Temporal Evolution of Electron Precipitation-Driven Ion Upwelling and Coupling to Neutral Particles

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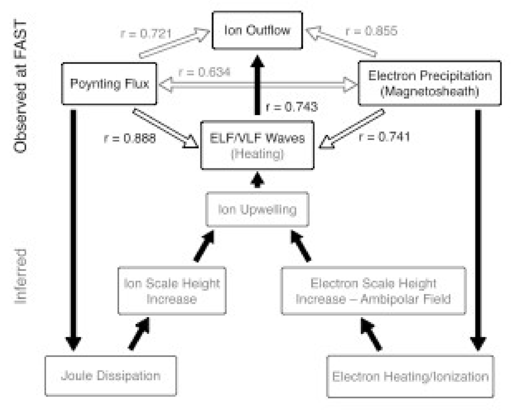
1. Evolution of ion upwelling from soft electron precipitation

Cusp neutral density enhancements observed by CHAMP may be associated with ion upwelling from soft electron precipitation. (eg. Sadler et al. 2012) An accurate time-line of the response of electron and ion response to soft precipitation facilitates understanding the subsequent effects on neutrals.

We distinguish between *ion upwelling* (lower altitude) and *ion outflow* (higher altitude) processes as described in the ion outflow literature. (eg. Strangeway et al. 2005 JGR.) (See also Horwitz and Moore (1997) for a review.)

In general, the time evolution of ion upwelling from soft precipitation is described as follows:



Strangeway, et. al., 2005

Altitudes:

800-1000+ km

500-600 km

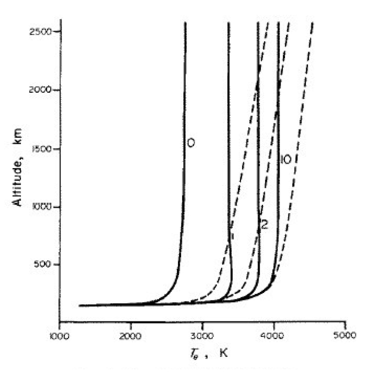
200+ km

Sufficiently soft electron precipitation (< ~500 eV) initiates a strong upward plasma expansion above the F-region which increases with altitude. The precipitation quickly transfers energy to the ambient electron "gas" resulting in an electron temperature increase. The electron temperature increase is substantial and correlates to both decreasing electron energy and increasing electron energy flux. The electron gas subsequently undergoes a thermal (upward) expansion, establishing a vertical ambipolar field which pulls the ions upwards through the parallel electric field arising from the need for charge neutrality.

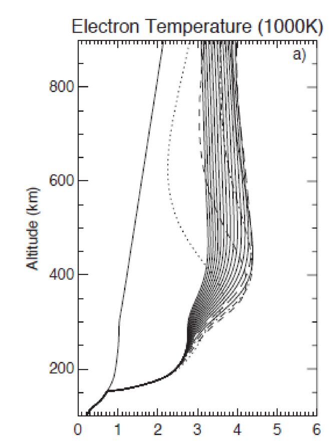
Model predictions of the temporal evolution of electron and ion upwelling response are given below. Published predictions are from Whitteker, 1977 Plant. Space Science, and Su, et al, 1999 JGR. Both are one-dimensional, two-fluid, time-dependent models with inertial ion terms. Comparisons are made with model from Sadler et al. 2012, a two-dimensional, three-fluid model.

Electron temperature rise: 1-3 minutes.

- Whitteker 1977 shows quick T_e rise to a higher asymptote
- 3-fluid model shows quicker T_e rise then a fall to more typically observed values
- Both models use "instant-on" electron precipitation ("eP"): full strength at t=0.



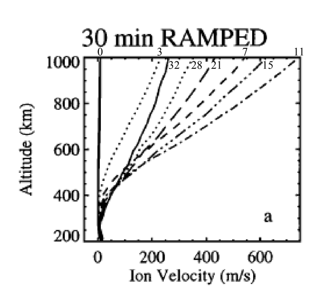
Electron temperature evolution vs altitude from Fig. 5, Witteker 1977. Solid and dashed lines show different soft (~ 100 eV) electron precipitation spectra; dashed line has ~ double energy flux. Lines shown for t = {0, 1, 2, 10} minutes.



