Interpreting Accelerated Ion Dynamics in the Wave-Particle Interaction Regime Leading to Pressure Cooker Scenario

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1. BACKGROUND

- Transport of Ionospheric plasma to the magnetosphere involves ion heating, expansion and up-flow with perpendicular acceleration and conversion of transverse energy into field-aligned escape energy(Strangeway et. al. 2005, Zheng et. al. 2005).
- In the up-flow region ions are accelerated by the magnetic mirror force with Broad Band Extreme Low Frequency (BBELF) and Very Low Frequency (VLF) wave energization by ion cyclotron resonance(André et. al. 1998, Crew et. al. 1990).
- BBELF and VLF wave driven ion-cyclotron resonance heating produces ion conics with energies ~ 10 eV to 1000 eV.

2. QUESTION

- How strongly are ionospheric ions energized by waves?
- Does the pressure cooker mechanism contribute to this energization process?

3. METHODS AND MATERIALS

- This current study is based on the data from the Energetic Electron Analyzer (EEA) and Energetic Ion Analyzer (EIA), a top hat electrostatic analyzer and Fields and Plasma suite (FTP) on board VISIONS (VISualizing Ion Outflow via Neutral atom imaging during a Substorm), a 2013 sounding rocket mission by NASA.
- Each of EEA and EIA used 20 pixels of varying sizes (3°–12°), optimized for different pitch angles.
- Both had a geometric factor of 0.01 cm²·sr·s·keV/keV, 16% energy resolution, and 1 ms integration per energy step.
- EIA measured ions from 7.5 eV to 15 keV.
- The double probe instrument on board FTP gathered E-field measurement over a range of frequency bands.
- DC-coupled channels sampled at 2 kHz with ±833 mV/m range, 18-bit resolution, and ~0.5 mV/m accuracy.
- AC-coupled VLF channels with a 16 Hz high-pass filter, sampled at 32 kHz (18-bit, 15 bits downlinked) over ±45.7 mV/m.
- HF electric field channels sampled at 5 MS/s with 12-bit resolution.
- The rocket was kept aligned with the ambient B-field (within ~8°) and spun at ~ 0.48 Hz.

4. DISCUSSIONS

4a. THEORY

- Transverse heating of charged particles via cyclotron resonance is a well-established concept, extensively studied in laboratory plasmas (Hooke and Rothman 1964, Eldridge 1972, Golovato et al. 1985).
- Ionospheric ion population are primarily energized via ion cyclotron resonance interaction with the electromagnetic plasma turbulence, extracting energy from electric field fluctuations near their cyclotron frequency.
- Each ion is initially energized by a particular EMIC wave whose doppler-shifted frequency due to $k_{\parallel}v_{\parallel}$ matches locally the gyrofrequency of the ion $f_{ci} = \frac{qB}{2\pi m}$, where q and m are respectively the charge and mass of the ion.
- The magnetic mirror geometry converts part of the ion's transverse energy into parallel energy, causing it to drift upward along the field lines.
- BBELF waves with intensity of order of $10^{-8} - 10^{-6} \left(\frac{V}{m}\right)^2/Hz$ can yield appreciable heating. (Chang et al. 1986)
- Hence, the perpendicular velocity gain in time $\Delta\tau$ is $\Delta v_{\perp} = \frac{qE_{\perp}(l)}{m}\Delta\tau$, where $E_{\perp}(l)$ is perpendicular component of the wave electric field vector in the polarization mode that can resonate with the ion (left-hand polarized component for positive ions), l is altitude.
- For that brief time $\Delta\tau$, which is called the interaction time, (greater than the ion gyro-period), is limited to the correlation time of the incoherent electric field which is roughly the reciprocal of the bandwidth used to define $E_{\perp}(l)$, the ion gyrates in sync with an effective left-hand polarized electric field $E_{\perp}(l)$.
- Therefor, the net incremental increase in perpendicular energy $W_{\perp}$ for each ion of the generic pair of ions is $\Delta W_{\perp,res} = \frac{q^2|E_{\perp}(l)|^2}{2m_i}(\Delta\tau)^2$.
- And the corresponding net heating rate per ion is $\dot{W}_{\perp,res} = \frac{q^2|E_{\perp}(l)|^2}{2m_i}\Delta\tau$ (Crew et al 1990, Schulz and Lanzerotti, 1974)).

4b. ANALYSIS

- The following is the pitch angle distribution of the differential energy flux of electrons and ions as a function of energy and time taken from the VISIONS-2013 during the onset of an auroral substorm.
- Two distinct ion populations are seen at the 90° pitch angle: atmospheric ions energized up to 1 keV, and precipitating plasma sheet ions around 10 keV.

