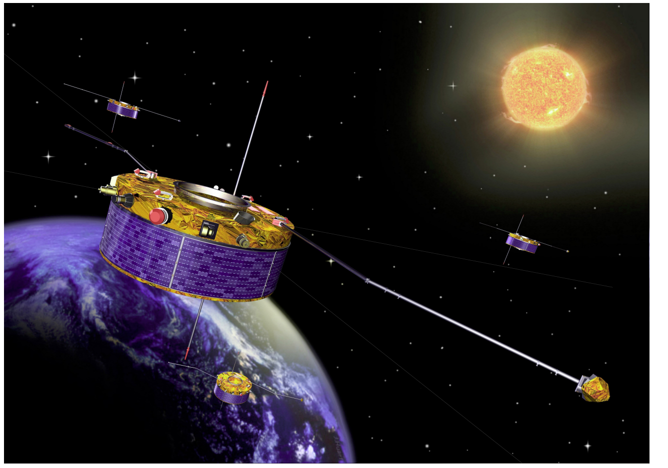

Cluster (ESA, launch 2000)

The escape of the upper atmosphere and a surprising way to detect this

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Atmospheric Escape

- **High energy tail of the velocity distribution, at the exobase (Jeans escape).**
- **Charge exchange with ions from the magnetosphere.**
- **Ions from the ionosphere.**

