10⁹-10¹⁰ cm⁻²s⁻¹ at 10,000km

outflow. This is a period of intense magnetospheric activity, and we think that precipitating electrons produc-Discrepancy points to importance of auroral processes not included in upward current region. Hence, the auroral emission and source for ionospheric outflow could be collocated in the same region of the same region of the ionosphere. Bunce et al. [2008], used Cassini and Hubble Space Telescope data to the ionosphere. The ionosphere Space Telescope data to the ionosphere Space Telescope data to th show that the southern auroral oval is located at the boundary between open and closed field lines. However, prior theoretical calculation.

magnetotail via the magnetotail lobes, as observed with CAPS/IMS and CAPS/ELS. We would expect the ion

³ . In the CAPS data, the ions are dom-

² and

SZA Dependence of Ne

[●] Comparison of Empirical fit to Akebono data and PWOM Calculation [●] Photoelectrons can explain the SZA structure in the quite time outflow

Glocer et al., [2012]

Modeling Effect of Ponderomotive Force

Glocer et al., [2015]

Effect of SEs on Composition

Studies including photoelectrons are primarily O⁺ to high altitude as photoelectron concentration increases. Secondary electrons act just as photoelectrons do. **E 20000.**

8000 '

30000.

25000.

E 20000.

15000.

10000.

30O00.

25000.

20000.

Plate 3. O+/H +density ratio as a function ofphotoelectron density and altitude. Same boundary conditions as Figure 1.

 σ occurs is the magnetic independent in the magnetic at least σ

a range of values from 2.9 ! 1019 cm² to 4.4 ! ¹⁰¹⁹ cm² at 10,000 km above the one bar level. Multiplying the polar cap area from the MHD simulation by flux of polar wind plasma yields the particle source rate. From the PWOM, we estimate that the polar wind number flux is between 7.3 !

Ionospheric Outflow at Saturn lowest neutral temperature case in Figure 6 corresponds to the lowest peak ion temperature, but the highest neutral Figure 4. The plot demonstrates the ambipolar electric temperature case does not correspond to the highest peak fields dependance on the neutral temperature. The cases with lower neutral temperatures have smaller electric field **Electron Density** 10000 $T = 400$ $6\overline{a}$ rate, but for obtaining a first estimate of the ionospheric n_e [10⁴ m 3] $---T=600$ ∇ $T = 800$ \mathbb{F}^1 [36] Because none of the previous cases showed strong 3 \bullet $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{4}$ $\frac{1}{4}$ $T = 1000$ agreement with the only available data set, we have tuned 8000 \mathbf{F} \mathbf{F} $\overline{2}$ the neutral atmosphere to obtain improved agreement. $-I=1000(b)$ 600 b Labeled case 1000(b) in Figure 5, we consider an increase $- - -$ T=1500 of a factor of 10 in H2 and 1000 in H2O density with a $\begin{bmatrix} 1 \\ 6 \\ 2 \\ 2 \\ 0 \end{bmatrix}$ $\begin{bmatrix} 400 \\ 200 \\ 200 \end{bmatrix}$ $400\left[-\frac{1}{2} \right]$ $\frac{3}{2}$ [e] Voyager 1 data 蚕畫 neutral temperature of 1000 K, and find a better match with ● # the observed electron density. Additionally, we let H2O 6000 Altitude(km) decrease with a shorter scale height, reflecting that the Ω neutral constituents are not well mixed at the altitudes $\frac{25}{20}$ considered. Increasing the H2 density could be reflective $[10^5$ cm⁻² s⁻¹] $20\frac{3}{2}$
 $15\frac{3}{2}$ of the importance of the energy input from Joule heating, n_{Cassini} **T** 4000 which Cowley et al. [2004b] estimate to be more than 10 10 $\frac{E}{E}$ $\overline{\mathbf{r}}$ $\mathbb{F}_{\overline{\mathbb{F}}}$ 重,垂 $\frac{1}{2}$ times the average solar input. Also, the density of water is $\overline{\Phi}$ $\overline{\Phi}$ $\frac{\Phi}{\Phi}$ $\frac{\Phi}{\Phi}$ $5¹$ not based on in situ measurement but rather on remote 0E measurements. The uncertainty of the estimate is therefore $\frac{28}{16}$ greater. Moreover, Connerney and Waite [1984] note that 2000 the influx of H2O is not spatially uniform. In particular, they **I** ₹ $8¹$ note that at latitudes (!38!, +44!), which are magnetically **Journal of Geophysical Research: Space Physics** 10.1002/2015JA021648 connected to the inner B ring, the water influx may be approximately 50 times greater than the global average. The 14:00 15:00 16:00 Voyager 1 data shown in Figure 5 was taken at 71!S which $\mathbf 0$ **Figure 12.** Estimates of the number flux associated with the polar wind. (a) The measured electron density at Cassini, (b) corresponds to L " 8.5, or just past the edge of the E ring. 2.5 3.0 3.5 4.5 4.0 5.0 the estimated ion speed at Cassini, (c) the estimated number flux at Cassini, and (d) the number flux estimated at an Increasing the water density to this level has been studied by $log(Density[cm³])$ altitude of 10,000 km above Saturn at 78∘ latitude. Majeed and McConnell [1991] and Moses and Bass [2000] Ionospheric outflow and corresponds to an influx of about 10⁸ molecules cm!³ $H⁺$ (CAPS) . The flux is the largest considered in these studies but simulations, where number is the number of ions in the number of ions in the number of ions in the speed of ions in t the tail, and used conservation of magnetic flux to scale these to their values closer to Saturn. The generalization low numbers of counts during this event make the ion moment calculations challenging, so \sim we assume that the ion number density was equal to the electron number density. The ion speeds were density was estimated by fitting the ion spectra with Gaussian plus a background. Fits were filtered using the *𝜒*² for each fit and a manual inspection of the fit. The fits were performed on the IMS anodes where peak fluxes were observed. The peak energy from this fit was taken as the ion bulk flow energy (actually an upper limit since \mathcal{L} the connection out thousand to be a 400 km s−1 at about 1340 km s−1 at about 1340, and α + (INCA). with the speed slowly diminishing to \mathcal{L} Figure 12 shows the number density, speed, and calculated tail number flux, ntvt. We assumed 10% uncer-**Figure 11.** In the schematic we represent different field lines with different colors. In point A the spacecraft is in the

