

Multi-spacecraft study of the 21 January 2005 ICME

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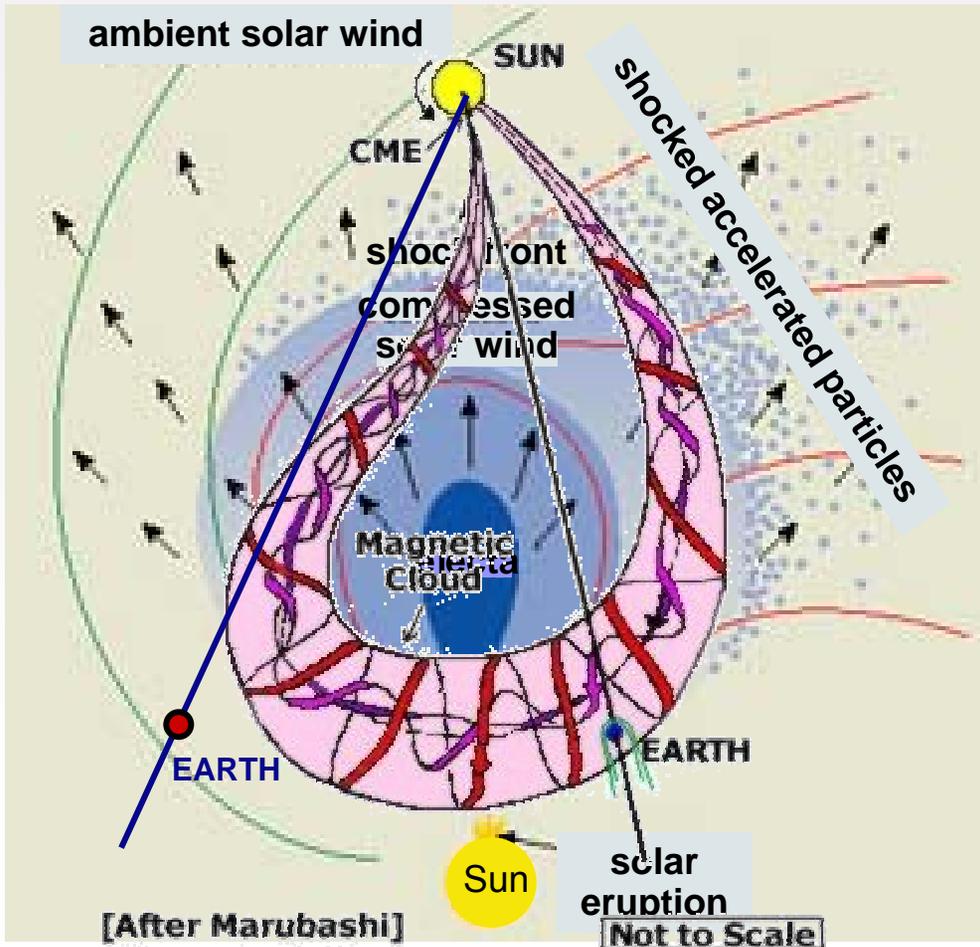
Nancy U. Crooker

Boston Univ., MA USA

With thanks to:

PIs from Wind, ACE, Cluster, Geotail and Ulysses

Introduction



ICMEs

- Shock
- Sheath (draping of IMF)
- Ejecta

Magnetic clouds (MCs): subset of ICMEs

- Ejecta: flux rope
- Large scale topology from large and coherent rotation of the B-field vector

Possibly all ICMEs contain flux ropes

but s/c skims the flanks
 → azimuthal field lines, rounding the flux rope axis [Marubashi, 1997]

Intense Solar Energetic Particle (SEP) event of 20 January 2005

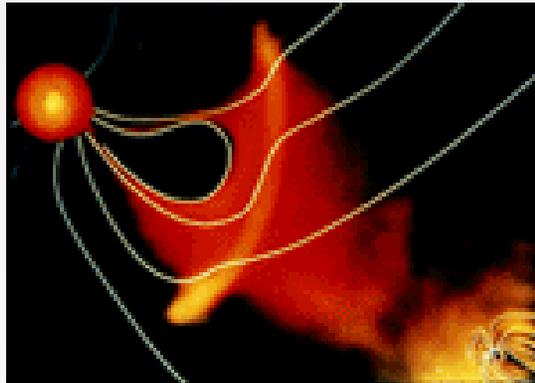


Exceptional characteristics

- High energy particles: rapid arrival, intensity and energy spectra
- High speed of the associated CME

What happens further out?

- Global geometry of associated ICME?
- Specific properties useful for model development?

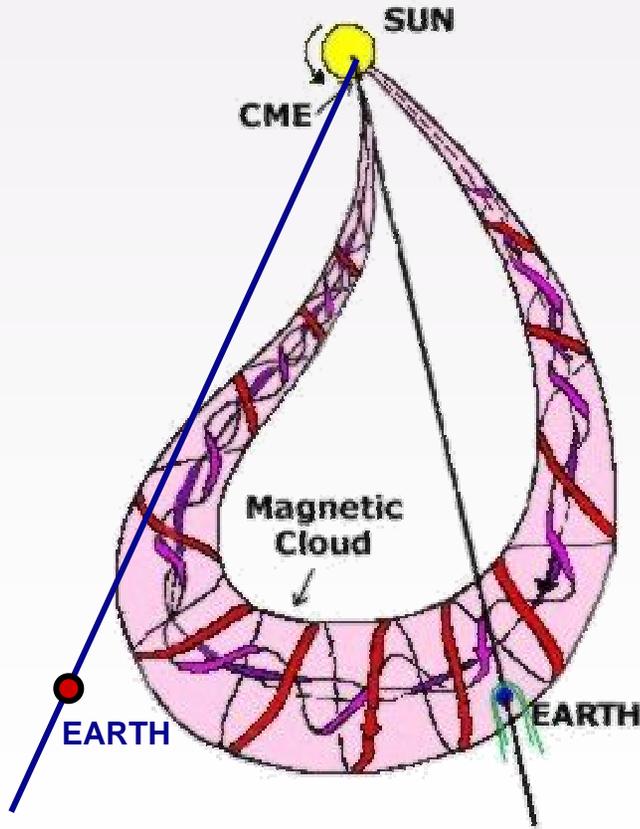


Global Geometry

Event on 21- 22 Jan 2005

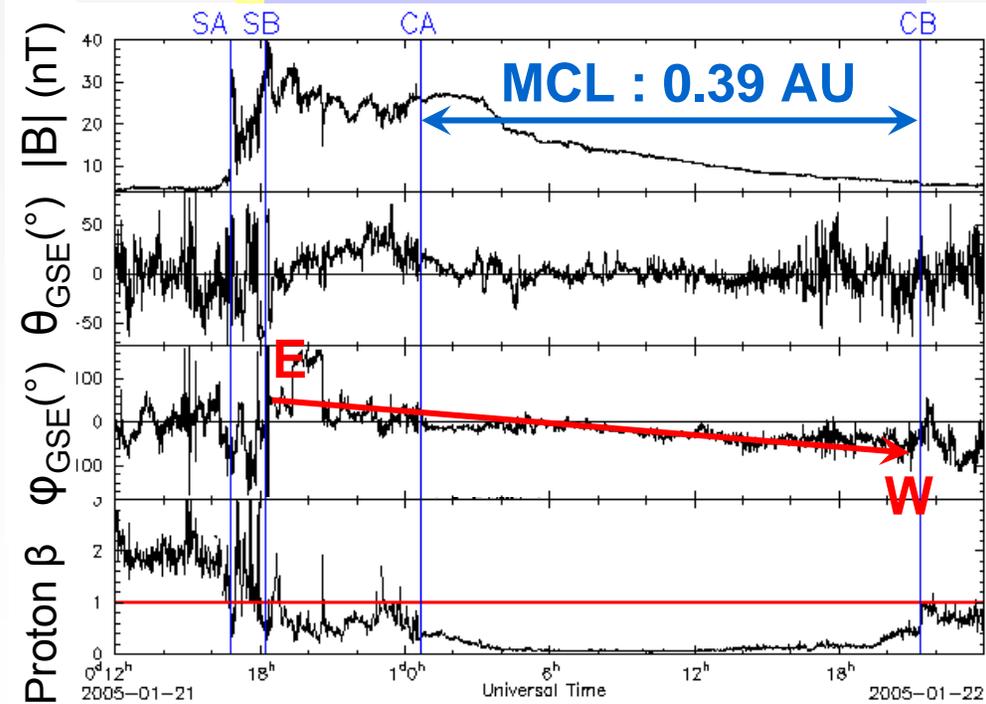
Linked to intense Solar Energetic Particle (SEP) event of 20 Jan 2005