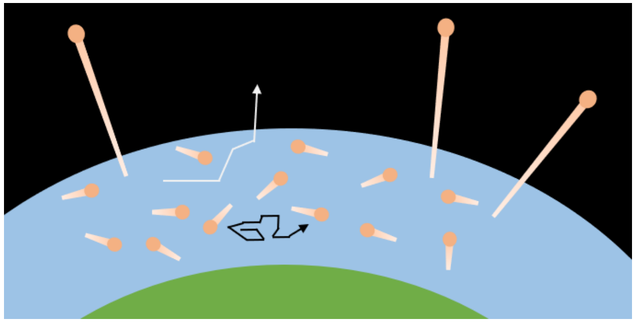


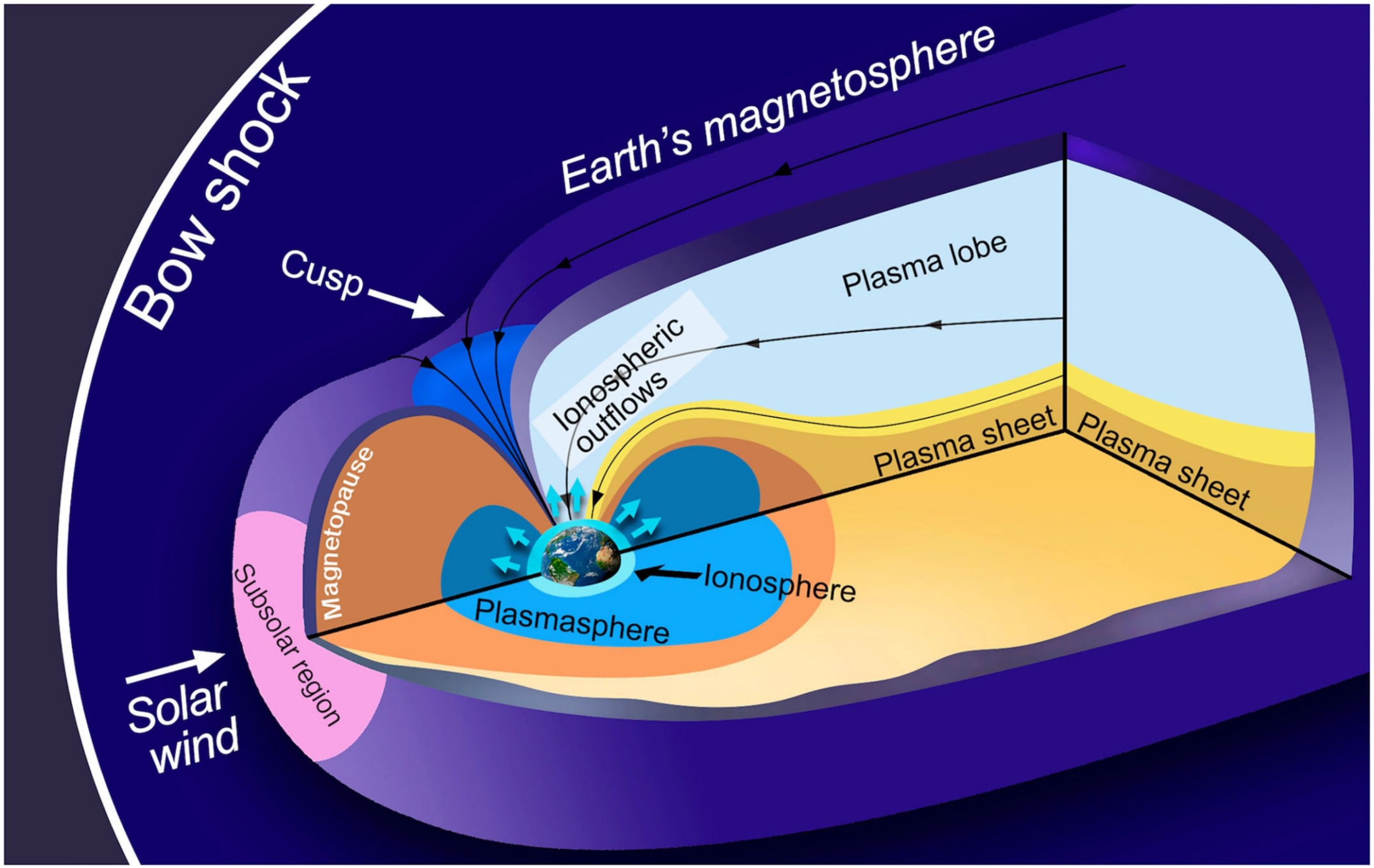
Fig: Wikipedia

H, He, O and more

10^{26} /s   1 kg/s   30,000 ton/year

Present outflow small on geological timescale.
Similar to inflow of small (< mg) particles.

The Magnetosphere



Solar wind

Polar lobes

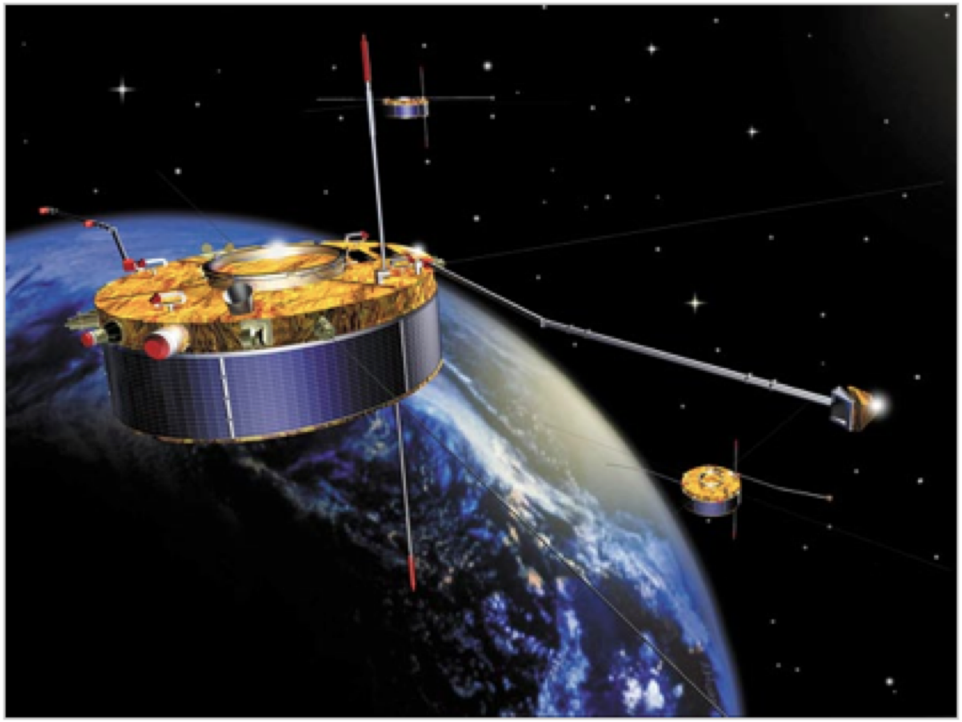
Ionosphere

(Fig. from Toledo-Redondo et al., Rev. Geophys. 2021)

NATIONAL GEOGRAPHIC Daily News

Giant Veil of "Cold Plasma" Discovered High Above Earth

Clouds of charged particles stretch a quarter the way to the moon, experts say.



