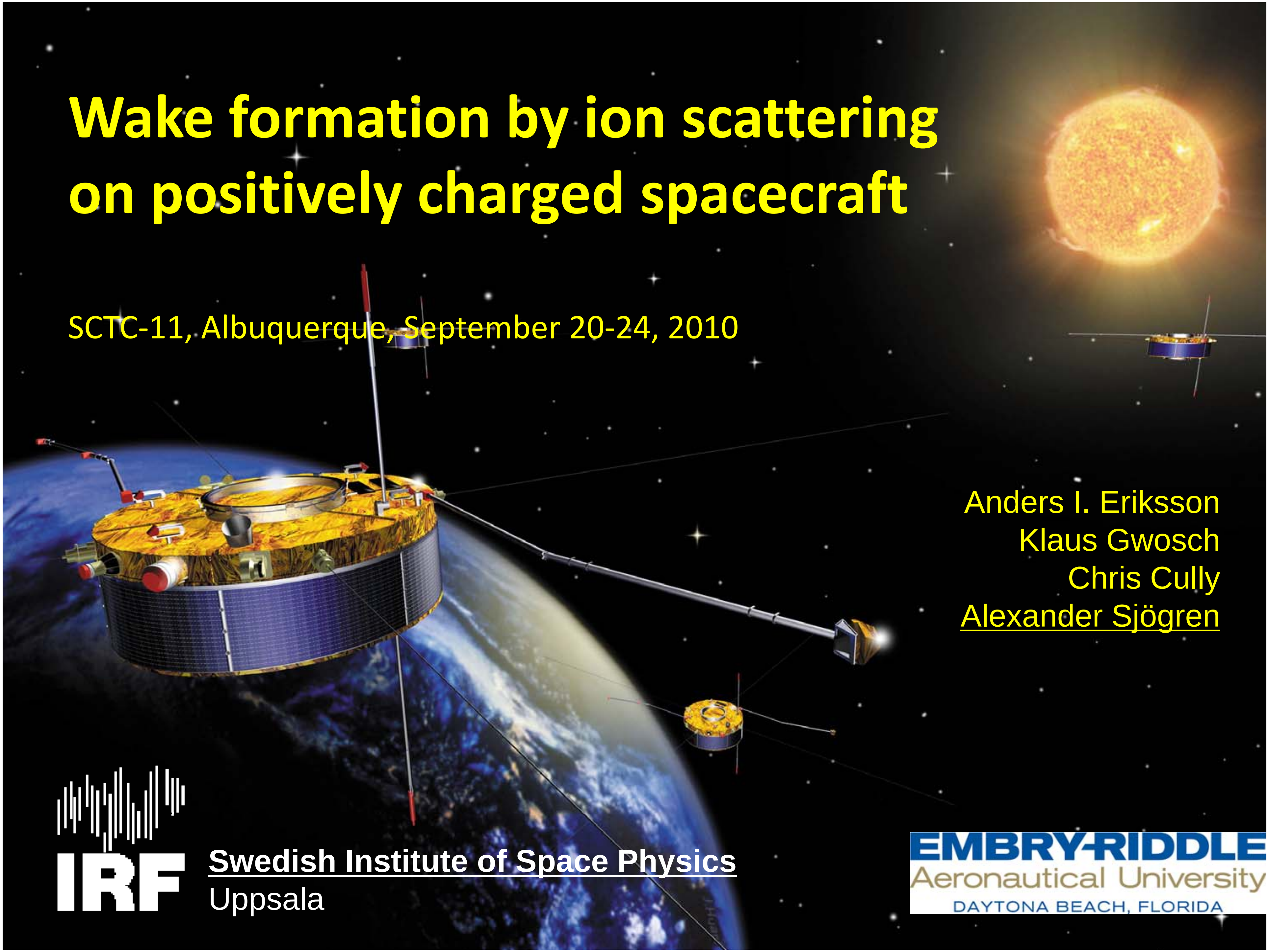
Wake formation by ion scattering on positively charged spacecraft

SCTC-11, Albuquerque, September 20-24, 2010



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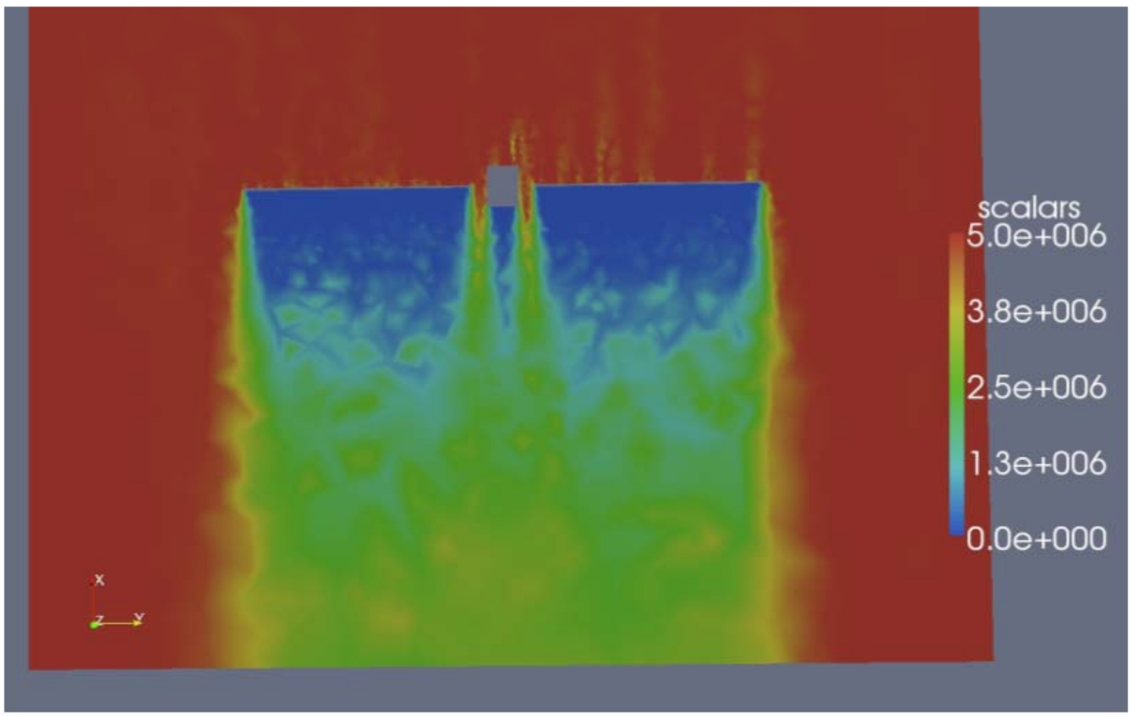
Wakes