Magnetic cloud-like structure (MCL)



[After Marubashi]

Not to Scale



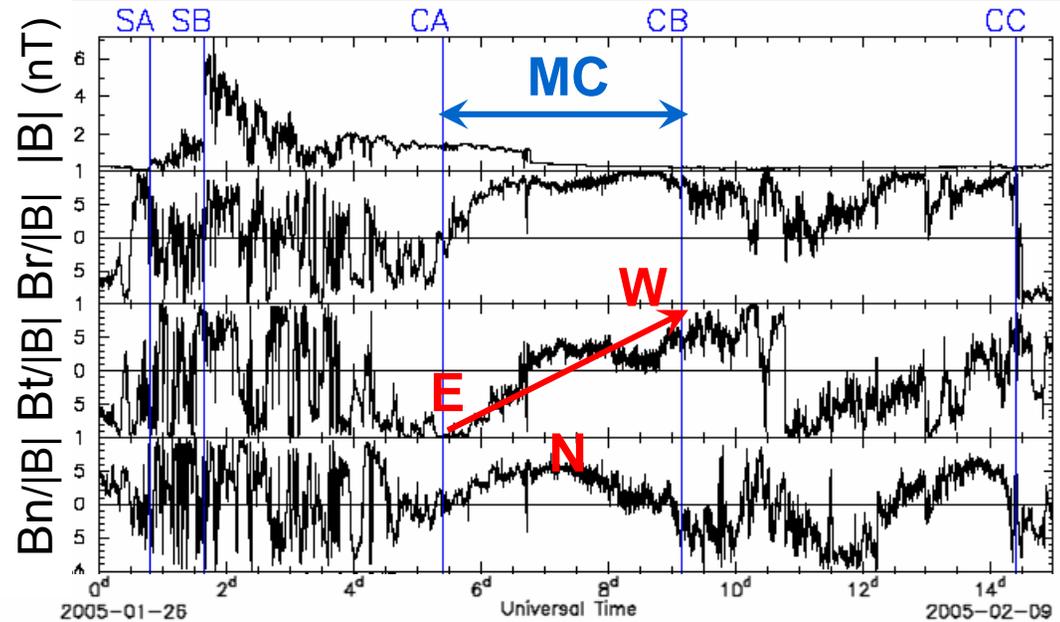
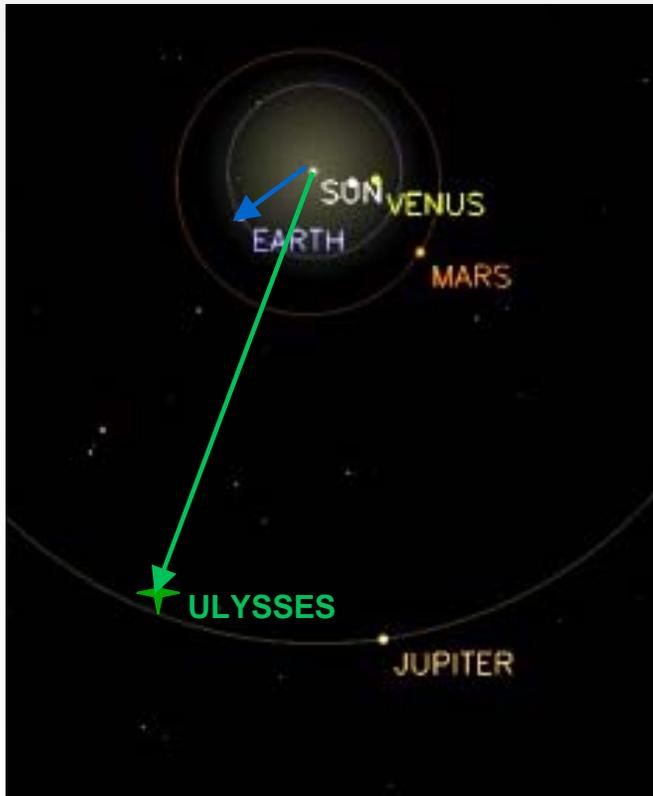
ACE

SA Shock, SB Ejecta Front, CA-CB MCL

ICME in the heliosphere

Ulysses, 5.3AU, 17° south of the ecliptic, 27° from the Sun-Earth line to the west

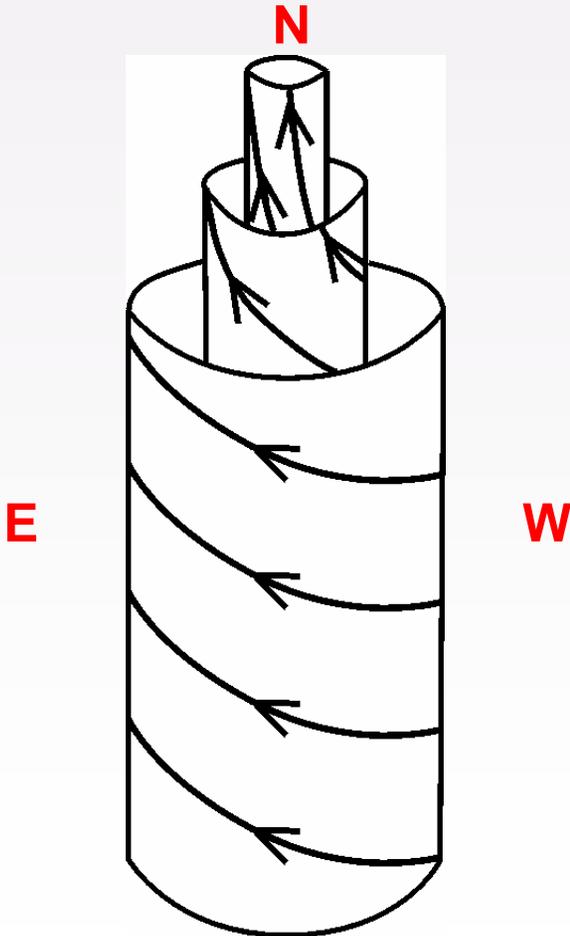
**MCL-MC connection:
Flux rope of type ENW**



