Cold Ion Outflow from the Polar Cap

S. Haaland, M. Andre, L. Baddeley, A. Barakat, R. Chappell, V. Eccles, A. Eriksson, C. Johnsen, K. Li, L. Maes, R. Schunk, D. Welling
Outline of talk

* Motivation: Why do we care?
  - “Cold” ions and “Polar Cap”

* Why are ions escaping?

* Observations
  - flux
  - role of solar activity and geoactivity
  - source & fate; lost or recirculated?

* Global context
  - mass and matter balance
Sources of plasma for the Earth's magnetosphere

Solar wind

Plasmasheet
Cusp:
- precipitation
- wave heating
- Poynting flux
- ...

e.g., Lockwood et al., 1985, Yau et al., 1987
Cusp:
- precipitation
- wave heating

Auroral zone:
- precipitation
- FAC
- $E_{\parallel}$
- Joule heating
- ...

e.g., Wahlund et al, 1989, Winser et al, 1989
Cusp:
- precipitation
- wave heating

Open polar cap
- ambient $E$
- polar wind
- low energy (cold)

Auroral zone:
- precipitation
- $E_{||}$

Motivation: why do we care about cold ion outflow?

The Ionosphere as a Fully Adequate Source of Plasma for the Earth’s Magnetosphere

C. R. Chappell, T. E. Moore, and J. H. Waite, Jr.

Space Science Laboratory, NASA Marshall Space Flight Center, Huntsville, Alabama

A series of recent measurements of the outflow of ionization from the ionosphere have further heightened our awareness of the strength of the ionospheric source of magnetospheric plasmas. In this paper the ionospheric contribution of the polar wind and cleft ion fountain at energies less than 10 eV has been added to the previously measured sources; this total ion outflow has then been used to calculate the resulting ion density in the different internal regions of the earth’s magnetosphere: plasmasphere, plasma trough, plasma sheet, and magnetotail lobes. Using estimated volumes for these regions and an ion residence time characteristic of each region, we have found that the observed magnetospheric densities can be attained in all cases with no contribution from the solar wind plasma. In the case of the plasma sheet the ionospherically supplied density is more than enough to match the observations and even suggests an invisible component of low energy plasma (<10 eV) which has never been observed. A detailed comparison between the calculated ionospheric source effects in the plasma sheet and those recently measured by ISEE shows excellent agreement and suggests a direct polar low-energy ion source for the plasma sheet which has remained unmeasured because of spacecraft potential effects. Although the solar wind is clearly the earth’s magnetospheric energy source and energetic solar wind ions are observed in the magnetosphere, these calculations suggest the possibility that the ionospheric source alone is sufficient to supply the entire magnetospheric plasma content under all geomagnetic conditions.
Motivation: why do we care about ion outflow?

Low-energy ions: A previously hidden solar system

M. André¹ and C. M. Cully¹

Received 4 November 2011; revised 23 December 2011; accepted 23 December 2011; published 1 February 2012

[1] Ions with energies less than tens of eV originate from the Terrestrial ionosphere and from several planets and moons in the solar system. The low energy indicates the origin of the ions.

2. Some Methods to Detect Low-Energy Ions

[3] Remote sensing of low-energy ions can be performed in several ways. Act...
Forces: Why do matter escape?

Neutrals:

\[ F_1 = \sim \text{gravity} \]
\[ F_2 = \text{e.g., thermal pressure} \]
Ions:

\[ F_1 = \text{e.g., gravity} \]

\[ F_2 = \text{electromagnetic forces} \]

\[ E = 0 = \frac{1}{2}mv_{\text{ESC}}^2 - gMm/r \]

Earth:

\[ E_{\text{ESC H+}} \sim 0.7 \text{ eV} \]

\[ E_{\text{ESC O+}} \sim 10 \text{ eV} \]
Field aligned acceleration of cold ions are primarily governed by:

