Kinetic modeling of auroral ion Outflows observed by the VISIONS sounding rocket

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The VISIONS (VDistalizing Ion Outflow via Neutral atom imaging during a Substorm) sounding rocket was launched on Feb. 7, 2013 at 8:21 UTC from Poker Flat, Alaska, into an auroral substorm with the objective of identifying the drivers and dynamics of the ion outflow below 100km. Energetic ion data from the VISIONS polar cap boundary crossing shows evidence of an ion “pressure cooker” effect where ions emerge via transverse heating in the topside ionosphere upward and are impelled by a parallel potential structure at higher altitudes. VISIONS was also instrumented with an auroral neutral atom (ENA) detector which measured neutral particles (<0-100 eV energy) presumably produced by charge-exchange with the energized outflowing ions. Hence, influences about ion outflow may be made via remotely-sensing measurements of ENAs. This investigation focuses on modeling energetic outflowing ion distributions observed by VISIONS using a kinetic model. This kinetic model traces large numbers of individual particles, using a guiding-center approximation, in order to allow calculation of ion distribution functions and moments. For the present study we include mirror and parallel electric field forces, and a source of ion cyclotron resonance (ICR) wave heating, thought to be central to the transverse energization of ions. The model is initiated with a steady-state ion density altitude profile and Maxwellian velocity distribution characterizing the initial phase-space conditions for multiple particle trajectories. This project serves to advance our understanding of the drivers and dynamics in the auroral ionosphere and to improve data analysis methods for future sounding rocket and satellite missions.

Motivation

The ionosphere plays a significant role in loading the magnetosphere plasma populations (Zeng, [2008]). Moreover, the energization and outflow of ions in the polar ionosphere was first observed by Shelley et al. [1972], and has been reported by other satellite and balloon missions and simulation models (Rettler, [1983]; Crew, [1990]). Unlike the strongly field-aligned beam distribution generated in the dayside electrojet, the ion conics form in the cusp have peak fluxes at a pith angle relative to the field-aligned directions. The conic formation in velocity space is thought to be generated by gradual heating of ions. In this study, we present ion conic distributions generated by a 3D kinetic ion model with ICR wave heating. This model is used to reconstitute ENA trajectories and ion outflow source regions as observed by satellites and sounding rockets – and in this case the VISIONS sounding rocket.

Magnetic Dipole Coordinates

The Earth’s magnetic dipole field is with no free currents and spherical boundary conditions $\mathbf{B} = 0$ at $r = \infty$ and $\mathbf{B} = \mathbf{B}_{0}$ at $r = r_{0}$ given by

$$\mathbf{B}(r, \theta, \phi) = \frac{R^{3}}{r^{5}} \left( \begin{array}{c} \hat{e}_{\theta} \cos(\theta) - \hat{e}_{\phi} \sin(\theta) \\ \hat{e}_{\phi} \\ \hat{e}_{\theta} \sin(\theta) + \hat{e}_{\phi} \cos(\theta) \end{array} \right)$$

where $R = r \cos(\theta)$, $r = \sqrt{x^{2} + y^{2} + z^{2}}$, $R_{0} = \sqrt{x^{2} + y^{2}}$, $\theta$ is the dipole angle, and $\phi$ is the dipole longitude.

Phase-Space Initialization

The guiding center kinetic model includes the magnetic mirror force $\mathbf{F}_{\mathbf{B}} = \mathbf{B} \times \mathbf{v}$ and the field-aligned Earth’s gravitational force $\mathbf{F}_{\mathbf{g}} = \mathbf{g} \times \mathbf{B}$, where $\mathbf{g} = -\nabla \mathbf{M}$ is the magnetic moment. The acceleration term that is integrated for particle position and velocity is

$$\mathbf{a}(\mathbf{r}, \mathbf{v}) = \mathbf{F}(\mathbf{r}, \mathbf{v}) / m = \frac{1}{m} \left( \mathbf{B}(\mathbf{r}) \times \mathbf{v} + \mathbf{g}(\mathbf{r}) \times \mathbf{B}(\mathbf{r}) \right)$$

Initial velocities have a 3D Maxwellian distribution in Cartesian coordinates where the field-aligned components are $v_{\parallel} = 0$ and $v_{\perp} = \sqrt{2k_{B}T_{\perp}/m}$. This transformation gives an energetically relaxed ionic distribution. When ICR heating is turned off, the distribution is a drifting Maxwellian with time, otherwise, $v_{\perp}$ is updated accordingly.

Conclusions & Future Work

The phase-space distributions generated in the presence of a magnetic mirror force, gravity, and ICR heating are ion conic (loss cone) distributions. Ion conics have been observed by several studies of the Dynamic Explorer I satellite (Crew, [1990]), and replicated by numerical studies (Bostrom, [2003]). The source regions of ion outflow direct the trajectories of the ENAs detected by the VISIONS sounding rocket. Future work includes scaling the number of particles up to create smooth distributions functions with MPI and developing a fluid-electron energy equation solver to produce a downwind parallel electric field consistent with the electron pressure. This ambipolar electric field will be tested against the ICR heating to gauge the “pressure cooker” effect across the field-aligned potential structure. Ultimately a 3D-kinetic ENA model will be constructed to complement this ion model. Virtual rockets flown through the computational domain will thus lead to a reconstruction of the ENA source region and subsequent outflows ion populations detected onboard.

References


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