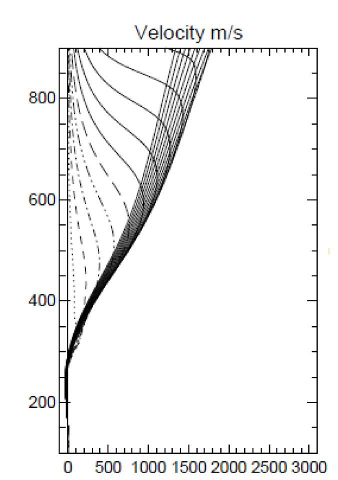
Comparable plot from 3-fluid model (150 eV, 4 mW/m2). Lines shown for t = (.33, .67, …, 6.67} minutes.

Ions upward velocity increase: 3-5 minutes.

- Su et al. 1999 shows large rise in V_i followed by slower decrease (30 min. ramped eP)
- 3-fluid model shows similar progression (eP "instant-on" at t=0)
- Difficult to make direct comparisons due to ramped vs instant-on eP
- Su et al. 1999 shows gradual velocity decline: 30-60 minutes



Ion velocity evolution vs altitude from Fig. 6a, Su et al. 1999. Electron precipitation (125 eV, 1.0 mW/m2) was "ramped on" linearly from t=0 to t=30 minutes. Lines shown for t ~= {0, 3, 7, 11, 15, 21, 28, 32} minutes.



Comparable plot from 3-fluid model (125 eV, 1 mW/m2). No ramp: full eP turned on at t=0. Lines shown for t = (.33, .67, …, 6.67} minutes.

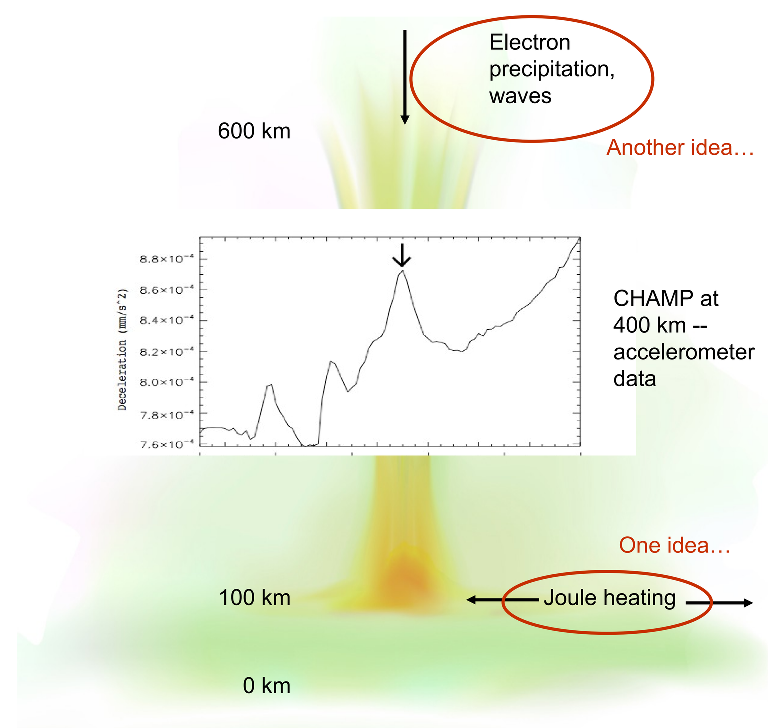
Model comparisons such as these provide a more complete understanding of the physics behind this process. In addition, comparing model results to observational data will verify model predictions. In-situ data is particularly valuable in this regard.

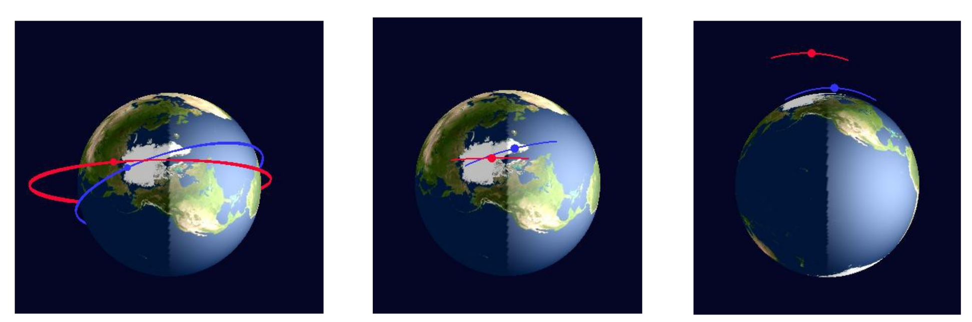
2. Effect on Neutrals

The phenomenon of the density increase of thermospheric gas in the Earth's magnetic cusp was reported by Lühr et al. [GRL 2004] and was thought by those authors to be due to small-scale Joule heating in the cusp. Since that report was published, however, several other ideas have emerged which offer plausible explanations for this phenomenon.