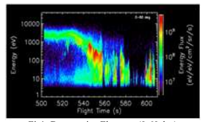
Fig1. Down-going Electrons (0-60 deg)

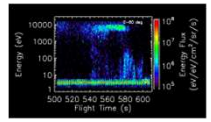
Fig2. Down-going Ions (0-60 deg)

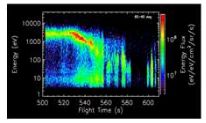
Fig3. Nearly perpendicular Electrons (60-90 deg)

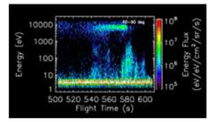
Fig4. Nearly Perpendicular Ions (60-90 deg)

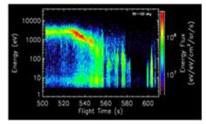
Fig5. Nearly Perp. Electrons (90-120 deg)

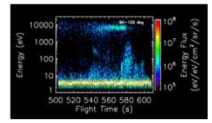
Fig6. Nearly Perp. Ions (90-120 deg)

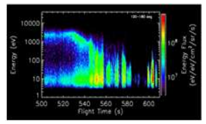
Fig7. Up-going Electrons (120-180 deg)

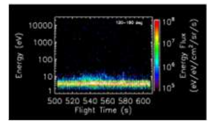
Fig8. Up-going Ions (120-180 deg)

- Two distinct ion populations are seen at the 90° pitch angle: atmospheric ions energized up to 1 keV, and precipitating plasma sheet ions around 10 keV.
- This study investigates the energization mechanisms of these atmospheric ions.

4c. WAVE RESONANCE HEATING

- We examine the resonant heating of these ions by EMIC waves in the BBELF band that align with the gyrofrequency of the O^+ ions as these waves are less effective at accelerating the H^+ ions due to drop-off in wave energy at the H^+ gyrofrequency (Chang et al. 1986).
- The rocket's latitude for the specified time frame is shown below along with its altitude through out the flight.

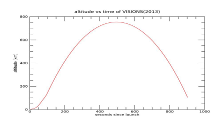
Fig9. altitude vs time of flight

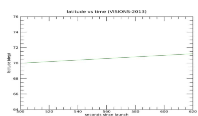
Fig10. latitude vs time of flight

- Based on the IGRF model for February 7, 2013 (VISIONS 2013 launch date and launch site Poker Flat, Alaska), the O^+ gyrofrequency is 6.8 Hz at of ions at $1R_E$ ($|\boldsymbol{B}| = 7.17 \times 10^{-6}$ T), 40 Hz at 720 km ($|\boldsymbol{B}| = 4.16 \times 10^{-5}$ T), and 48.89 Hz at 350 km ($|\boldsymbol{B}| = 5.1 \times 10^{-5}$ T).
- Now, when a cold atmospheric O^+ ion drifts upward, it falls out of resonance with the initial EMIC wave band near its original gyrofrequency $f_{ci}(l)$ and comes into resonance with a new band at its updated gyrofrequency $f_{ci}(l')$.
- Hence, the expressions for the net heating rate and net incremental increase in perpendicular energy works perfect as it incorporates this continuous process.
- The wave power for the corresponding EMIC waves around 48.89 Hz which can resonate with these ions is $E_{\perp}^2 = 0.026\frac{\left(\frac{mV}{m}\right)^2}{Hz} = 2.6 \times 10^{-8}\frac{\left(\frac{V}{m}\right)^2}{Hz}$.

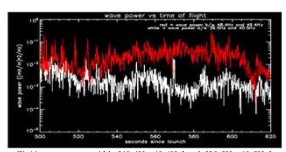
Fig11. wave power within [48.4Hz, 49.4Hz] and [39.5Hz, 40.5Hz]

- Hence, the corresponding velocity gain, energy gain, and heating rate in the perpendicular direction is 19.71 m/s., $3.27 \times 10^{-5}\ eV$, and 0.00159 eV/s.
- As this ion ascends to the altitude of 720 km it interacts with a wave having a spectral density of $E_{\perp}^2 = 3 \times 10^{-3}\frac{\left(\frac{mV}{m}\right)^2}{Hz} = 3 \times 10^{-9}\ (V/m)^2/Hz$.
- Then, the corresponding velocity gain, increment of $W_{\perp}$ for each ion of the generic pair, and the heating rate in the perpendicular direction is 8.28 m/s, $5.63 \times 10^{-6}\ eV$, and $2.2 \times 10^{-4}\ eV/s$, respectively.
- Similarly, at the altitude of $1R_E$ the velocity gain is 39.61 m/s corresponding to $E_{\perp}^2 = 2 \times 10^{-9}\ (V/m)^2/Hz$.
- Therefore, the average velocity gain can be taken as $\Delta v_{\perp} = 22.53$ m/s due to different wave intensities contributing to the resonant heating. But it's insufficient to fully explain the observation, unless the ion interacts with the waves for a significant number of times. This phenomena leads to the discussion of pressure cooker mechanism.

