Wake formation by ion scattering on positively charged spacecraft

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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

(a) \( m v_i^2/2 > KT_i, m v_i^2/2 >> eV_{sc} \)

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

(b) \( K T_i < m v_i^2/2 < eV_{sc} \)

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:

\[ eV_{sc} > m\, u_i^2/2 > KT_i \]

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

Eriksson et al., Ann. Geophys., 2006
PIC simulations verify concept...

Ion density

Simulations using PicUp3D and SPIS

Condition for enhanced wake formation:

\[ K_T i < \frac{m v^2}{2} < eV_{sc} \]

Potential

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

- $\mathbf{u}_{\text{perp}}$ known from EDI ($\mathbf{E} \times \mathbf{B}$)
- Direction of $\mathbf{u}$ known from wake direction
- $\mathbf{B}$ direction known from magnetometer
- Together these give full info on direction and magnitude of ion flow velocity $\mathbf{u}$
- 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!
"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 $V_{sc}$ 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, E_{ram} = 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