INVESTIGATING THE ION THERMODYNAMICS OF THE F-REGION IONOSPHERE

UNIVERSITY OF SASKATCHEWAN

LINDSAY VICTORIA GOODWIN*, JEAN-PIERRE ST-MAURICE, AND MIKE NICOLLS

*Email: Lindsaygoodw@gmail.com, Phone: +1 (306)-966-5296

NSERC CRSNG

ABSTRACT

Ion heating by friction with neutral particles is known to have a significant impact on the F region ion temperature in the presence of large electric fields, particularly when the ions become supersonic relative to the neutral background population with which they collide. However, what has not been fully characterized is the impact this heating has on ion temperature anisotropy, as well as the influence of these non-Maxwellian velocity distributions on the shape and interpretation of incoherent radar spectra. To study this, reconstructions of incoherent radar spectra made from Monte-Carlo simulations of velocity distributions are being analyzed along-side radar campaigns capable of giving insight into such things as the collision cross-section of different collisions (such as the resonant charge exchange of O+ ions with O). For this research, an experiment was devised to scrutinize the plasma along the magnetic meridian so as to extract electric field and ion temperature information at altitudes where frictional heating plays an important role. The results of this work indicate that, as expected, the line-of-sight component of the plasma drift extracted from different altitudes is consistent throughout the ionosphere above 150 km. However, owing to competition with processes such as heat exchange with electrons, neutral atmospheric uncertainties, and heat conduction from above, extracting information about the effect of frictional heating is difficult unless the electric field is very strong. Here, the first electric field and ion temperature results from these special magnetic meridian scanning modes will be shown.

ELECTRIC FIELDS IN THE HIGH LATITUDE IONOSPHERE

- It is known that (*St.-Maurice and Schunk,* Planet. Space Sci., 25(3):243-60, 1977):

$$T_{i||} = T_n + \beta_{||} m_n \frac{v_{in}^2}{2k_b} \quad (1) \qquad T_{i\perp} = T_n + \beta_{\perp} m_n \frac{v_{in}^2}{2k_b} \quad (2) \qquad T_i = \frac{T_{i||} + 2T_{i\perp}}{3} \quad (3)$$

- T_i is the ion temperature, $T_{i||}$ and $T_{i\perp}$ are T_i parallel and perpendicular to the magnetic field (respectively), T_n is the neutral temperature, m_n is the neutral mass, v_{in} is the magnitude of the relative drift between the ion velocity, $\mathbf{v}_i$, and the neutral velocity, $\mathbf{v}_n$, and k_b is the Boltzmann constant.
- $\beta_\perp$ and $\beta_{||}$ are constants that depend on the collision cross-section between two species, which is uncertain for O and O$^+$ collisions due to resonant charge exchanges (RCEs).
- Letting T_{ilos} be the line-of-sight T_i and ϕ be an angle with respect to the magnetic field direction, we can write (Raman et al., JGR, 86(A6):4751-4762, 1981):

$$T_{ilos} = T_{i||} \cos^2\phi + T_{i\perp} \sin^2\phi \quad (4)$$

- Through the T_{ilos} measured by ground-based Incoherent Scatter Radars (ISRs), it should be possible to resolve $\beta_\perp$ and $\beta_{||}$
- Calculated ISR spectra created from Monte-Carlo simulations of ion velocity distributions can give insight into the influence of different collision cross-sections.

SPECIAL STUDY OF E/B AND ION TEMPERATURE (SSEBIT)