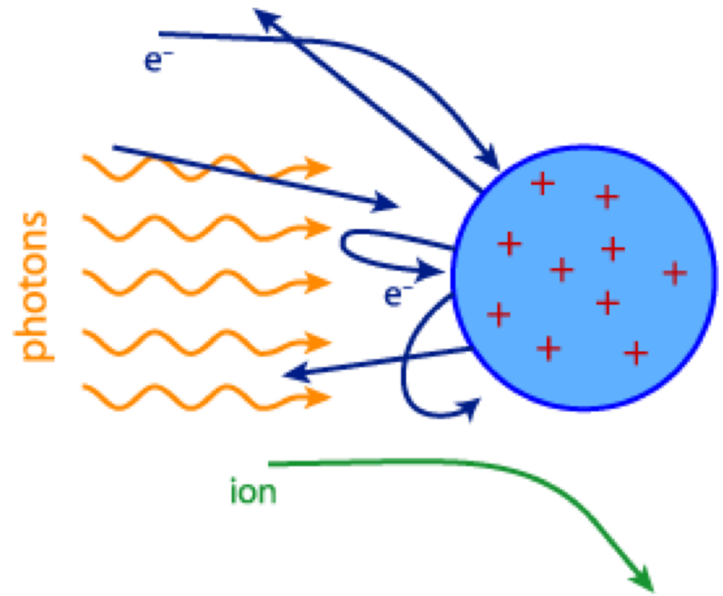
An artist's rendering of ESA's Cluster II spacecraft in orbit.

Illustration courtesy J. Huart, ESA

Dave Mosher
for National Geographic News
Published January 26, 2012

Clouds of "cold plasma" reach from the top of Earth's atmosphere to at least a quarter the distance to the moon, according to new data from a cluster of European satellites.

Problem: Spacecraft Charging



Conducting SC in sunlit plasma

- **Solar EUV => Escaping photo e^-**
- **Incoming plasma e^- (i^+ much slower)**
- **Result 1: (often) positive SC (tens of V)**
- **Result 2: Low energy i^+ (few eV) cannot reach the SC**

(From EFW for Dummies, web-page, C. Cully. 2002)

Solution: Wake Physics

Collisional fluid or gas

"The wake is the region of disturbed flow downstream of a solid body moving through a fluid" (adapted from Wikipedia)

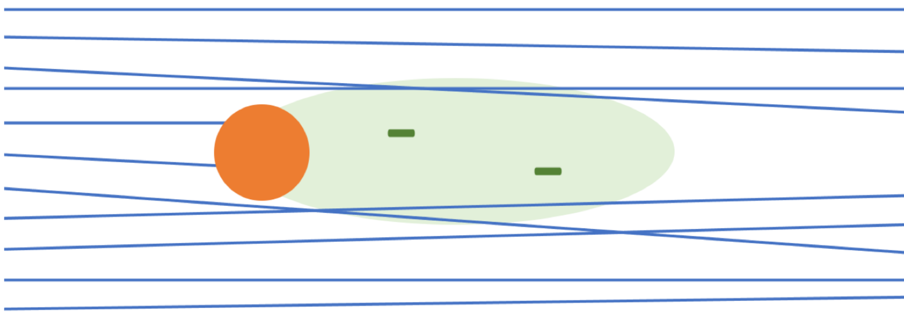
Subsonic or supersonic (V_{sound} vs. V_{drift})