- Form behind an obstacle in a supersonic flow
- Space plasma flows usually mesosonic (supersonic for ions, subsonic for e-) => wake charges negatively
- Size usually set by spacecraft size

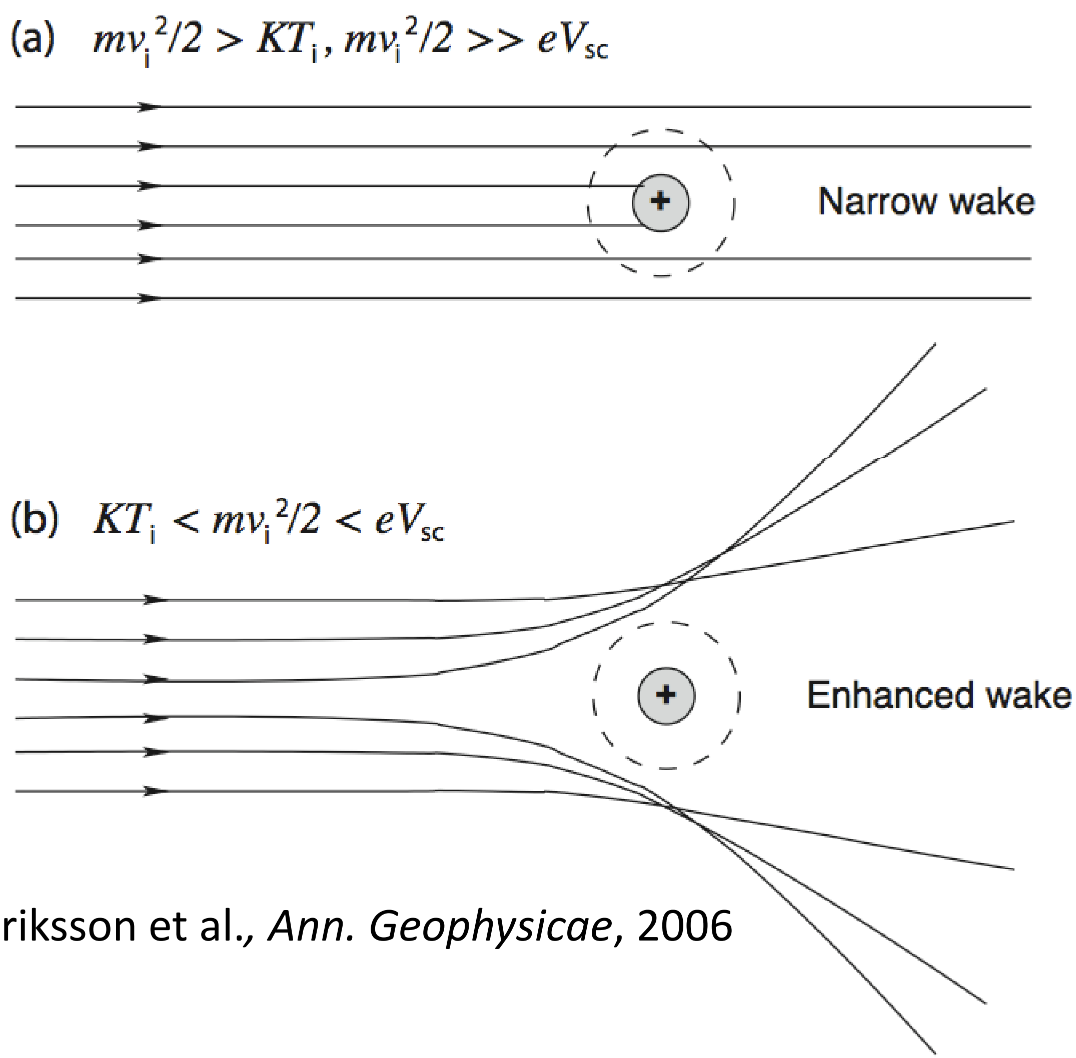


PIC simulation of wake behind Rosetta in the solar wind (SPIS code)
(see poster by Sjögren et al!)

Ion density:
Blue = 0
Red = 5 cm-3 =
= ambient

The negative side of being positive

Wake formation behind a positive spacecraft



Eriksson et al., *Ann. Geophysicae*, 2006

In tenuous magnetospheric plasmas, λ_D >> s/c dimensions. A wake of s/c transverse dimension thus charges only to a fraction of KT_e/e.

But: if the ion ram flow energy is below the s/c potential**, a huge wake results,** that may charge to order KT_e/e, and give a quasi-sinusoidal spin signature hard to remove.

When does this happen?

When the plasma is so tenuous that the spacecraft potential goes sufficiently positive:

$e V_{sc} > m u_i^2/2 > KT_i$

Not the case in e.g the solar wind or the ionosphere

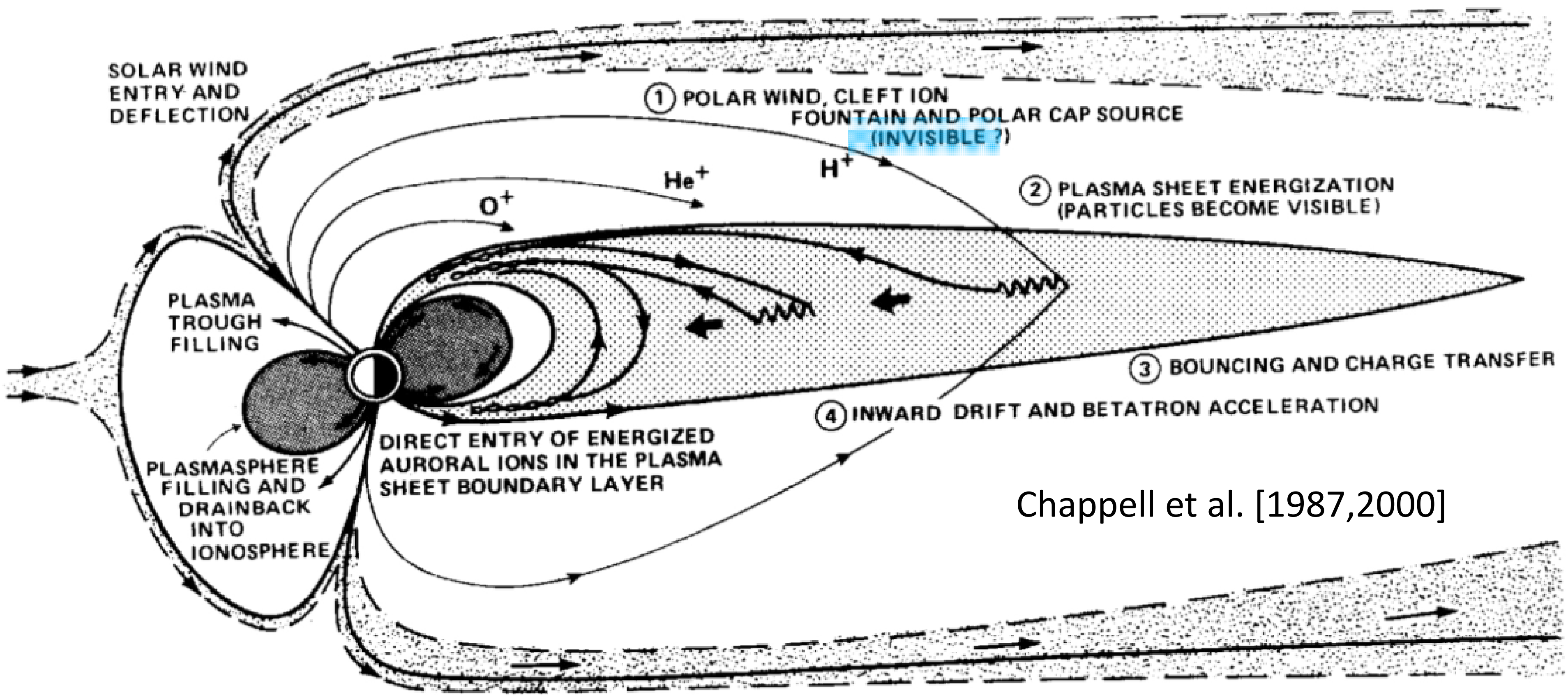
So where could this be a problem?

The "invisible" plasma flow in the lobes of the magnetotail

Tenuous plasma => high s/c potential (20-60 V)

Ions have low energy (<10 eV) => cannot reach s/c

Conditions for forming a huge wake met?



Chappell et al. [1987,2000]