Joule heating from the lower ionosphere / thermosphere was one popular idea. Ion upwelling effects from soft electron precipitation was suggested in Sadler et al. 2012, JASTP.

In-situ data was taken from two satellites, CHAMP and FAST, in conjunction over the dayside cusp region. (CHAMP in blue; FAST in red.)

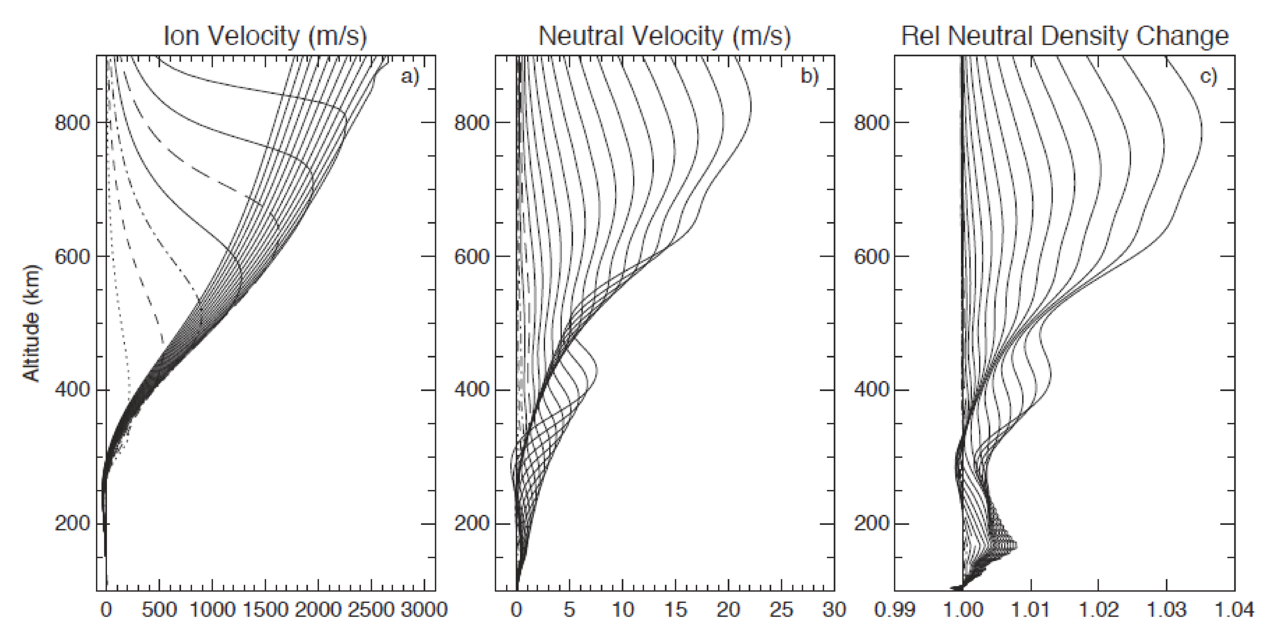




Electron precipitation data from FAST provided input data for a 3-fluid numerical simulation (based on OTTO 2003). Values of 4 mW/m[2] precipitation energy flux and 150 eV characteristic energy were used.

Model outputs for ion and neutral response to these inputs are shown in the following figures. Time evolution snapshots begin on the left with the solid line and progress every 22.5 seconds, generally to the right.

The first plot shows a very large ion acceleration, which at 800 km altitude results in a peak upward velocity of 2.35 km/s in only 2.7 minutes. (Average initial acceleration is approximately 15 m/s[2].) After this peak is reached, the velocity drops somewhat but still remains significant. Lower, at 400 km, the ion velocity rises and stabilizes more quickly to a somewhat modest 500 m/s. (Average initial acceleration is approximately 12 m/s[2].)



The upward neutral velocities are much smaller than the ions', as expected, but still reach about 7.5 m/s at altitudes of 425 km and about 22 m/s at higher altitudes. Even though the neutral population greatly out-numbers that of the plasma, the momentum carried by up-flowing ions is significant and capable of dragging neutral gas upward. In this case, the term "drag" should be taken loosely to mean either elastic or inelastic collisions and include, for example, charge exchange.