Collisionless plasma

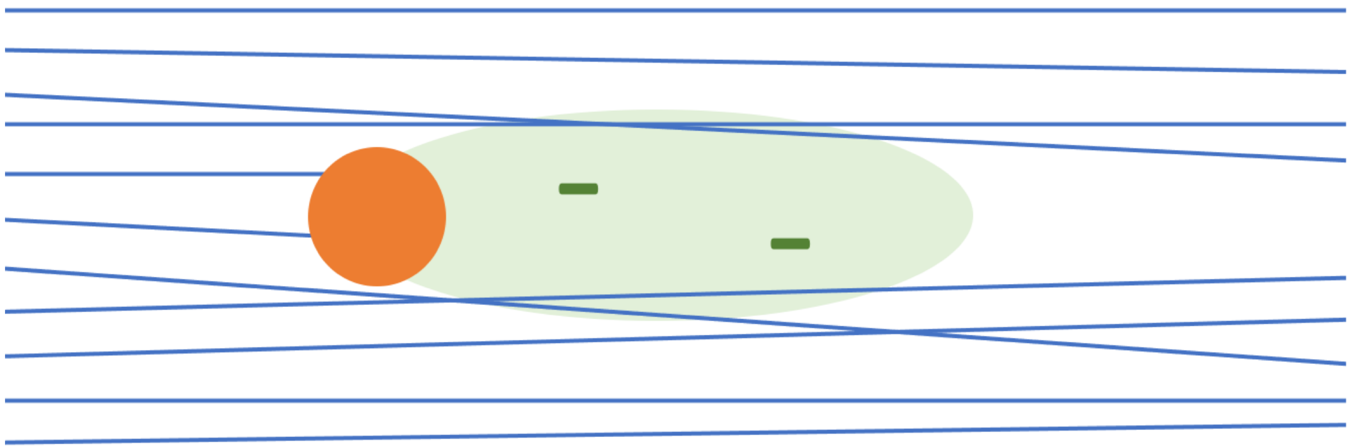
Often $V_{i, thermal} < V_{drift}$; $V_{e, thermal} > V_{drift}$

Ions supersonic; electrons subsonic: Mesosonic

($V_{ion\ acoustic} \approx V_{i, thermal}$ for $T_e \approx T_i$)