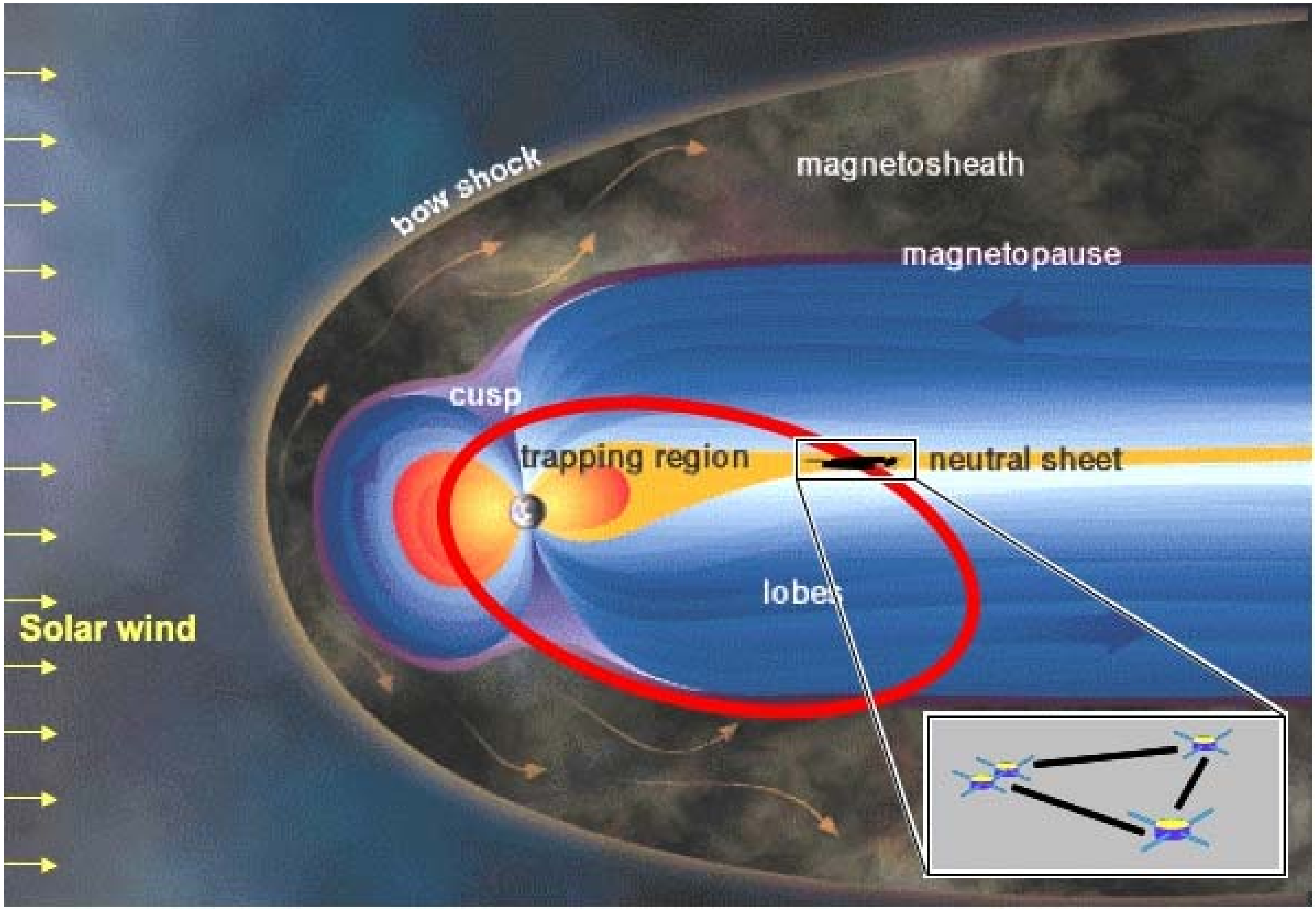
Cluster

ESAs four-spacecraft mission to the magnetosphere

In orbit since 2000, operational since 2001

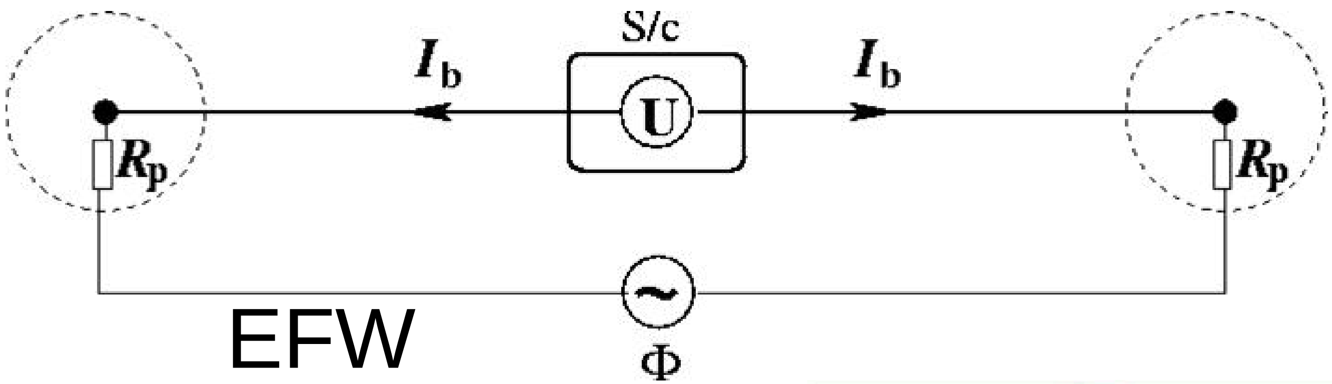
Full orbit coverage since 2002

Initial orbit 4 x 22 RE



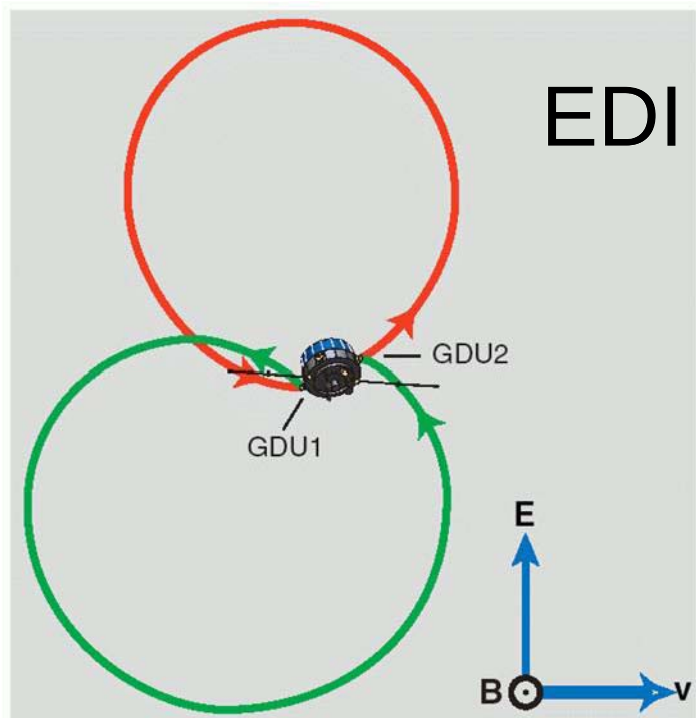
Cluster orbit in autumn: long time spent in tail lobes

Cluster electric field instruments



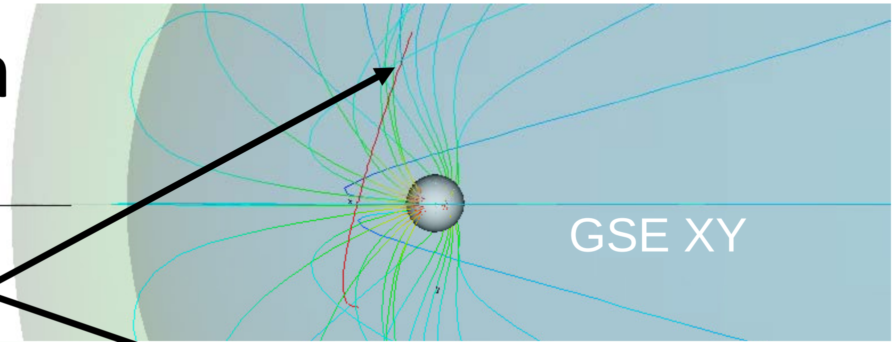
EFW: Potential differences from double probes – will cross a wake