4d. LOSS CONE

- The estimated size of the loss cone is $\alpha_{LC} = \sin^{-1}\sqrt{\frac{B_l}{B_{mirror}}} = \sin^{-1}\sqrt{\frac{4.16\times10^{-5}T}{5.64\times10^{-5}T}} \approx 59°$, which seems consistent with the observations of VISIONS depicted in Fig8., which shows almost none of the down-going ions are getting reflected upward.

4e. MIRROR FORCE

- The magnetic mirror force $F_{\parallel} = -\mu\frac{dB}{ds}$, transforms a portion of the ion's perpendicular energy into parallel energy, driving it upward along the magnetic field lines.
- $\mu = -\frac{mv_{\perp}^2}{2B}$, the first adiabatic invariance; $\boldsymbol{B} = \frac{M}{r^3}\left(-2\sin\lambda\,\hat{r} + \cos\lambda\,\hat{\lambda}\right)$, the dipole magnetic field spherical coordinate, with $|B| = \frac{M}{r^3}\sqrt{1 + 3(\sin\lambda)^2}$, $\lambda(\approx 71°)$ (Fig10.) being the latitude $v_{\perp}$ being the initial velocity at 0.5 eV energy step.0
- Upon plugging in all the values and calculating the necessary steps, we get $F_{\parallel} = \frac{6.92\times 10^{-27}\times(v_{\perp}+\Delta v_{\perp})^2}{(R_E+r_0)r_0}\sqrt{(4.04\,r_0 - 1.56\,R_E)^2 + (2.47r_0 + 1.51R_E)^2}$, where $r_0(=l)$ is the altitude.
- The expression $(v_{\perp} + \Delta v_{\perp})$ includes the effect of wave resonant heating, as the ions gain $\Delta v_{\perp}$ velocity per interaction under wave resonance. Hence, for ~2000 interaction, the net velocity gain is $2000 * \Delta v_{\perp}$, and the resultant velocity of that cold ion would be$(v_{\perp} + 2000 * \Delta v_{\perp})$, and μ doesn't remain constant anymore.
- Therefore, the corresponding change of kinetic energy is thus (as a function of altitude) $mv\frac{dv}{dl} = 1.87 \times 10^{-17}\frac{\sqrt{(4.04l-1.56\,R_E)^2+(2.47l+1.51\ _E)^2}}{(R_E+l)l}$.
- Therefore, the increase of parallel energy (converted from the perpendicular energy gain) due to the mirror force between 350 km and $1R_E$ of altitude is $1.03 \times 10^{-16}\,J = 643.5\ eV$.

5. THE PRESSURE COOKER

- In the pressure cooker scenario, ions bounce between the magnetic mirror point and high-altitude ($\sim 1R_E$) potential drop, repeatedly crossing the wave acceleration region (Gorney et al. 1985)
- During this motion, they resonate with local EMIC waves multiple times, gradually gaining energy.
- VISIONS observations may support this theory as a possible explanation for the EIA ion signatures. The ~600 eV ion population could represent trapped ions in a pressure cooker regime, gaining transverse energy via wave resonance and moving upward along field lines due to magnetic mirroring.
- We propose that the ion originated at 350 km, traveled to $1R_E$, encountered a potential barrier, and was reflected by the mirror force—repeating this cycle ~2000 times and gradually gaining energy to match observations.
- During this process, ions repeatedly interacted with gyro resonant waves, resulting in sustained heating up to 225.8 eV.
- Combining energy from mirror geometry and wave resonance closes the gap in observed energy, aligning with VISIONS data.

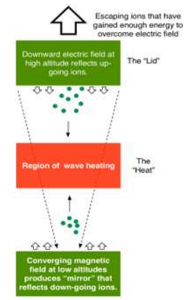

Fig12. Schematic diagram of pressure cooker mechanism @Rowland, AGU-2013

6. SUMMARY

- Wave resonant heating is present but not the primary driver. Soft electron precipitation, supported by observed signatures, may play some role—particularly by generating resonant plasma wave.
- The observed ion population is best explained by the pressure cooker mechanism, where mirror force and wave resonance together energize the ions. Variations in the number of interactions lead to different heating levels, consistent with observations.
- Omitting the pressure cooker mechanism eliminates the primary heating explanation, without which the observed phenomena cannot be accounted for.

7. REFERENCES