Wake Electric Field



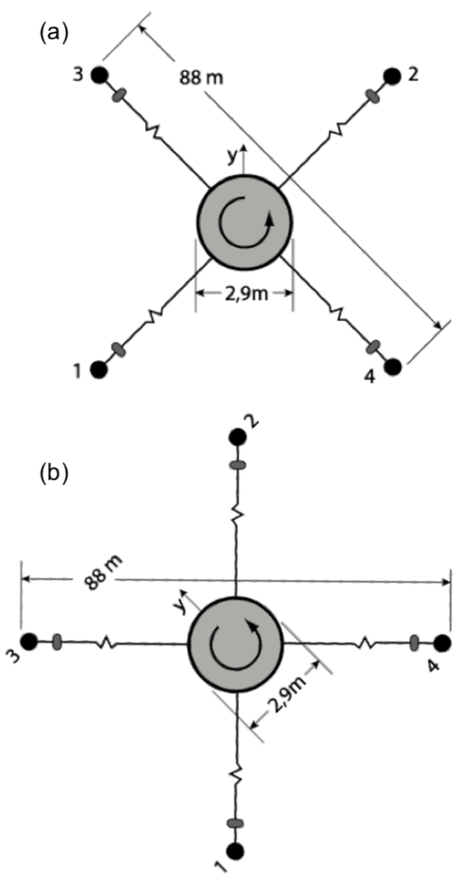
Plasma V_{drift} =>

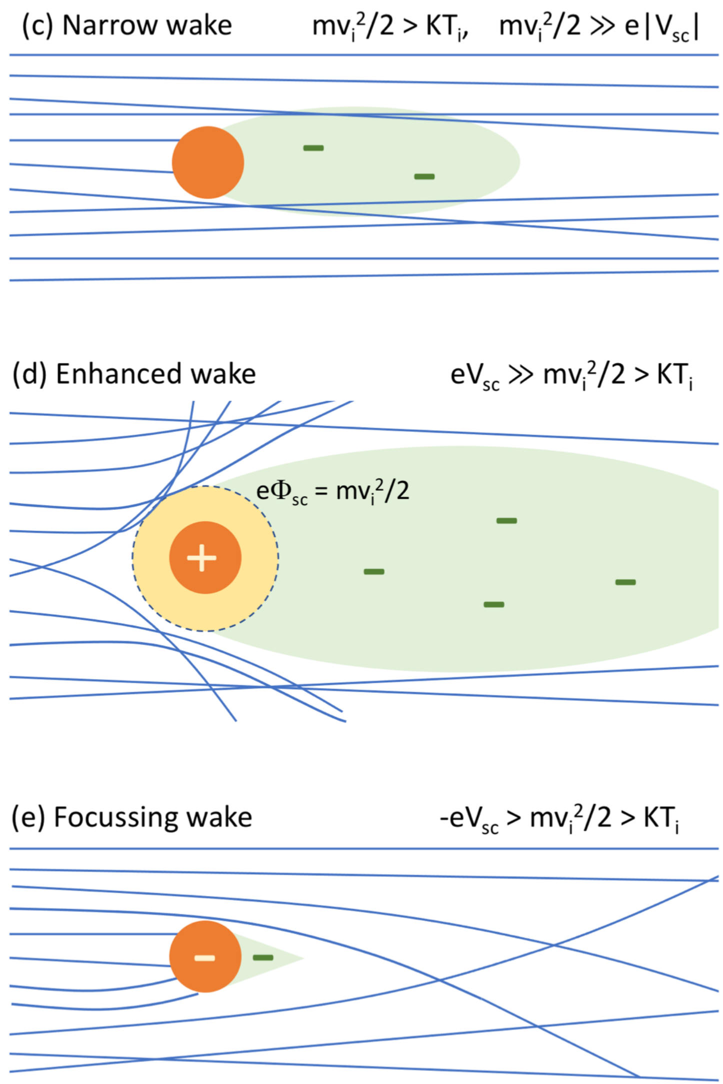
$V_{i, thermal} < V_{drift}$; $V_{e, thermal} > V_{drift}$

Wake filled with electrons: Electric field

Wakes Behind Spacecraft

Cluster





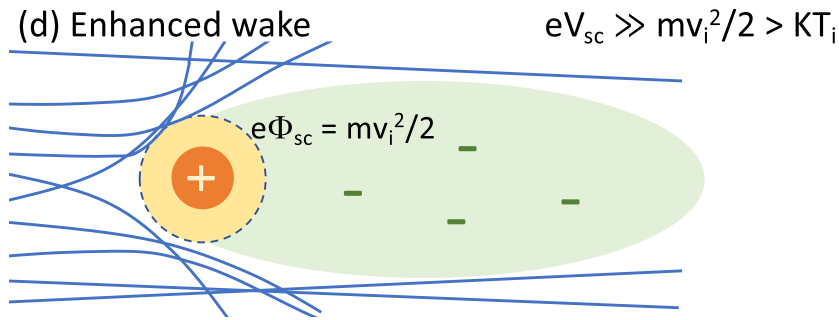
Narrow
(Solar wind)

Enhanced
(Polar lobes)

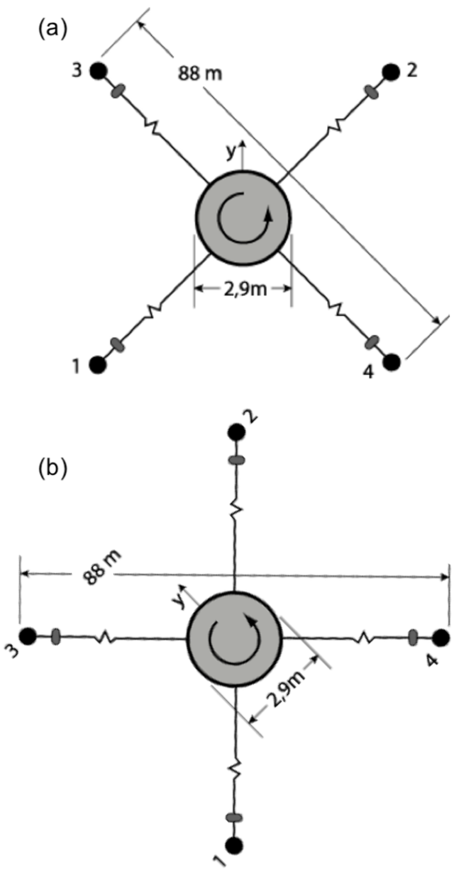
Focused
(Ionosphere)