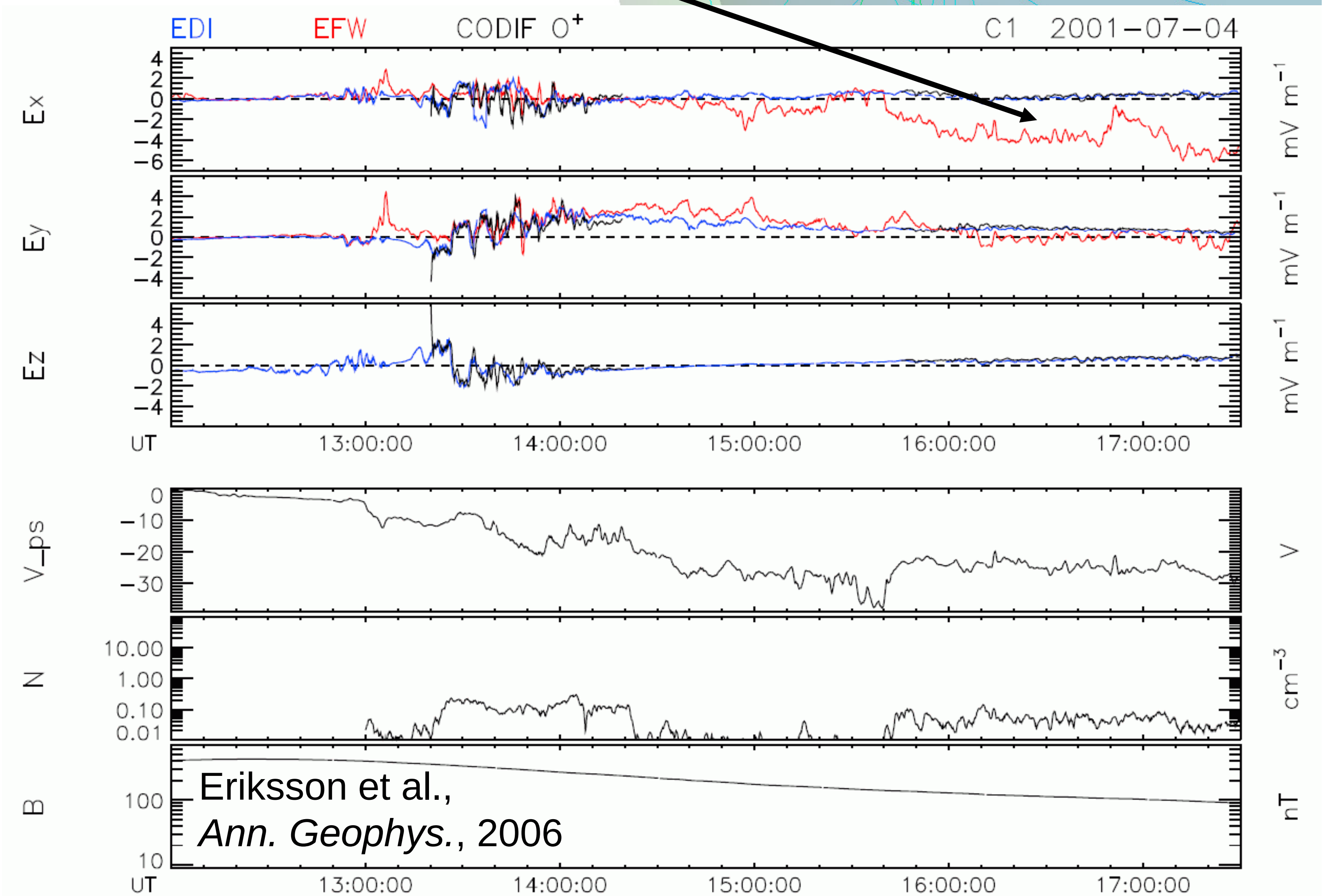
EDI: Electron Drift Instrument using keV e- going kilometers from the s/c – "immune" to wakes



In the lobes, EFW & EDI often disagree on the E-field

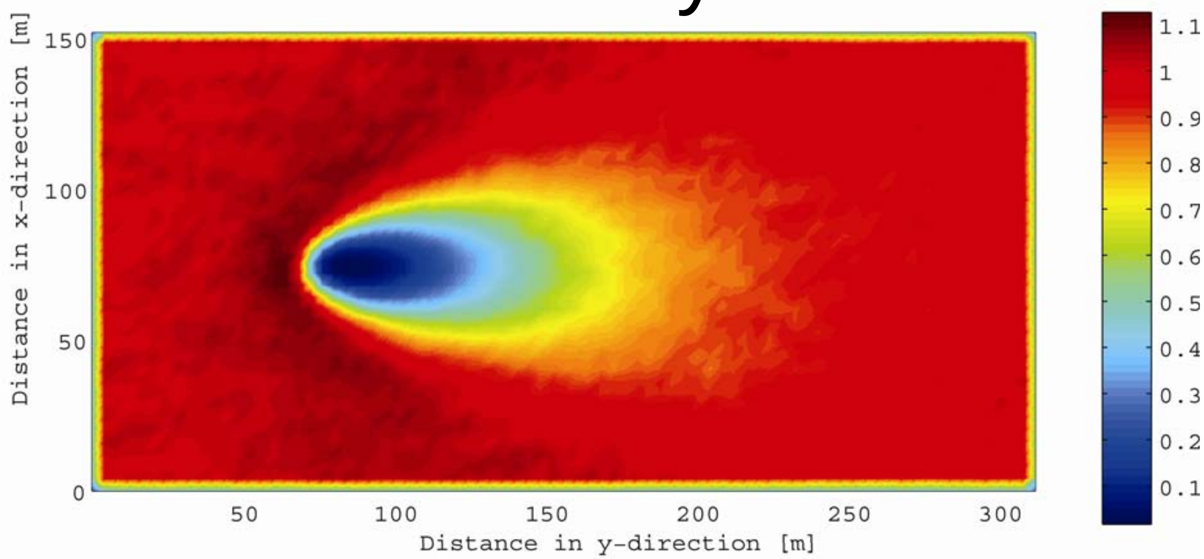
As expected if there is a strong wake forming



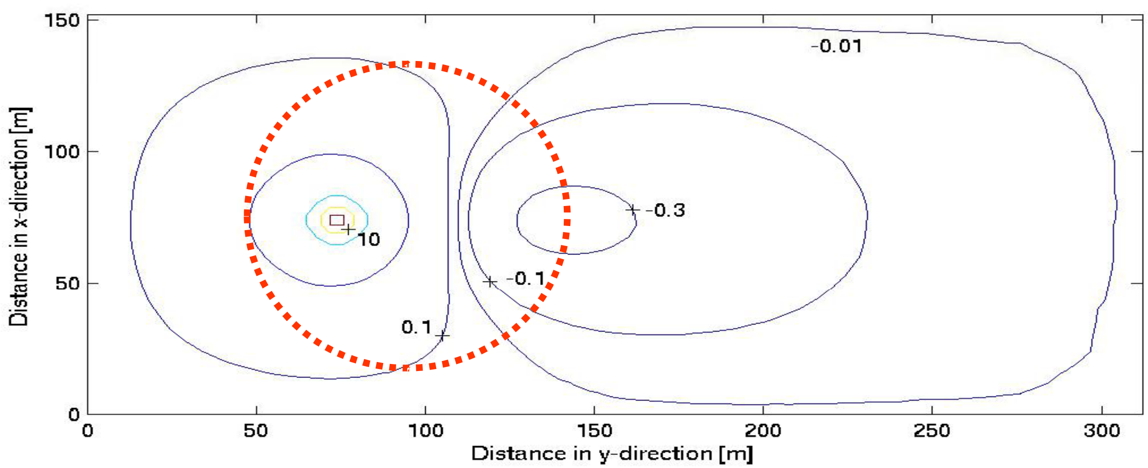


PIC simulations verify concept...