The third plot shows the resulting change in neutral density (ratio of time-varying density vs. initial value). Physically, the upward neutral motion shifts the neutral column slightly higher which leads to a moderate density increase, in this case up to 1.3% to 3.5% of the original density in about 7 minutes. Since atmospheric density decreases with altitude on an exponential scale, raising even a small quantity of "dense" neutrals in a vertical column can produce a measurable effect at the higher altitude.

3. Future work – e-POP Satellite

Previous investigation of the cusp neutral density enhancement typically required satellite conjunctions to acquire appropriate in-situ measurements. The CHAMP satellite provided magnetometer, neutral density, and electron information within the enhancement event. However, satellite or rocket conjunctions were required to obtain plasma and other detailed information. Combining CHAMP data with FAST or DMSP conjunctions (for example) provided additional in-situ data, but at the expense of spatial imprecision and a limited selection of events to study.

The recent launch of the e-POP science payload (CASSIOPE satellite), should greatly improve this situation. Simultaneous, single-point measurements from a suite of plasma, neutral, and field instruments will allow study of the anomaly without spatial or temporal separation of the instruments. The elliptical orbit will carry instruments through the region at a range of altitudes where plasma and neutral parameters are theorized to vary considerably.

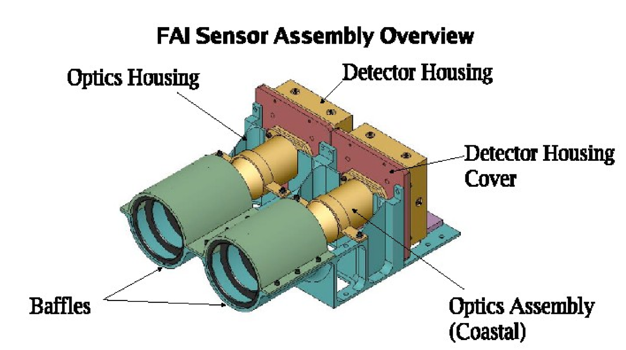
The e-POP science payload will carry a suite of 8 instruments.

Property	Characteristics
Orbit	325 km X 1500 km, 80° inclination
Attitude	3-axis stabilized; nadir-ram or latitude-longitude target pointing (slew)
Data system	Store and forward; 1-Terabit (Tb) onboard memory
Telemetry	Uplink: S band (125 kbps) Downlink: S band (1.6-4.0 Mbps), Ka band (300 Mbps)
Payload	8 instruments
Launch	September 29, 2013

Instrument	PI	Measurements
IRM - Imaging rapid-scan mass spectrometer	P. V. Amerl	0.5-70 eV ions
SEI - Suprathermal electron imager	D. J. Knudsen	1-200 eV electrons
NMS - Neutral mass and velocity spectrometer	H. Hayakawa	0.1-2 km/s neutrals
FAI - Fast auroral imagers	L. Cogger	630 nm, NIR
RRI - Radio receiver instrument	H. G. James	HF, VLF E(ω), k(ω)
MGF - Magnetic field instrument	D. D. Wallis	δB, $j_{\|}$
GAP - GPS attitude, position, and profiling	R. Langley	S/C velocity, attitude, TEC
CER - Coherent EM radiation tomography	P. A. Bernhardt	TEC and scintillation

The two imaging plasma sensors – the imaging and rapid-scanning ion mass spectrometer (IRM) and the suprathermal electron imager (SEI) – will measure particle distributions on the time scale of 10-ms and spatial scale of <100 m.

The magnetic field instrument (MGF) will measure field-aligned currents at comparable spatial resolution. The CCD cameras will perform auroral imaging on the time scale of 100-msec.



E-POP Auroral Imager
(Calibrated at UNH)

Property	FAI-SV (630 nm)	FAI-SI (NIR)
Field of view	27°	27°
Optics f/#	0.8	0.8
Pixels	128x128	256x256
Projected pixel size (apogee)	4.5 km	2.4 km
Projected pixel size (perigee)	0.2 km	0.4 km
Exposure time	0.5 s	0.1 s
Exposure interval	30 s	1 s
Sensitivity (SNR>3)	200 Rayleigh	100 Rayleigh

The e-POP payload contains a well-balanced suite of instruments appropriate for studying the effects of soft electron precipitation on neutrals. The combined plasma and neutral instrumentation data from the satellite's elliptical orbit will provide much needed data to help verify and tune predictive modeling efforts in this area.