André et al., JGR, 2021

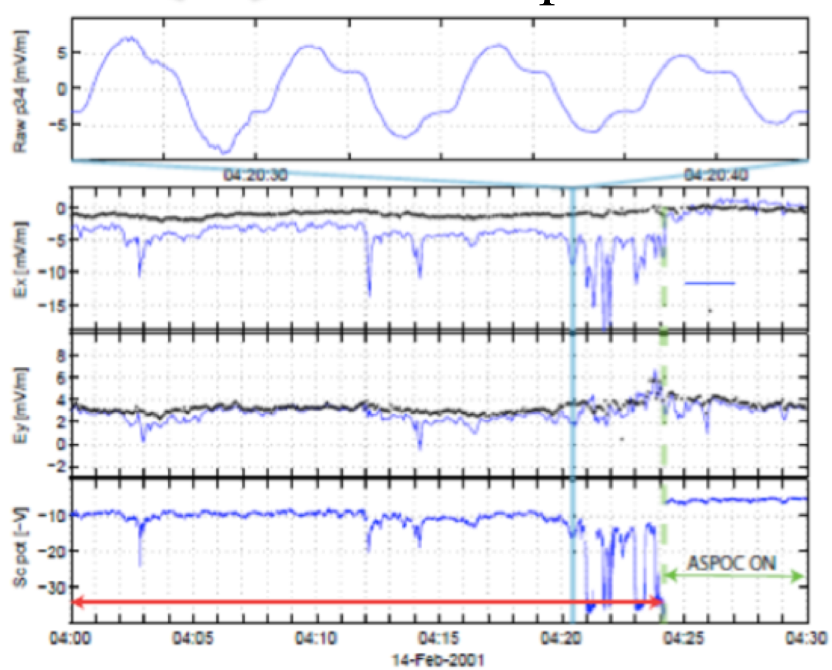
Enhanced Wake



Enhanced
(Polar lobes)



4 s SC spin

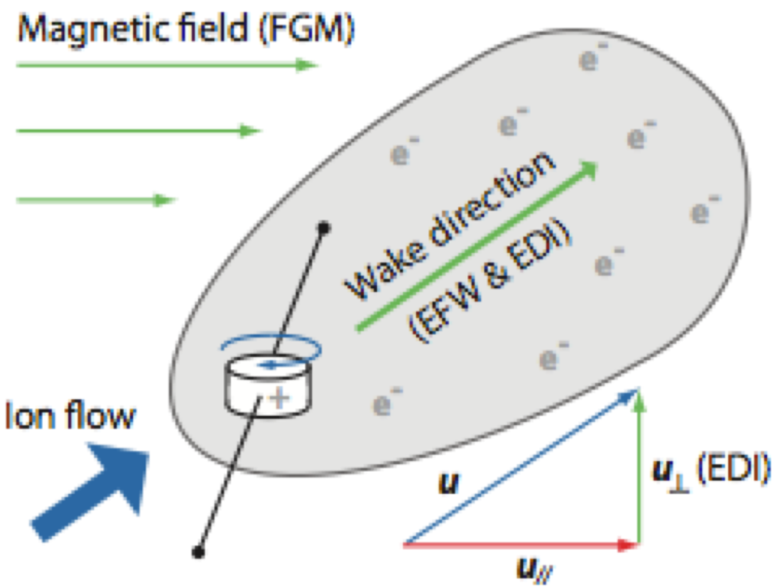


5 mV/m

E NOT geophysical
Low energy ions
NOT Ok

Flowing Low-Energy Ions

Cluster



$KT < mv^2/2 < eV_{sc}$

Velocity

Wake direction (EFW, EDI)

B direction (FGM)

$\mathbf{u}_{perp} = \mathbf{E} \times \mathbf{B}/B^2$ (EDI, FGM)