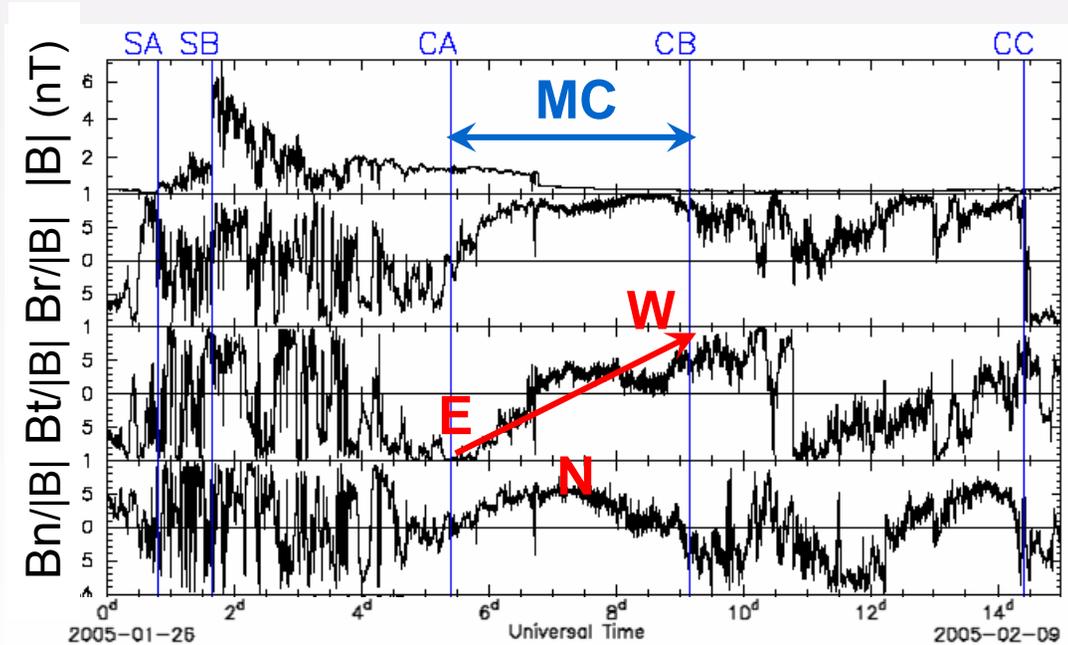
ICME in the heliosphere

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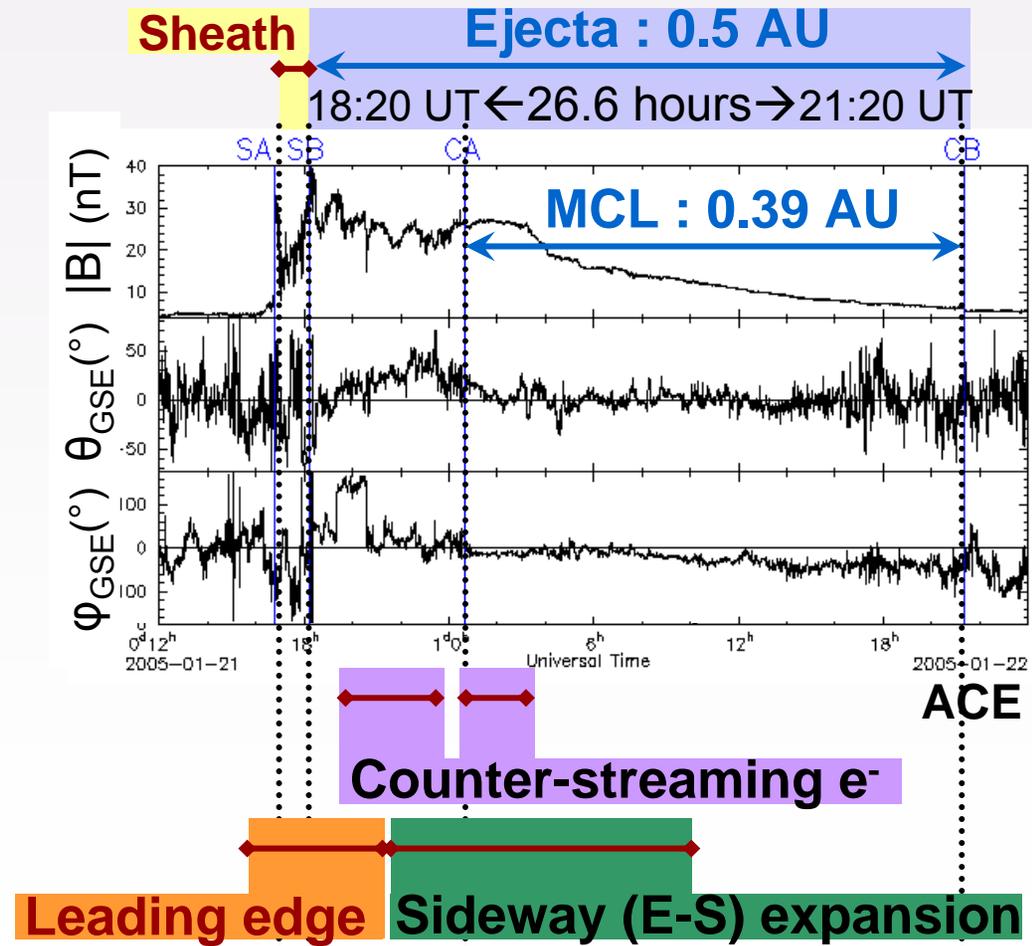
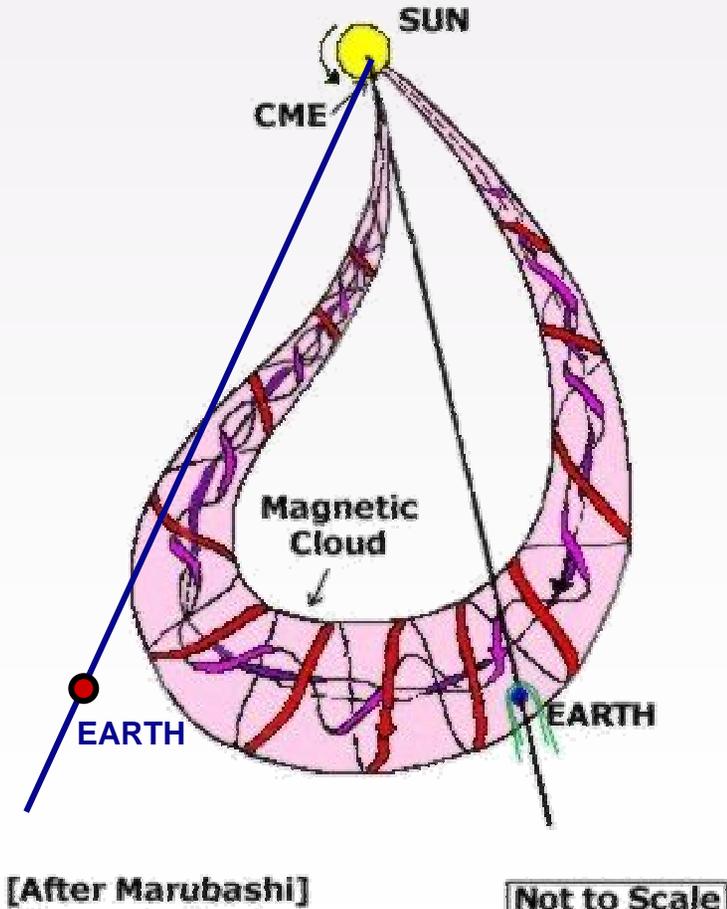
Looking towards the Sun