- **Gravity** (low altitudes)
- **Mirror force** (low altitude)
- **Centrifugal force** (intermediate altitudes)
- **Electric fields** (relevant at low altitudes otherwise $E_\parallel \sim 0$)
Polar wind ambient electric field

* Set up be escaping electrons
Spacecraft charging

Sunlight = photons, $E = h\nu$
Spacecraft charging

Sunlight = photons, $E = h \nu$

e- (photo electron → current)
Spacecraft charging

$V_{sc} = \text{spacecraft potential}$

$V_0 \sim V_p = \text{ambient plasma} = 0 \text{ V}$

Unless current balanced, spacecraft will be positively charged to $V_{sc}$. 

e- (photo electron $\rightarrow$ current)
Spacecraft charging

$V_{SC} - V_P$ from Cluster C4 on 11 Aug 2002

After Lybekk et al, 2012, Figure 10
Spacecraft charging

Cold ions, $E = \text{few eV}$

Spacecraft, positive potential

B-field
Spacecraft charging

Cold ions shielded from particle sensors...
Spacecraft charging

$\Delta E = eV_{sc}$

Can be measured with particle detectors

Cold ions can not be measured with particle instruments!

Spacecraft charging

... and if

\[ kT_i < E_k < eV_{SC} \]

wake formation, \( E_{WAKE} \)
in the bulk flow direction
How to measure low energy outflowing ions?
1: Ground based studies

e.g., Wahlund et al, 1992, Ogawa et al, 2000, 2003
1: Ground based studies

EISCAT Svalbard, 2014
(from Maes et al, 2016)

Cons:

- Max ~1500 km
- UPflow, not OUTflow
- ....

(from Maes et al, 2016)
2: Low orbit satellites

Pros:
- No/lower spacecraft charging
  - ...

Cons:
- Upflow or Outflow
  - ...

3: Active potential control

Keep $V_{sc} \sim 0 \rightarrow$ avoid shielding

e.g., Moore et al, 1997, Su et al, 1998 (using Polar)
3: Active potential control

e.g., Moore et al, 1997, Su et al, 1998  (using 3 orbits from Polar; PSI operating)
4: Utilize spacecraft charging and wake

Use $E_{\text{WAKE}}$ to get $U_\parallel$, and $V_{\text{sc}}$ to get density;

$$\text{Flux} = N \times U_\parallel$$

Engwall et al, 2009
4: Utilize spacecraft charging and wake

Cons:
- no composition (sensitive to H+)
- no moments

Engwall et al, 2009
Making the invisible visible:

Utilizing Cluster observations

$V_{\|}$  [Engwall et al, 2009, Andrè et al, 2015]

$N_e$  [Lybekk et al, 2012]

$E_{\text{CONV}}$  [Haaland et al, 2009]

Cluster:
Launch: 2002
4 x 19 Re polar orbit
Key feature: 2 complementary E-field instruments

**EFW**: measures $E_{\text{WAKE}}$

**EDI**: measures $E_{\text{CONV}}$
Technique: Use spacecraft charging

1) Derive electron (plasma) density, $n$

2) Combine $E_{\text{WAKE}}$ and $E_{\text{CONV}}$ to find $u_{||}$

3) Calculate flux, $f = n \times u_{||}$

4) Total outflow = Area $\times$ flux$_{1000}$

1) Electron density from spacecraft potential

\[ N_e \sim A e^{-\frac{V_{sc}}{B}} \]

2008

2001

\[ e.g., \text{Pedersen et al, 1998, 2001, 2008 Lybekk et al, 2012} \]
2: Find $U_{\parallel}$ outflow velocity

\[ E^W = g u \]

\[ E^W = E^{EFW} - E^{EDI} \]

\[ U_{\parallel} = \frac{E^W_x u + E^W_y u}{E^W_y B_x - E^W_x B_y} \]