Density

SC potential:

Lybekk et al. (2012)

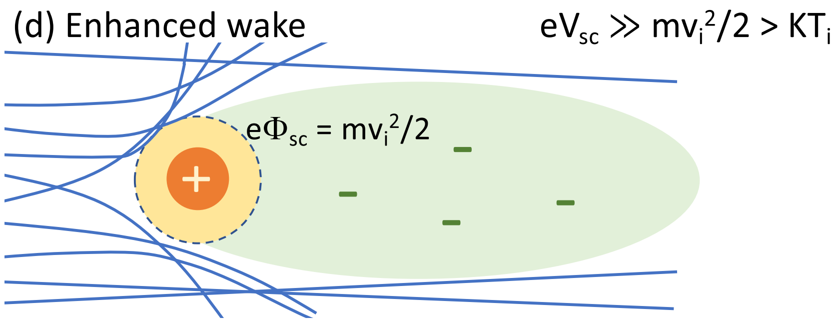
Haaland et al. (2017)

Flux

Engwall et al. (2009)

André et al. (2015)

Enhanced Wake



Enhanced

(Polar lobes)

E (local) not directly useful
Cold ions will not reach the SC

E (local, EFW) and E (geophysical, EDI)
B (geophysical, FGM)
SC potential (EFW) , proxy for density
=> Ion flux

Validation of the Cluster Wake Method

- **Statistics: 10 years, 1.68×10^6 for detection; 3.2×10^5 for flux.**
  (Data point: 4 s Cluster spin.) (André et al., JGR, 2015)

- **Compare nearby Cluster SC (ASPOC on/off)**
  (particle detector or wake method) (Engwall et al., GRL, 2006)

- **Simulations (e.g. Engwall et al., Phys. Plasmas, 2006)**

- **Solar wind wake results (André et al., JGR, 2021)**

- **Compare with results at lower altitude**
  (André et al., 2021, Toledo-Redondo, 2021)

Ion Outflow: Cold Ions Common

High latitude: Cusp/cleft, Polar Cap, Auroral Region

Spacecraft	Nominal energy range (eV)	Altitude (R_E)	Upflow rate (10^{26} ions/s); ion species
Cluster[1]	0 - 60	5 - 20	0.6 - 2.4 (mainly H^+)
Polar/TIDE[2]	<1 - 100	8	1.3 (mainly H^+)
Polar/TIDE[3]	<1 - 450	0.8	1.7 (mainly H^+)
Akebono[4]	<1 - 70	1 - 1.5	0.2 - 2(H^+ and O^+)
DE[5]	10 - 17,000	2.5-3.7	0.2 - 2 (H^+ and O^+)
Polar/TIMAS[6]	15 - 33,000	0.8	0.08 (H^+ and O^+)
Cluster/CODIF[7]	25 - 38,000	10 - 15	0.1 - 2.2 (O^+)

Low latitude: Magnetopause (plumes)

Spacecraft	Nominal energy range (eV)	Outflow rate (10^{26} ions/s)
Cluster[8]	0 - 1000	1 - 10
MPA[9]	1 - 40,000	2
IMAGE[10]	wide range	3.8 - 21

Low latitude: Magnetopause (wind)

Spacecraft	Nominal energy range (eV)	Outflow rate (10^{26} ions/s)
Cluster[8]	0 - 1000	0.1 - 1

[1]*André et al.* [2015], [2]*Su et al.* [1998], [3]*Huddleston et al.* [2005], [4]*Cully et al.* [2003],
[5]*Yau and André* [1997], [6]*Peterson et al.* [2006, 2008], [7]*Slapak et al.* [2017], [8]*André and Cully* [2012],
[9]Magnetospheric Plasma Analyzers *Borovsky and Denton* [2008], [10] *Spasojevic and Sandel* [2010],