ICME near Earth

Linked to intense Solar Energetic Particle (SEP) event of 20 Jan 2005

MCL: Outskirts of a MC in strong expansion



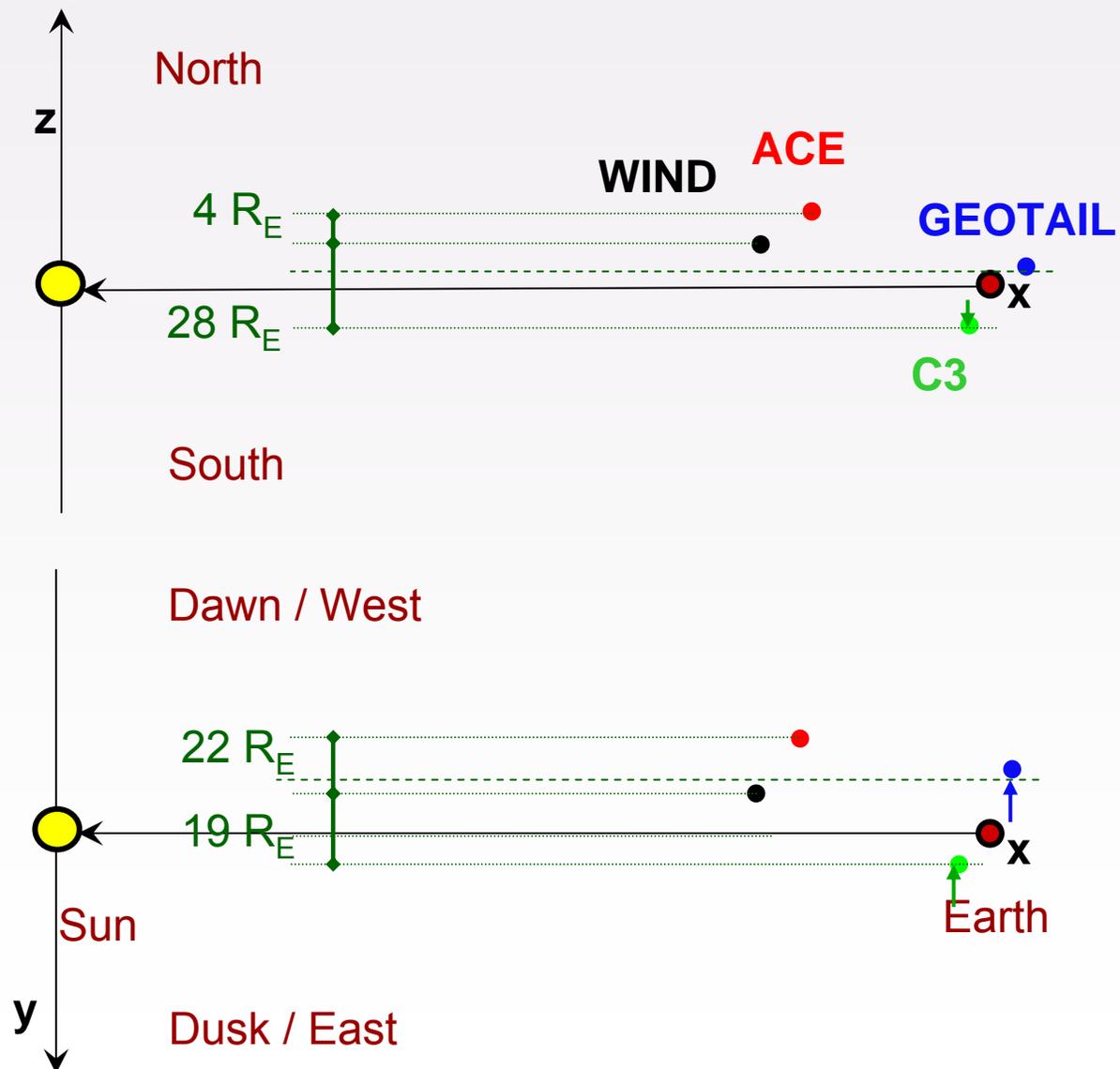
Near-Earth multi-spacecraft observations

Upstream near L1

- **Wind** North-dawn
- **ACE** North-dawn

Nearer the Earth

- **Cluster** South-dusk
- **Geotail** North-dawn



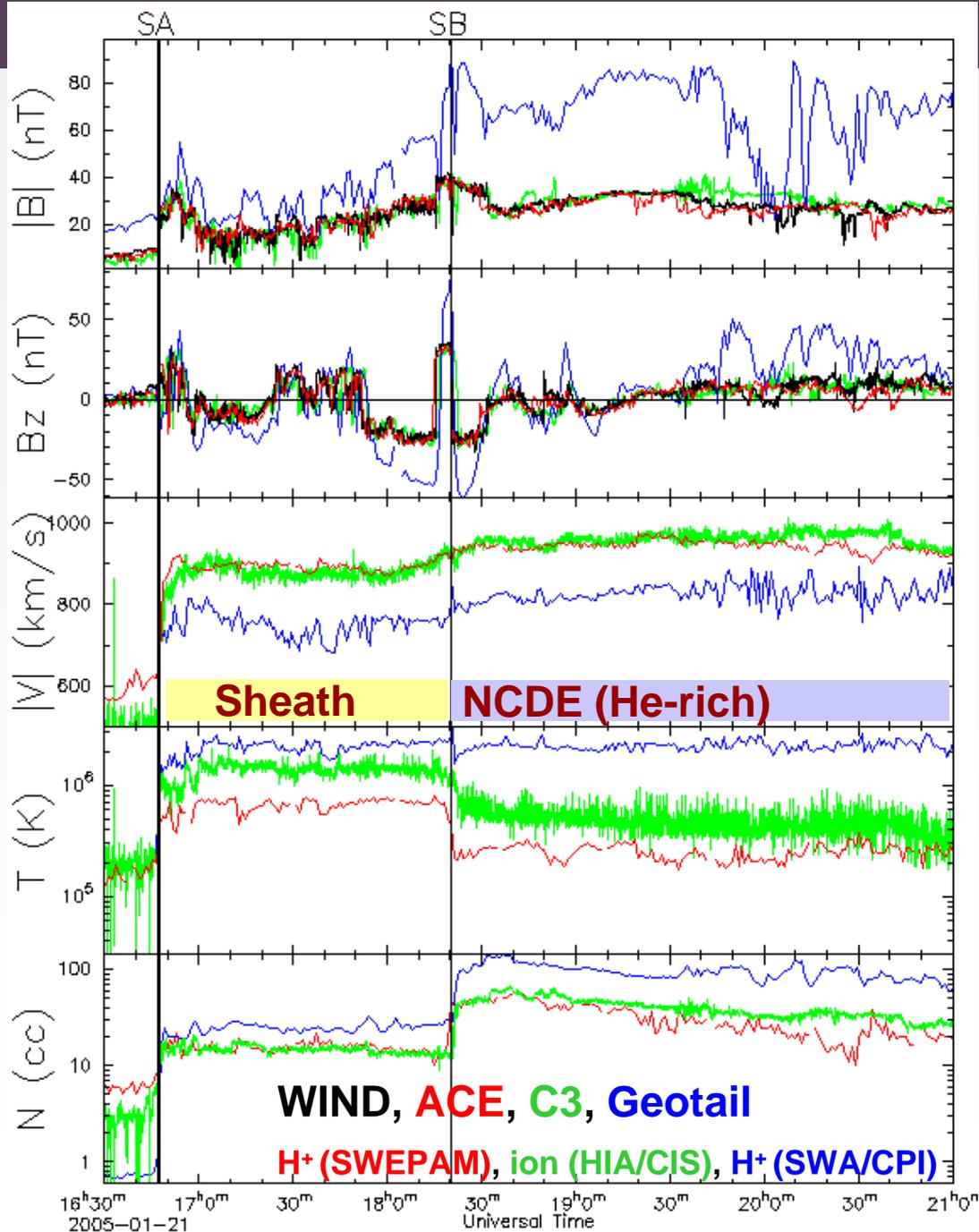
Study of magnetic discontinuities

Different scales

- Large-scale phenomena: observed by all s/c.
- Substructure: differences between s/c.