cooling is the formation of a temperature peak in Figure 6.

north lobe, only detecting ionospheric ions in CAPS/IMS. The ionospheric ions are represented with arrows, which get thinner approaching point B, in order to represent the dispersion. When the spacecraft is located in B, from 1845, cold ions from ionosphere are still detected in CAPS/IMS but meantime MIMI/INCA remote senses hot O⁺ from the plasma

tainty on the electron densities [Arridge et al., 2009]; the speed uncertainties were obtained by propagating the uncertainties in the peak energies found from our nonlinear fits. The number flux uncertainties were

Coupling PWOM to Global MHD

- A crude way to include the effects of SEs is to specify the topside electron heat flux. calculate the electric potential, which is in turn mapped back locations of the field line foot points in invariant latitude of field lines in the PWOM calculation.
- Schunk et al., [1986] proposed a "heat flux map" that could give electron temperatures roughly consistant with data (see left). Published the month to a noat nux map u strong O+ concentrations in the same regions. ancictant with date ,UNSISTANI WILLI UAL to the inner boundary of B in \mathbb{R}^n , B is the electric potential potential potential potential potential potential \mathbb{R}^n at could give $\mathfrak u$ could give order to drive the RAM‐SCB model. This code couples two $\cos \theta$ of the separate model and a $\sin \theta$ $\sqrt{5}$ upling these two produces selfconsistency between the particles drifting in the ring current
- We adapt a modified version of this in PWOM and the electron temperatures that result are shown on the right. <u>LITIS III FWUW dil</u> u value has a matrix a matrix u et al. [2009a] came to the same conclusion. It is only $h \circ \alpha$ dentron IG GIGCHOH interaction Model, or RAM [Jordanova et al., 1996, 1997], which solves the kinetic equation to \mathbb{R}^n averaged distribution function as a function of azimuth, radial distance, energy and pitch angle for three ion species
- However this is a very ill-constrained parameter! Proper treatment of SEs is needed to handle this problem properly. aline o parameter P person pressure to increase the values of the values o significantly change magnetic configuration Γ $\overline{}$ hall batse and aligned current sends field aligned currents to recover the current sends of the sends of the s
Aligned current of the sends of the sends of the sending of the sends of the sends of the sending of the sends \mathbf{f} magnetic (SM) equatorial plane with a radial span of 2 to 6.5 RE. It has an energy range of approximately 100 eV to 500 KeV. It includes charge exchange losses, Coulomb collision losses, and atmospheric loss at low altitudes. The dis- \mathcal{L} tribution function at the outer boundary is set by observation at the outer by \mathcal{L} or separate model results; the inner boundary holds the inner boundary holds the inner boundary holds the dist
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Interfacing PW and GM

- Secondary Electrons generated by impact
- **Mechanisms by which SEs affect outflow**
	- Formation of the self-consistent ambipolar electric field
	- Coulomb collisions between the superthermal and thermal electrons raising Te.