Engwall et al, 2009
Assumption: source area = open polar cap

From Milan et al, 2012
- 40,000 images of auroral oval: find $\Lambda$ of oval + 2°
- model: parametrize with $\Theta_D$ and Dst (open + close)
Results:

- Engwall et al, 2009, André et al, 2015:
  - outflow rates

- Li et al, GRL 2012:
  - source of cold ions
  - response to geoactivity

- Haaland et al, 2012a
  - fate of ions
Densities, fluxes and outflow rates

* Ionospheric fluxes $\sim 10^8$ cm$^{-2}$ s$^{-1}$

* Average outflow rate $\sim 10^{26}$ ions/s

Solar irradiance

F10.7 : outflow increases ~ factor 3
(mainly change in ionization/density)
...for comparison .. other sources

Supply rates:

* Solar wind: $10^{24} - 10^{27} \text{ s}^{-1}$ [1,2]
* High latitude: “up to $10^{27} \text{ s}^{-1}$” [3]
* Terrestrial outflow $\sim 10^{26} \text{ s}^{-1}$ [4]
  “Cold” (< 70 eV) dominating [5]

Source region

Particle tracing
Li et al, GRL 2012

\[
\frac{dv_{||}}{dt} = \vec{v}_{E} \cdot \frac{d \hat{b}}{ds} - \vec{g}_{||}
\]
Source region (Li et al, GRL, 2012)
Source region (Li et al, GRL, 2012)

Response to geoactivity:
- Polar cap expansion
- Enhanced flux

\[
A = 0.9 \times 10^7 \text{ km}^2 \\
F = 2.5 \times 10^{25} \text{ s}^{-1}
\]

\[
A = 2.8 \times 10^7 \text{ km}^2 \\
F = 7.6 \times 10^{25} \text{ s}^{-1}
\]
Fate of ions (Haaland et al, 2012a,b, Li et al, 2013)

- Quiet conditions, stagnant convection
  - direct loss downtail

- Intermediate geoactivity
  - 80-90% circulation
  - supply far downtail

- Disturbed conditions, strong convection
  - little downtail loss
  - supply close to Earth
Accretion: Asteroids, meteorites... $+6 \text{ kg/s}$

Loss:
- Neutrals $-1 \text{ kg/s}$
- Ions $-2 \text{ kg/s}$

Net balance $+3 \text{ kg/s}$

Roddy et al, 1995; Ceplecha et al. 1998; Flynn & Sutton, 2006; Plane, 2012,
### Mars
- $R_M \approx 3390 \text{ km}$
- $M_S \approx 0.65 \cdot 10^{24} \text{ kg}$
- $I_{SUN} \approx 600 \text{ W/m}^2$
- $E_{ESC \; H^+} \approx 0.2 \text{ eV}$
- $E_{ESC \; O^+} \approx 1.9 \text{ eV}$
- $L_{OUT} \approx 10^{24} \text{ ions/s}$ (mostly lost)

### Earth
- $6371 \text{ km}$
- $6.0 \cdot 10^{24} \text{ kg}$
- $1200 \text{ W/m}^2$
- $0.6 \text{ eV}$
- $9.7 \text{ eV}$
- $10^{26} \text{ ions/s}$ (mostly recirculated)

### Venus
- $6050 \text{ km}$
- $4.9 \cdot 10^{24} \text{ kg}$
- $2600 \text{ W/m}^2$
- $0.5 \text{ eV}$
- $8.6 \text{ eV}$
- $10^{25} \text{ ions/s}$ (mostly lost ?)
Summary, terrestrial cold ion outflow

- Cold ions can now be measured
- Cold ions constitutes a significant fraction of plasma in large regions of the magnetosphere
- Outflow rates $\sim 10^{26}$ ions/s ($\sim 2$ kg/s = 60'000 t/y)
- On average, ca 80 - 90% of outflowing ions are recirculated; only 10% directly lost downtail.
- Fate mainly governed by convection.