Different methods

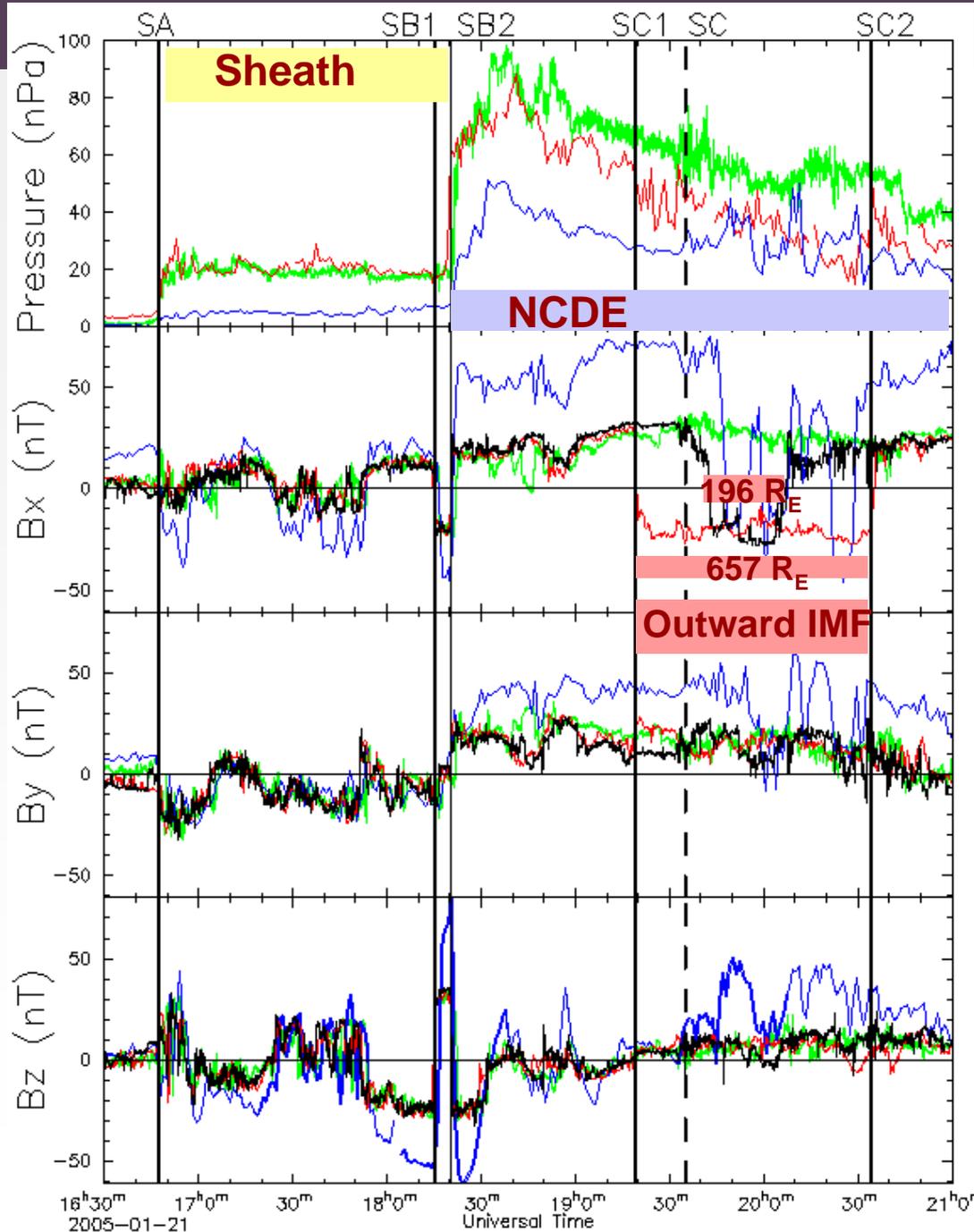
- Discontinuity normals and velocities from 4-s/c discontinuity analysis on timing difference between **C1**, **C2**, **C3**, **C4**
- Discontinuity normals only from MVA on single s/c: **C3**, **Wind** and **ACE**



Magnetic and plasma in-situ observations

- **Shock SA:** ICME shock arrival at ACE– time series shifted with SA.
- **From SA:** Hot pile-up i.e. the sheath
- **Front SB:** discontinuity – well synchronised.
- **From SB:** Colder, denser pile-up, known as *Non-Compressive Density Enhancement (NCDE)*

→ **Two distinct thermal structures**



Magnetic discontinuities

- **SB1-SB2**: discontinuity layer (outward and northward IMF), while IMF turns duskward.

- **SC1-SC2**: magnetic layer discontinuity (outward IMF)

- observed by **ACE**, **WIND** and **GEOTAIL** - but not C3.

- nested time intervals on dawn side

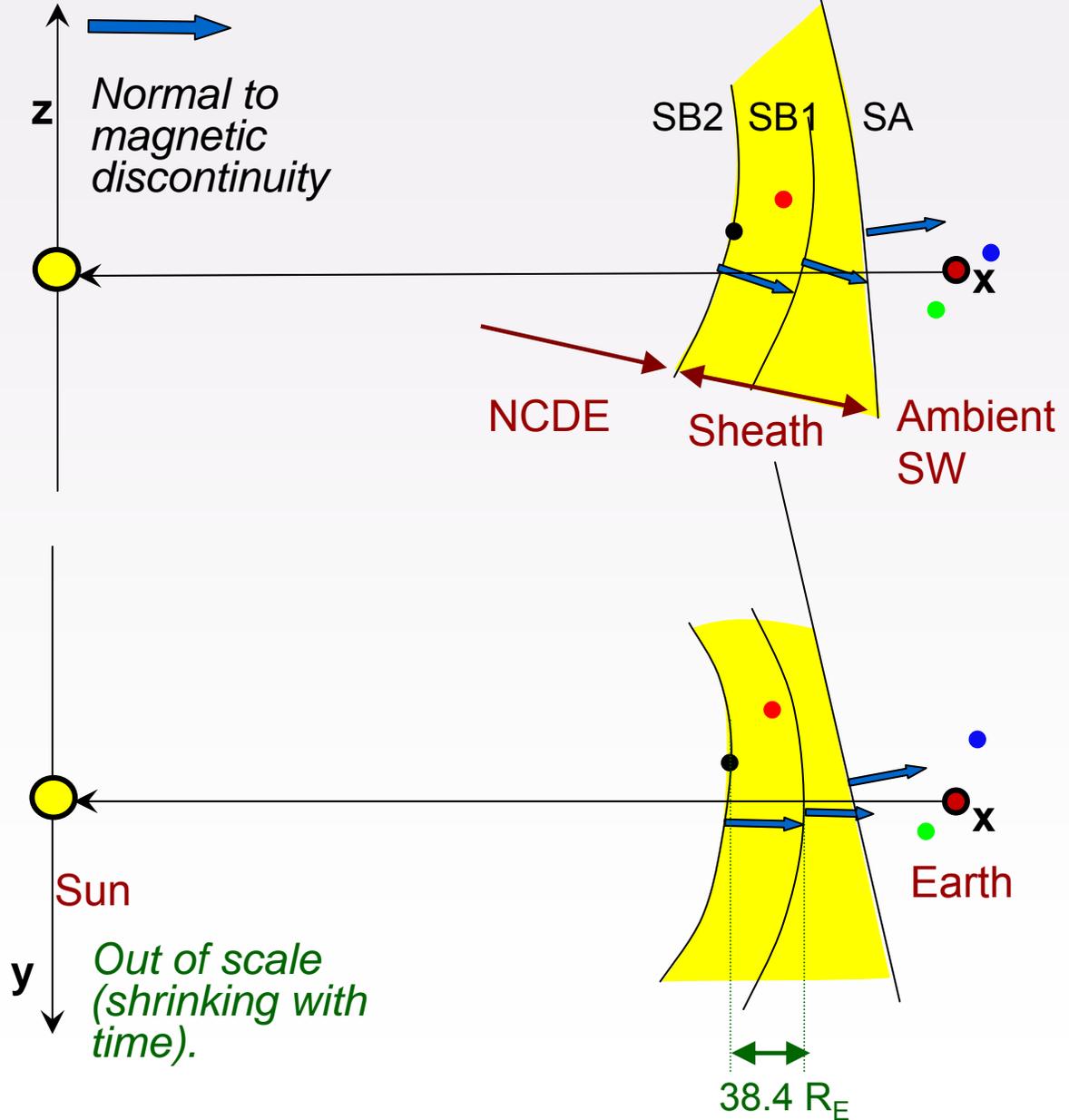
- ΔP on **GEOTAIL**

WIND, **ACE**, **C3**, **Geotail**

Geometry of discontinuities

- Agreement between MVA and 4 s/c timing
- Quasi-perpendicular upstream B-field with respect to normals