Ion density



Potential



Simulations using PicUp3D and SPIS

Condition for enhanced wake formation:

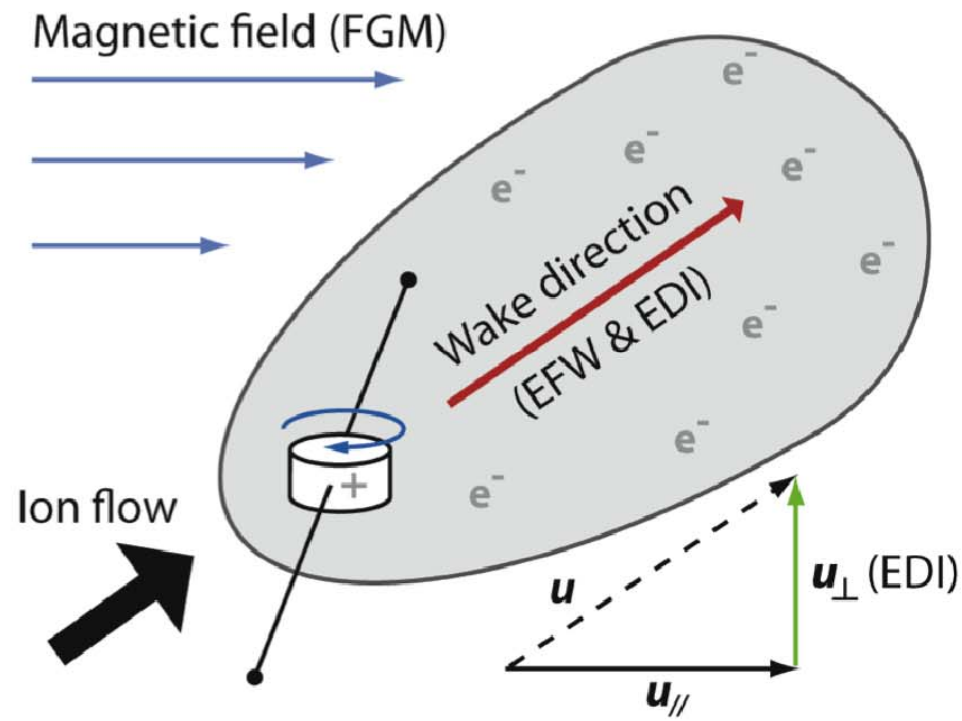
$KT_i < mv^2/2 < eV_{sc}$

The negatively charged wake behind the spacecraft will be seen by EFW (probe-to-probe separation 88 m) but not by EDI.

Engwall et al., *Phys. Plasmas*, 2006

…and a simple model relates the wake to flow properties

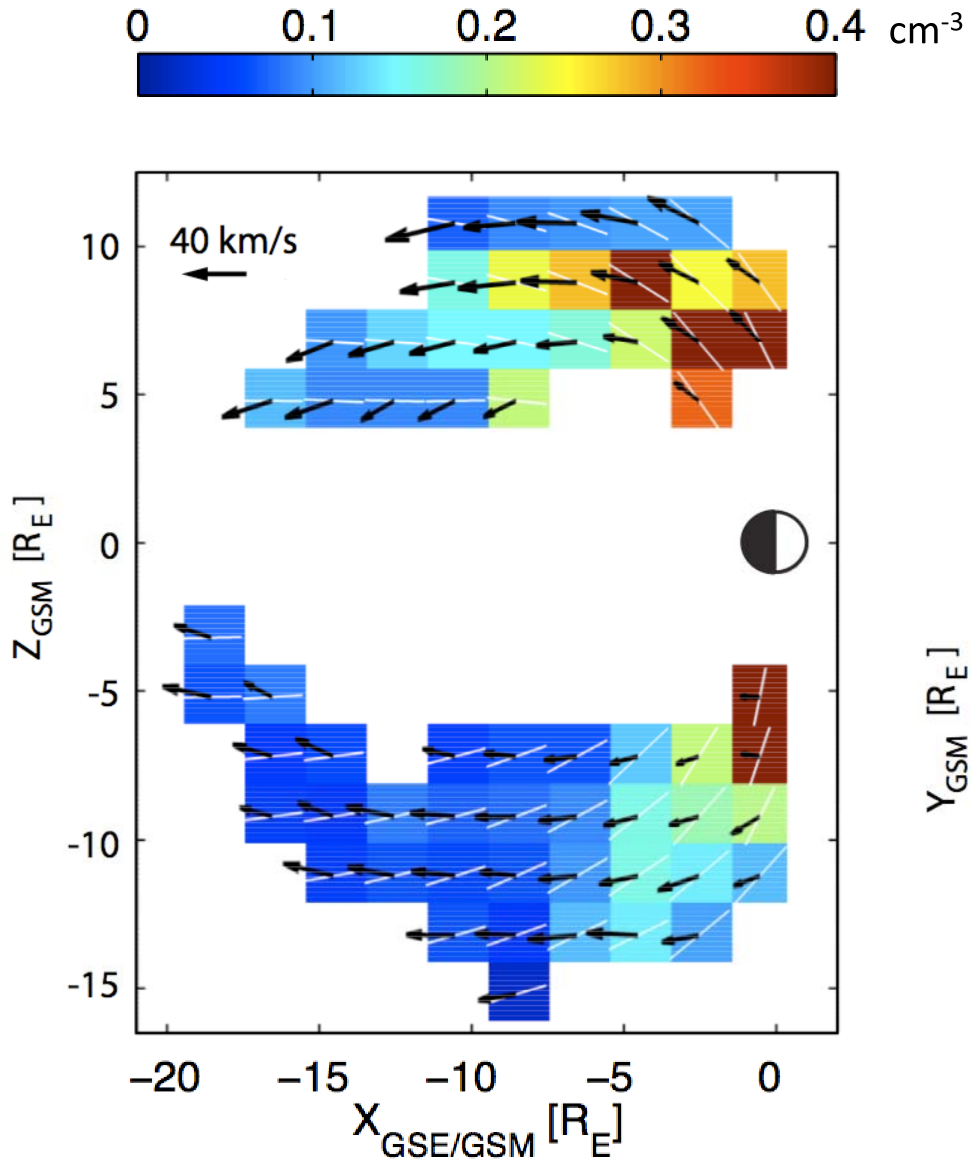
- **u**$_{perp}$ known from EDI (**E**x**B**)
- Direction of **u** known from wake direction
- **B** direction known from magnetometer
- Together these give full info on direction and magnitude of ion flow velocity **u**
- Combine with n from Vsc to get flux



- We can thus get mean velocity and flux for the "invisible" ion flow that cannot reach the s/c or its particle detectors!