Typical: 10^{26} ions/s

André et al., AGU monograph, 2021

Update: Toledo-Redondo et al., Rev Geophys, 2021

Impact: Space Weather

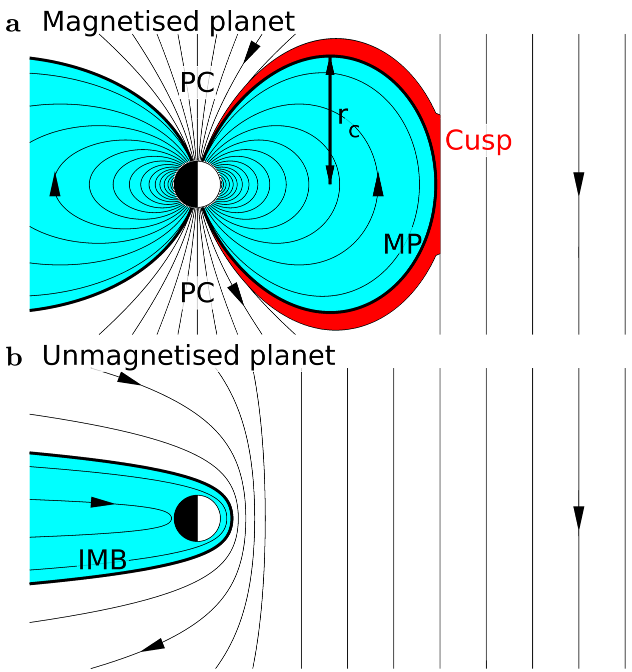
Plasma content near-Earth space

Schrijver et al., 2015

Owens et al., 2021

Beedle et al., 2022

Impact: Astrobiology



An intrinsic B-field does NOT protect the atmosphere

Gronoff et al., 2020

Ramstad and Barabash, 2021

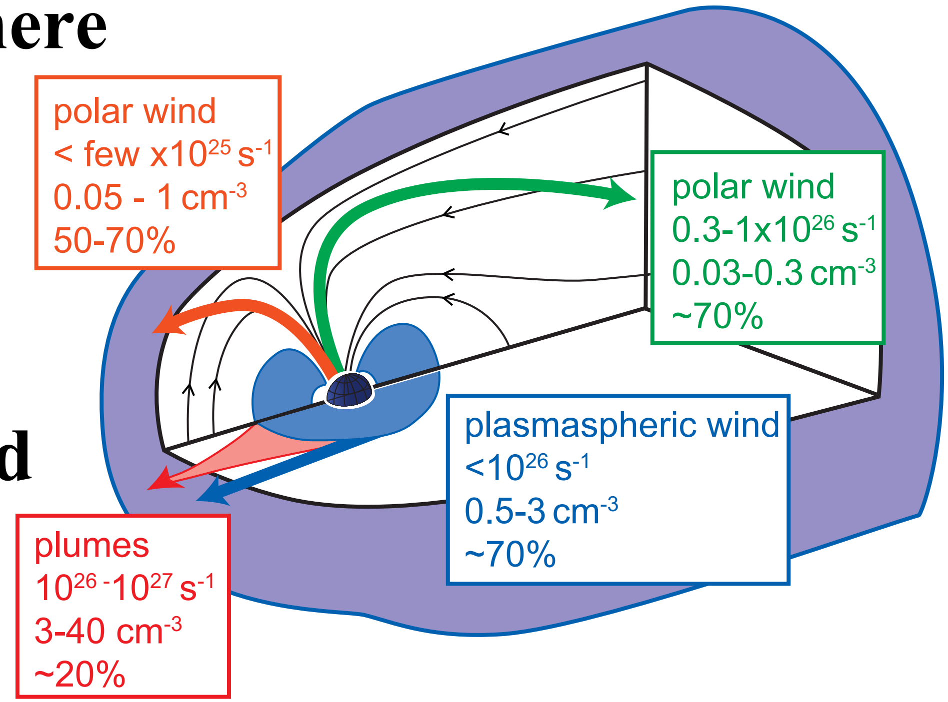
Gunell et al., 2018

Impact: Space Physics

Cold (few eV) ions dominate

- **Most of the magnetosphere**
- **Most of the time**
- **Much of the outflow**

- **Change the Alfvén speed**
- **Change magnetic reconnection**



André and Cully, GRL, 2012

Toledo-Redondo et al., Rev Geophys, 2021
André et al., JGR, 2021
Delzano et al., JASTP, 2021