Normals SA, SB along Sun-Earth line but slight differences



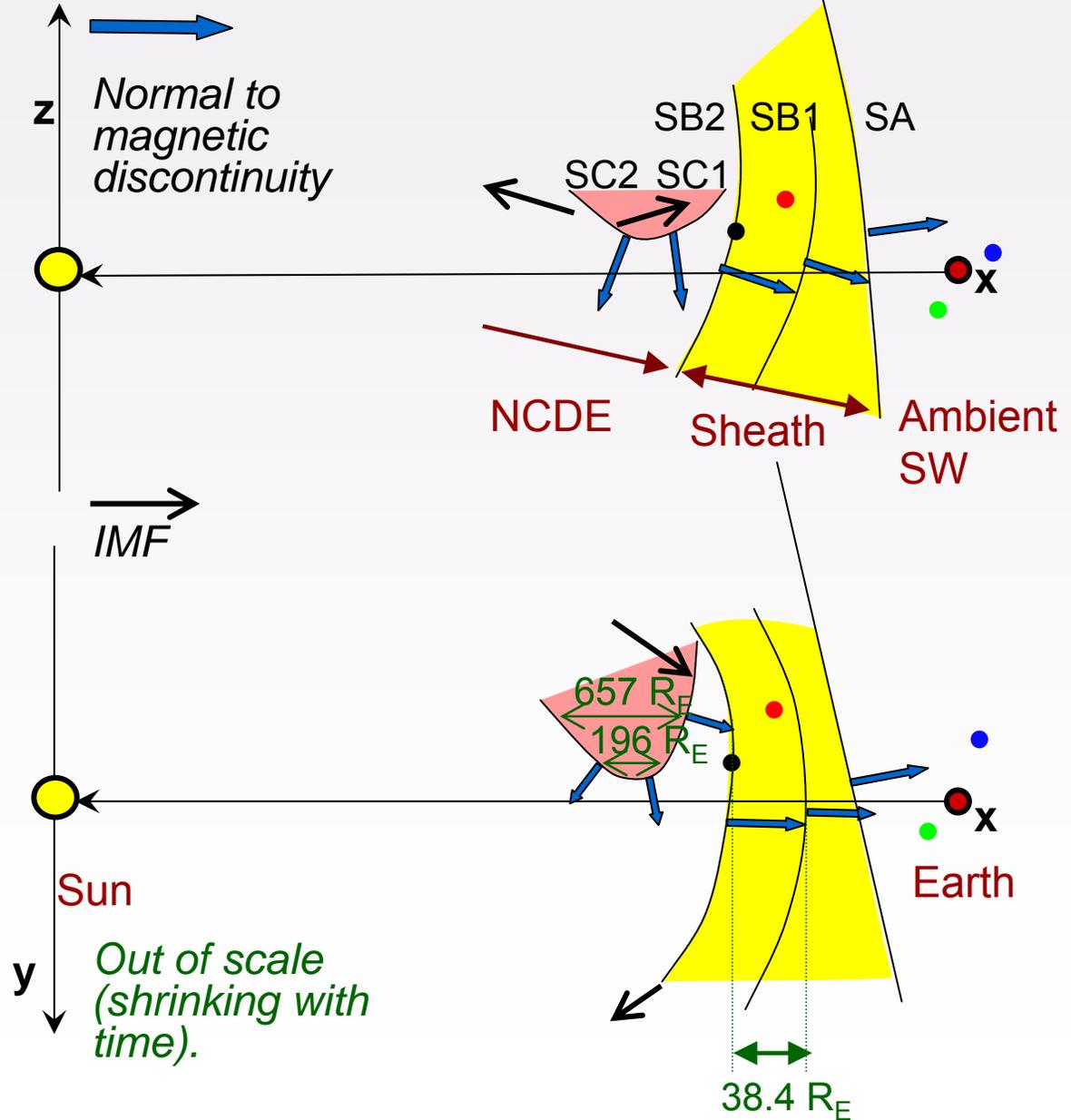
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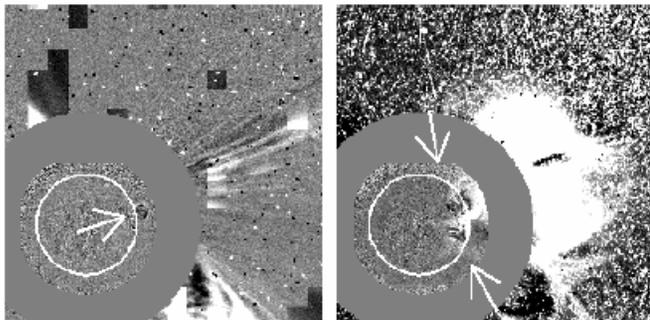
Normals SA, SB along Sun-Earth line but slight differences

SC1-SC2 form tilted, curved current sheet

Centre of curvature in the north-west

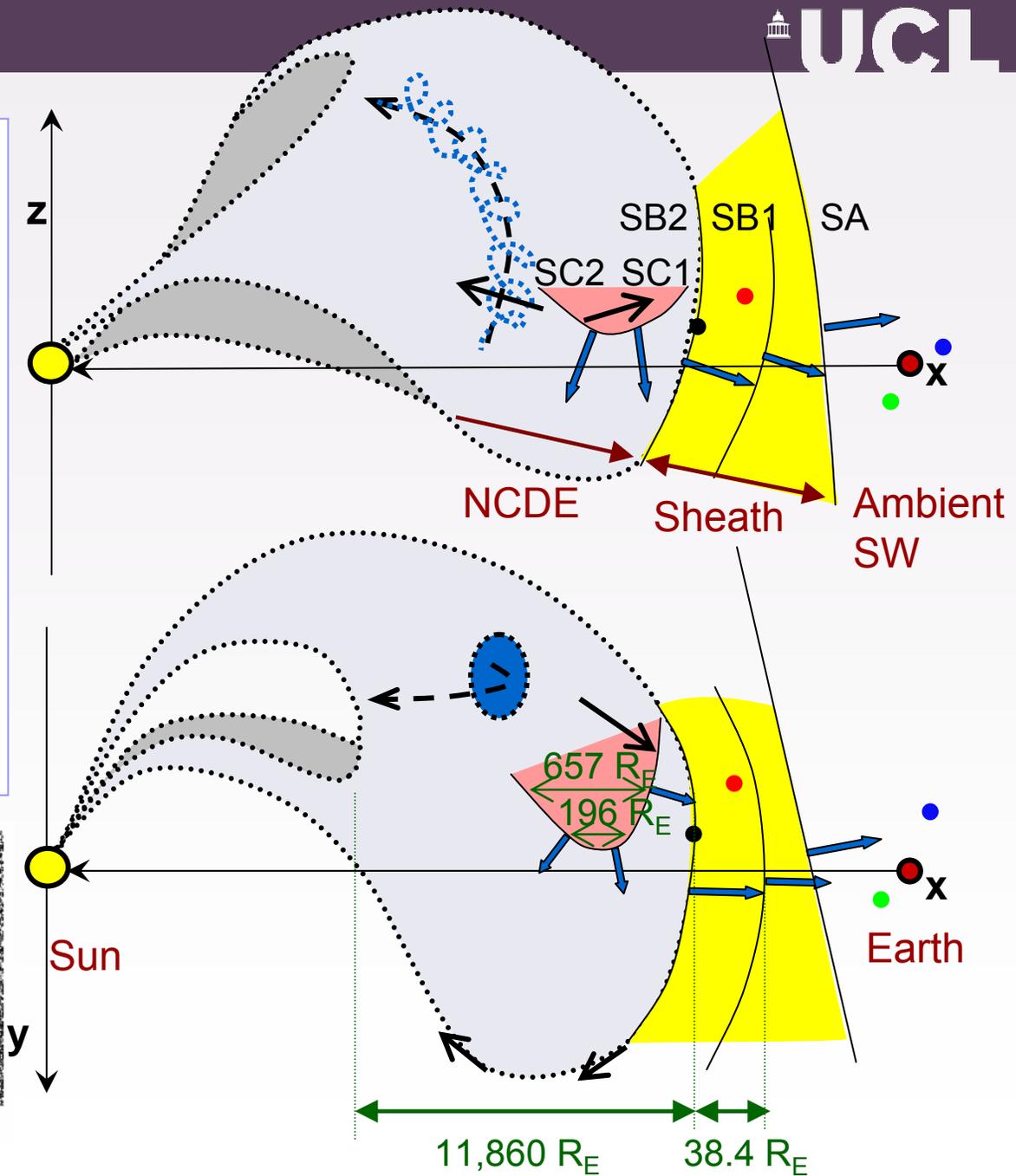


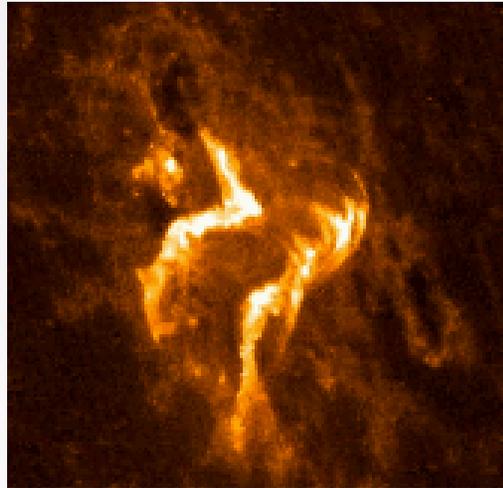
- Tilted current sheet draped within overlying cloud canopy
- Bulk of cloud in N-W sector (primary direction of travel of the fast halo CME)
- Axis perpendicular to shock and ejecta normals: cloud driving the shock
- But difference: ejecta front SB due to expansion of cloud (towards E-S), while fast driven shock SA maintains N-W orientation.