Engwall et. al, *Ann. Geophysicae*, 2009

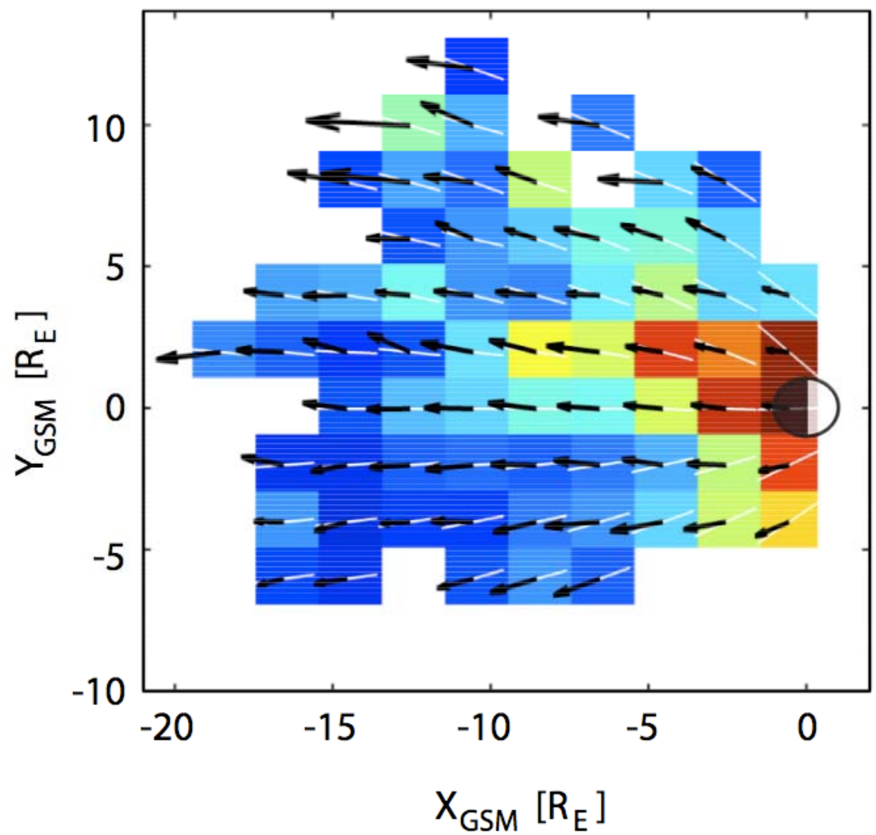
"Invisible" magnetotail flow mapped by wake study



First map of observed cold ion flows in the tail!

Black arrows: flow velocity

White lines: B-field



Need for Analytical Model

- Motivation:
  - PIC simulations demonstrated the concept of the enhanced ion wake forming by ion scattering on the spacecraft potential field
  - Simple model allowed deriving the parallel flow velocity
  - Other parameters, e.g. Mach number and electron temperature, also influences the wake structure
  - Could we estimate these parameters as well from observations of the wake?
  - Quite possible…
  - … but we need an analytical model for how they influence the wake
  - Deriving such a model from many PIC simulations would take a lot of time (for CPU and scientist alike)
- Task: Analytical model for the ion wake

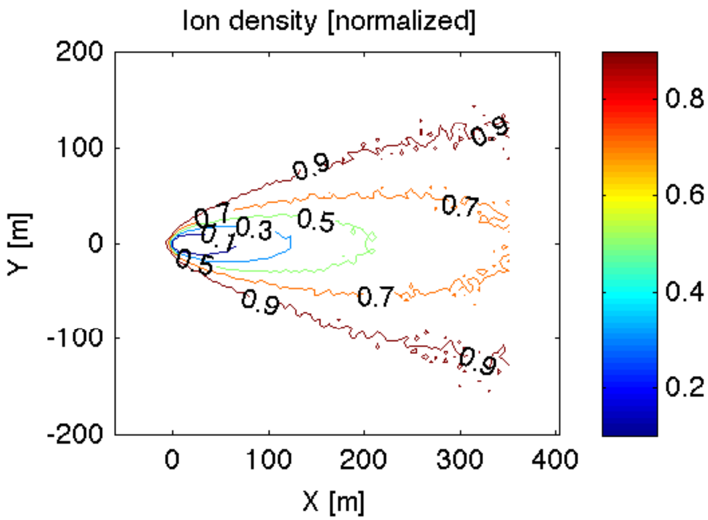
Model assumptions

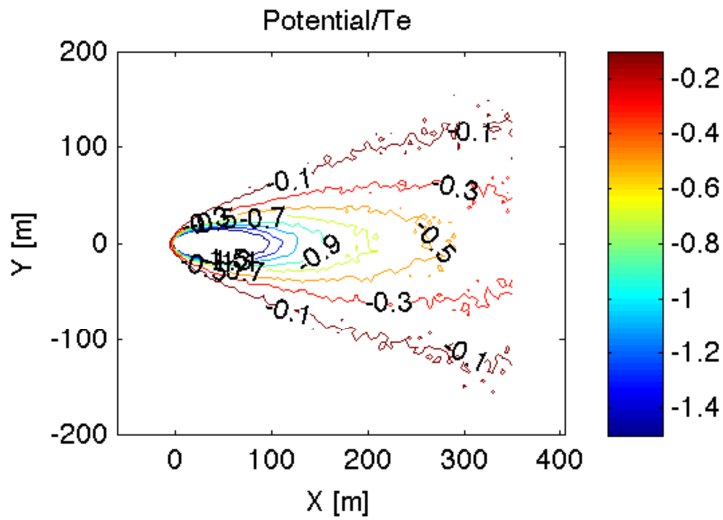
- Spherical spacecraft
- 1/r potential from s/c
  - Means vacuum conditions
  - Reasonable in the tenuous plasmas where Vsc is so high that this kind of wake can form
- Neglect wake influence on ion motion