Ionospheric O+ can dominate during storms

Glocer et al [2009]

several quantities to work with

- FACs are directly applicable in the current conservation equations. $\overline{1}$
- The cross polar cap potential allows us to describe the perpendicular drift. \vee
- Precipitation can also be used in more comprehensive way.
- Using the energy flux and average energy we can define a precipitating spectrum and calculate secondary production and E field as well as ion production.

Calculating Secondary Production

Using different primary spectra but the same energy flux and characteristic energy we computed secondary production.

- The secondary electron spectra have similar shapes but the integrated flux is different by a factor of \sim 3
- If we have the shape of the primary spectrum from data we can do the calculation precisely.
- Global models, however, are not able to provide the shape of the primary spectrum

The Next Step

Creating a Merged Fluid-Kinetic Model

- **B** Issue: All SE populations should be treated together in the context of the ionospheric outflow.
- **Approach:** Use the PWOM code to represent the ions and thermal electrons and a kinetic FP code for the SEs

Features of the merged code:

- Treats all SE populations together
- Handles arbitrary precipitation source
- Includes photoelectron and secondary electron production
- Includes energy cascade and pitch-angle scattering
- Formation of the self-consistent E-field to accelerate ions and restrain SEs
- Energy deposition to thermal electrons from collisions
- When including SEs solution the topside electron heat flux can be set arbitrarily small.

• Model development is complete and first results are shown shortly.

$$
\sum_{\substack{\beta \\ \sqrt{E} \\ \partial t}} \frac{\partial \Phi}{\partial t} + \mu \frac{\partial \Phi}{\partial s} - \frac{1 - \mu^2}{2} \left(\frac{1}{B} \frac{\partial B}{\partial s} - \frac{F}{E} \right) \frac{\partial \Phi}{\partial \mu} + EF\mu \frac{\partial \Phi}{\partial E} = An_e \left\{ \frac{\partial}{\partial E} \left[1 + \frac{m}{M_i} + 2 \frac{m}{M_i} \frac{\sigma_m^{\sigma} E^2 n_n}{A n_e} \right] \frac{\Phi}{E} \right\}
$$
\n
$$
+ \left(T_e + T_i \frac{m}{M_i} + 2 \frac{m}{M_i} T_n \frac{\sigma_m^{\sigma} E^2 n_n}{A n_e} \right) \frac{\partial}{\partial E} \left(\frac{\Phi}{E} \right) + \frac{FP \text{ collisional Operator}}{\text{e- Neutral Boltzmann}} \left(1 - \mu^2 \right) \frac{\partial \Phi}{\partial \mu} \right] + n_n \left\{ \int_0^{2\pi} \int_{-1}^{1} I_m(E, \mu_x) \Phi(\mu) \sin \chi dx \, dt + \sum_{j,k \in J} \left[\Delta_n^j \sigma_m^k (E + E_{jk}) \Phi(E + E_{jk}) + \Delta_n^k \sigma_m^k (E - E_{jk}) \Phi(E - E_{jk}) \right] + \frac{2\pi + E_n^*}{\text{Excitation and Deexcitation}} \left(\frac{2\pi}{\pi} \int_{-1}^{2\pi} \int_{-1}^{1} I_m(E, E) \right) \left[\int_0^{2\pi} \Phi(E, \sqrt{1 - \mu^2} \cos \epsilon) \right] dE - \frac{1}{\pi + E_n^*} \left(\frac{\Delta_n^j \sigma_m^{\beta} + \Delta_n^k \sigma_m^{\beta} + \sigma_n^* + \frac{n_i}{n_i} \sigma_i^{\gamma}}{\text{Loss and Gain form}^{\gamma} \text{Cascade}} \right)^{\beta} dE
$$
\n
$$
- \left[\sigma_m + \sum_{j,k > j} \left(\Delta_n^j \sigma_m^{\beta} + \Delta_n^k \sigma_m^{\beta} + \sigma_n^* + \frac{n_i}{n_i} \sigma_i^{\gamma} \right) \right] \Phi \right\} + q.
$$
\n
$$
\text{lls} =: Solving in E and \mu coordinates makes particle trajectories curved relative to grid potentially leading to overestimate of trapping and heating
$$

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Region of Existence for SEs

Region of existence for SEs in the presence of a field aligned potential. 5

The grid is aligned with particle trajectories when working in ϵ , μ_0 variables. 图

Region of Existence for SEs

Absolutely no PA scattering results from numerical diffusion in these coords. 5 Verification: Specify upward flux in ionosphere of $1x10⁵$ (red) and see 5 nothing in trapped region.

ionospheric flux