- The SSEBIT experiment ran from 23-20 Universal Time 5-6 August 2015 on the Resolute Bay ISR-North (RISR-N), and contained several beams looking towards the magnetic meridian at different elevation angles, allowing us to examine one magnetic field line at multiple angles.
- The component of the line-of-sight $\mathbf{v}_i$ perpendicular to the magnetic field, $v_{i\perp}$, from different beams at the same magnetic latitudes show the same trends, meaning that the overlapping F-region range gates are analyzing the same processes at the same magnetic latitudes (Figures a and b show one example).
- Since two F-region gates at the same magnetic latitudes are examining the same processes, it is therefore reasonable to repeat this study with the T_{ilos} (Figure c and d show one example).
- The SSEBIT experiment shows no clear relationship between the T_{ilos} of different aspect angles at similar magnetic latitudes, but it may be possible to resolve a relationship by binning the data, or removing outlying data points.
- One complication of this study is that T_{ilos} increases with altitude and in order to study temperature anisotropy this must be removed.
- A second complication is that in some cases the higher altitude (larger aspect angle) responds more strongly to the electric field and in other cases it's the lower altitude (smaller aspect angle).

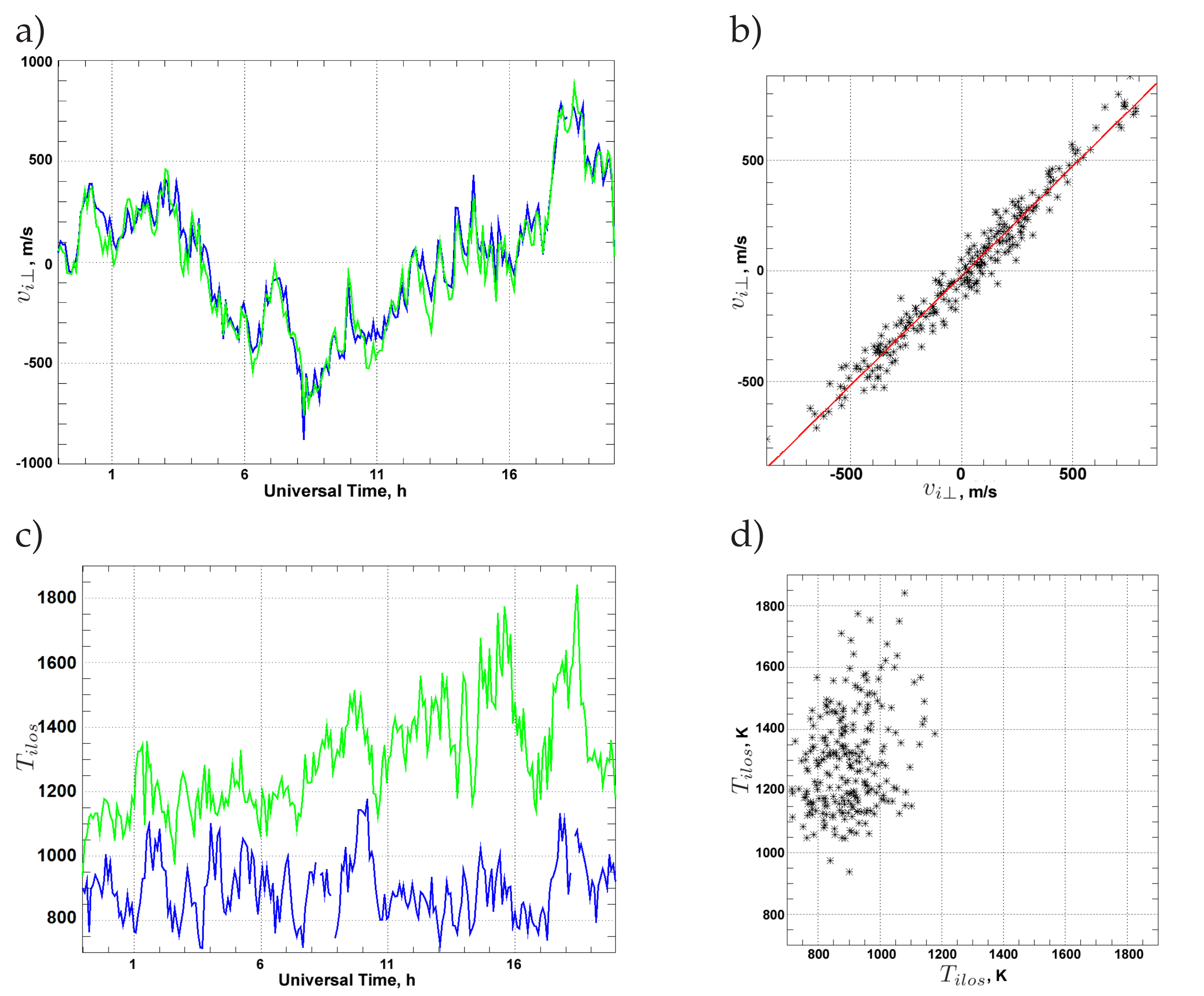

Figure 1: SSEBIT readings (5-6 August 2015, RISR-N) from two separate radar beams pointing towards the magnetic meridian at a corrected geomagnetic latitude of 84.42°. a) $v_{i\perp}$ as a function of time. Blue is a range bin at 211.51 km (aspect angle 130.95°) and green is 358.96 km (aspect angle 145.66°). b) $v_{i\perp}$ from 358.96 km against the corresponding $v_{i\perp}$ at 211.51 km. line-of-best fit: $y = (0.987 \pm 0.013)x + (-23.510 \pm 4.171)$ m/s. c) Same as a, but with T_{ilos}. d) Same as b with line-of-sight T_i.

ION VELOCITY DISTRIBUTIONS AND SPECTRA SIMULATIONS

- In the presence of an electric field the 3D ion velocity distribution is toroidal in shape (*St.-Maurice and Schunk,* Rev. Geophys.,17 (1), 99-134, 1979), owing to RCE and elastic collisions.
- Using the (Winkler et al. 97(A6):8399-8423, 1992) Monte-Carlo simulation, torodial ion velocity distributions influenced by O-O$^+$ RCE and elastic scattering can be formed (see Figure 2).
- ISR spectra can be obtained from ion velocity distributions using (Sheffield, Academic Press, Inc., 1975.):

$$S(\mathbf{k},\omega) = \frac{2\pi}{k}\left|\frac{1+G_i}{\epsilon}\right|^2 g_{0e} + \frac{2\pi}{k}\left|\frac{G_e^2}{\epsilon^2}\right| g_{0i} \quad (5)$$

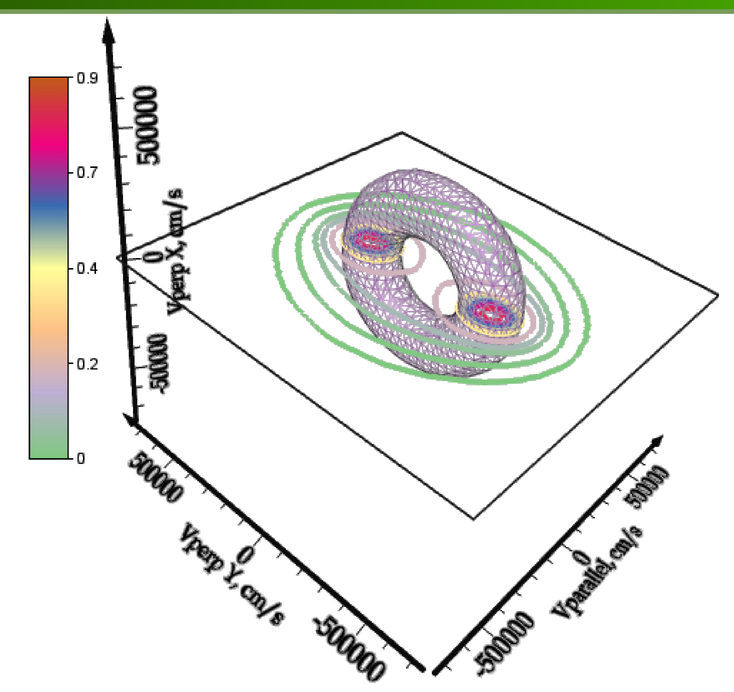

Figure 2: 3D ion velocity distribution in the presence of a 150 mV/m electric field.