C2: 06:30 EIT: 06:36 C2: 06:54 EIT: 06:48

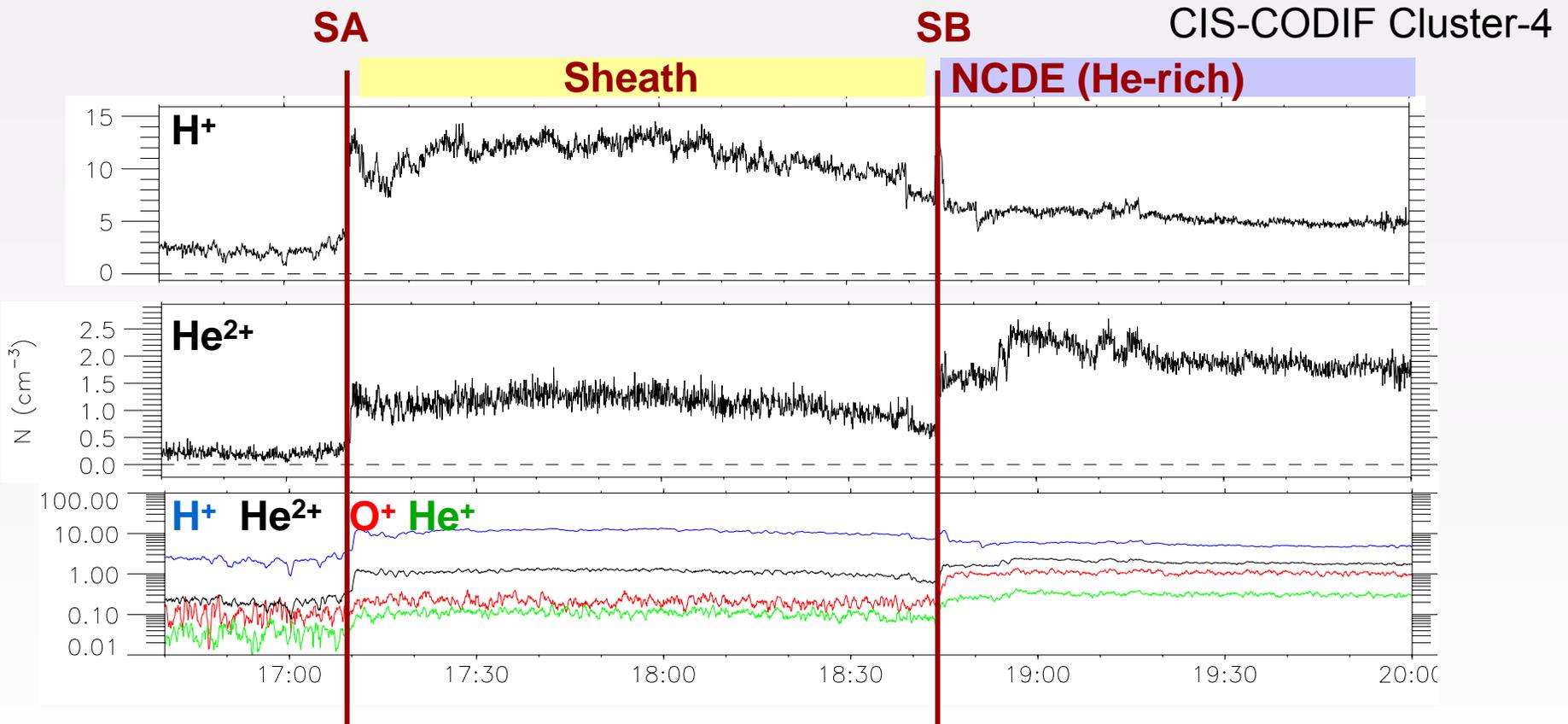
[Gopalswamy et al. 2005]





Specific Properties

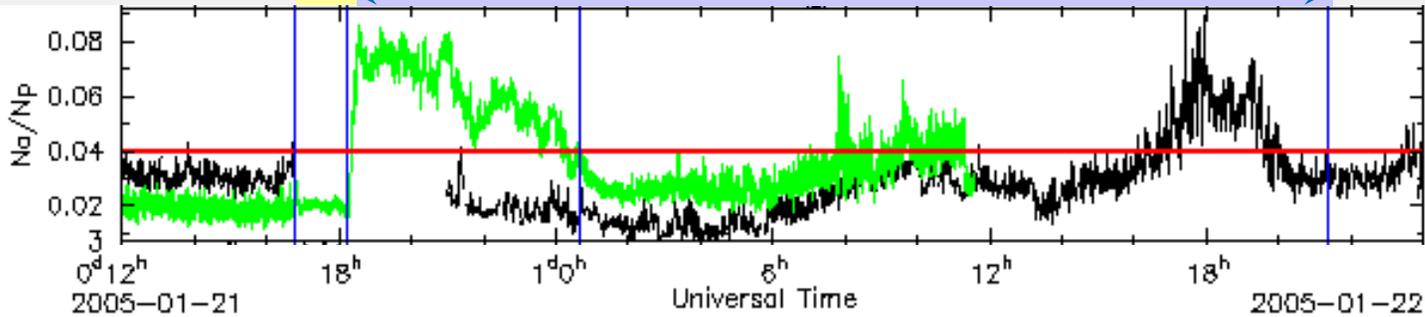
1. NCDE and helium enhancements



At Cluster, 'ion data' contaminated by He ions. Likely also at ACE ('proton measurements').

Sheath

Ejecta

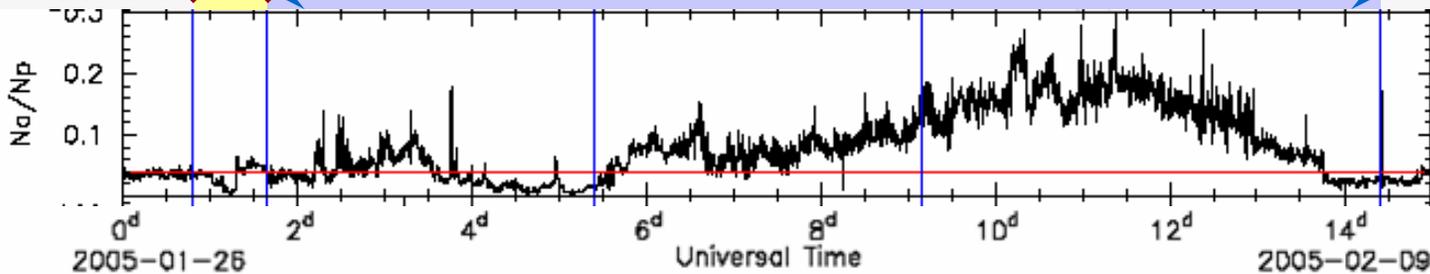


ACE

Cluster-4
(scaled down by 5)