Semi-Analytical Model

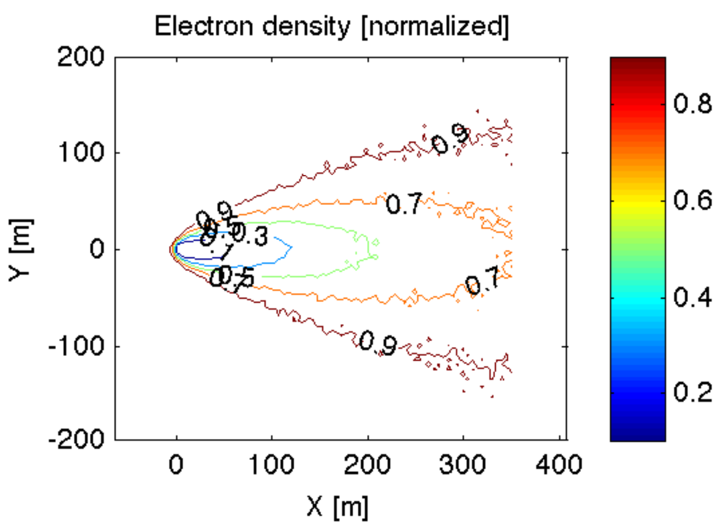
- Find ion trajectories around s/c
  - Kepler problem for repelling potential
- Find the distribution function:
  - Use Liouville's theorem
  - Follow trajectories backwards to infinity
- Integrate distribution function to density
  - Combine analytical and Monte Carlo methods
- Assume Boltzmann electrons
- Numerical integration to find potential in wake

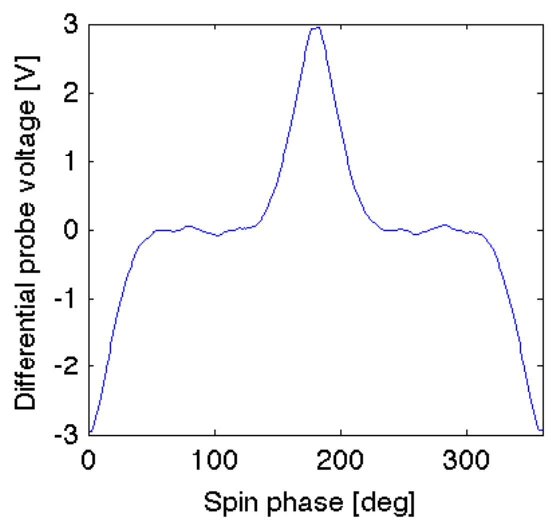
Model Example





Ne = 0.1 cm-3
Ti = 1 eV
Te = 1 eV
Ei = 10 eV
Vsc = 35 V



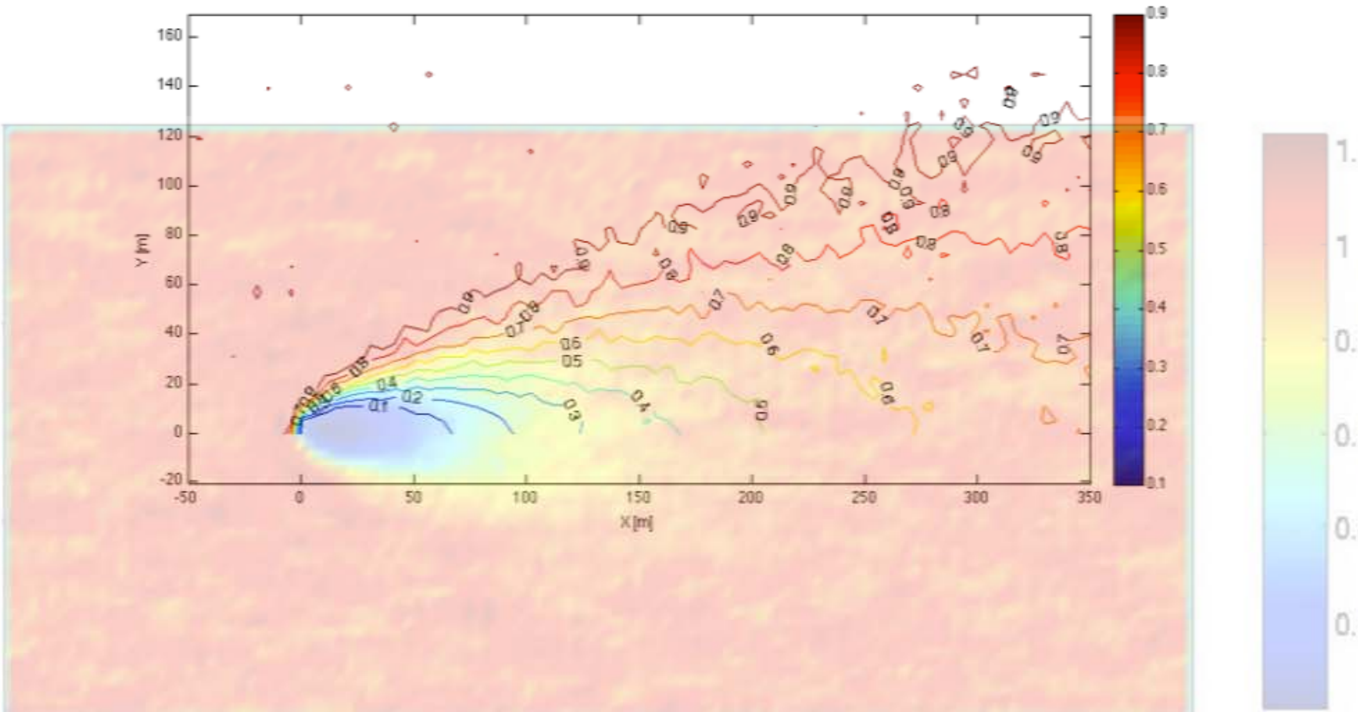


Resulting spin signal for the Cluster EFW electric field instrument

Comparison: PIC vs. Semi-Analytic

Plots show density, surroundings = 1

Flow direction   Vs = 35 V, T = 2 eV, Eram = 10 eV



Semi-analytic overlaid on PicUp3D

Very good agreement

Semi-analytic model handles 10 times the particle number in 1/10 of the PIC run time => Less noise

Summary (1/2)

- Cold plasma flows in tenuous plasma give huge wakes: $KT_i < mv^2/2 < eV_{sc}$
  - Common in magnetotail lobes
  - Problem for E-field measurement, but…
  - …yields velocity of otherwise invisible plasma (also density from s/c potential)
- Cold plasma statistics in the tail
- Method works precisely when ordinary ion detectors fail!

Summary (2/2)

- PIC simulations verify wake formation
- PIC models detailed but time-consuming
- New semi-analytical Monte Carlo model well reproduces PIC results
  - Assumes spherical symmetry
  - Provides easy comparison to data
  - Intended use: investigate if plasma parameters like ion Mach number and e- temperature can be found from wake