- ϵ is the longitudinal dielectric function, k is the radar wavevector, ω is the angular frequency, g_{0e} is the electron velocity distribution function, g_{0i} is the ion velocity distribution function, G_e is the electron function, and G_i is the ion function, which along the wavevector, is:

$$G_i(x_i) = \frac{\omega_{pi}^2}{(bk)^2}\left(\mathcal{P}\int_{-\infty}^{\infty} dy \frac{\frac{\partial f_{0i}}{\partial y}}{x_i - y} + i\pi \frac{\partial f_{0i}}{\partial y}\bigg|_{y=x_i}\right) \quad (6)$$

- $\mathcal{P}$ denotes a principal value integral, ω_{pi} is the plasma frequency, y is the ratio of the velocity to the ion thermal speed, x_i is the ratio of the angular frequency to the ion thermal speed and the magnitude of the wavenumber, and f_{0i} is the one-dimensional ion velocity distribution.
- The real component has a singularity at $x_i = y$, which is solved through a change of variables (e.g. $c = y - x_i$), and then an integration around the singularity with an even-numbered Gaussian quadrature.
- This technique has been tested against the well-known analytical solution to the Maxwellian, as well as noiseless, collisionless simulated ion velocity distributions skewed by ion heat-flows (see Figure 3).
- Before this technique can be applied to the ion velocity distributions produced by the Monte-Carlo simulations, the noise introduced by the simulated collisions must first be reduced.

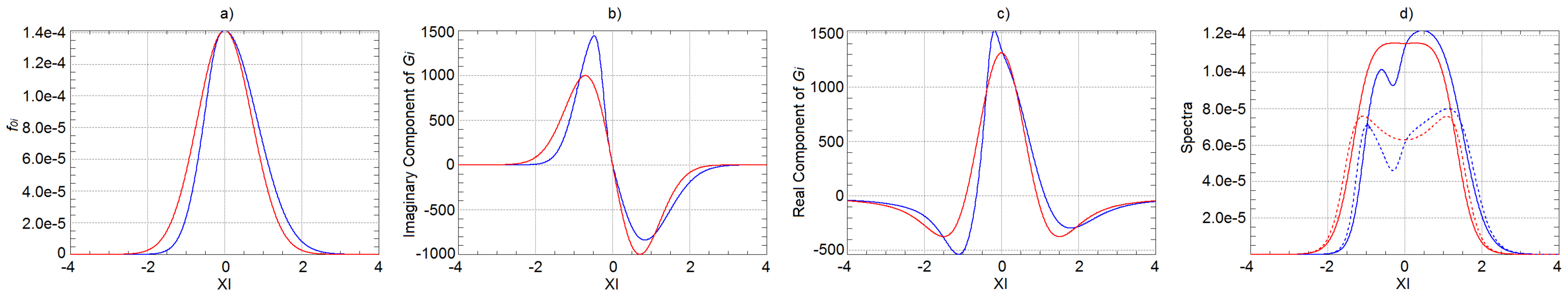

Figure 3: The red line shows the results of a Maxwellian velocity distribution, while the blue line shows a noiseless, collisionless simulated ion velocity distributions skewed by ion heat-flows. a) f_{0i}. b) The imaginary component of G_i. c) The real component of G_i. d) Spectra. The solid lines in the calculated spectra represent an electron to ion temperature ratio of 1, while the dashed lines represents a ratio of 2.

CONCLUSION AND FUTURE WORK

- Although there is a clear relationship between the $v_{i\perp}$ of two range gates at the same magnetic latitude, the T_{ilos} shows less of a correlation, and will require further analysis.
- In order to characterize the collision cross-section, more SSEBIT data must be processed until there are enough good events to characterize T_i anisotropies.
- In some SSEBIT cases the higher altitude (larger aspect angle) responds more strongly to the electric field and in other cases it's the lower altitude (smaller aspect angle). Given equations 1 and 2, we suspect $\mathbf{v}_n$ might be the culprit, but this will require further investigation.
- Through fitting techniques, the amount of noise present in the ion velocity distributions produced by the Monte-Carlo simulations will be reduced in order to create spectra of varying collision cross-sections.

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