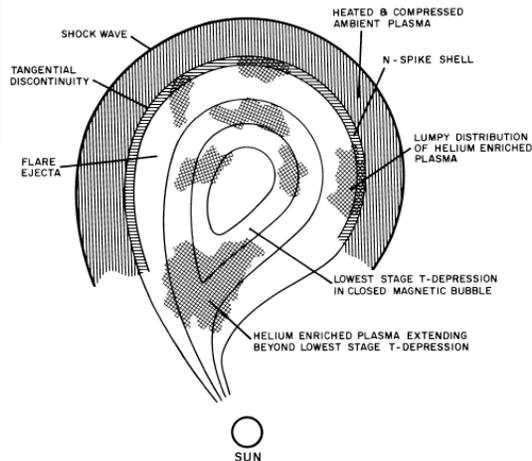
Sheath

Ejecta



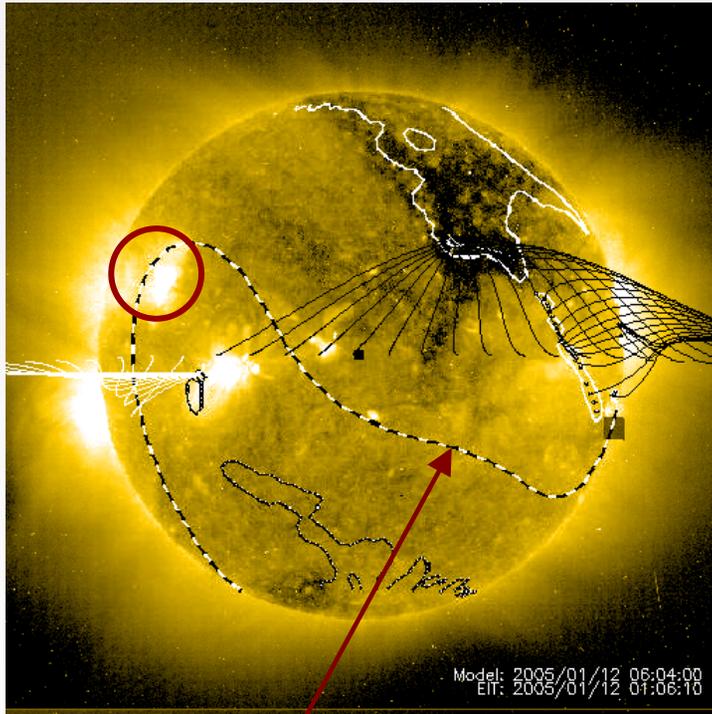
Ulysses

A POSSIBLE GEOMETRY OF FLARE EXPELLED PLASMA DRIVING A SHOCK WAVE



Large spatial variations in helium enhancements

non-homogeneous 'raisin pudding' or lumpy distribution [Bame et al. 1979]



HCS

EIT 284 A 2005/01/12 01:06

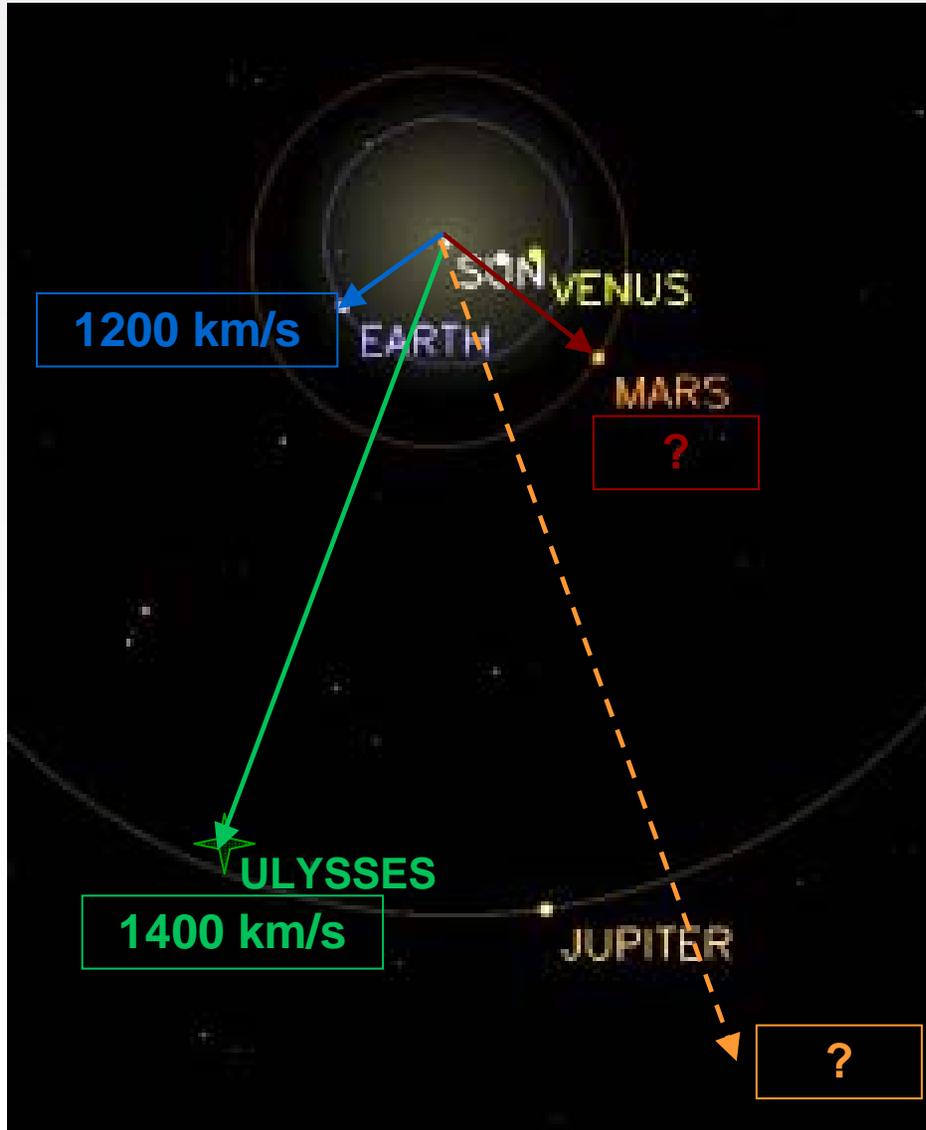
VSL Solar and Heliospheric
Weather model

NCDE generally associated with low-helium region of the *streamer belt* [Gosling et al. 1981]

Helium enrichment may be attributed to the arrival of *flare driver gas* [Hirshberg et al. 1972; Bame et al. 1979]

Position near streamer belt of the flaring Active Region NOAA 10720 associated with the CME (N14 W67 at time of event).

2. Speeds and expansion



Solar corona

20 Jan 6 UT

2500-3700 km/s

[Gopaswalmy et al. 2005;
Tylka 2006]

Earth

At **Cluster**, 21 Jan, 4 s/c
timing analysis

Net shock 930 km/s

(relative to upstream SW:
374 km/s, $M_A=5.9$, $\beta=1.7$)

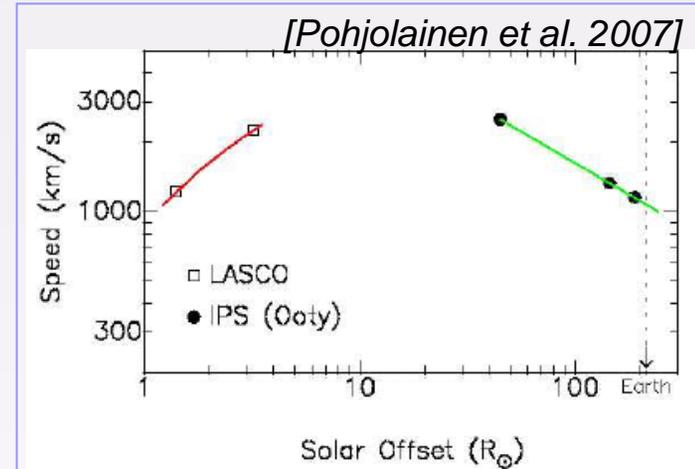
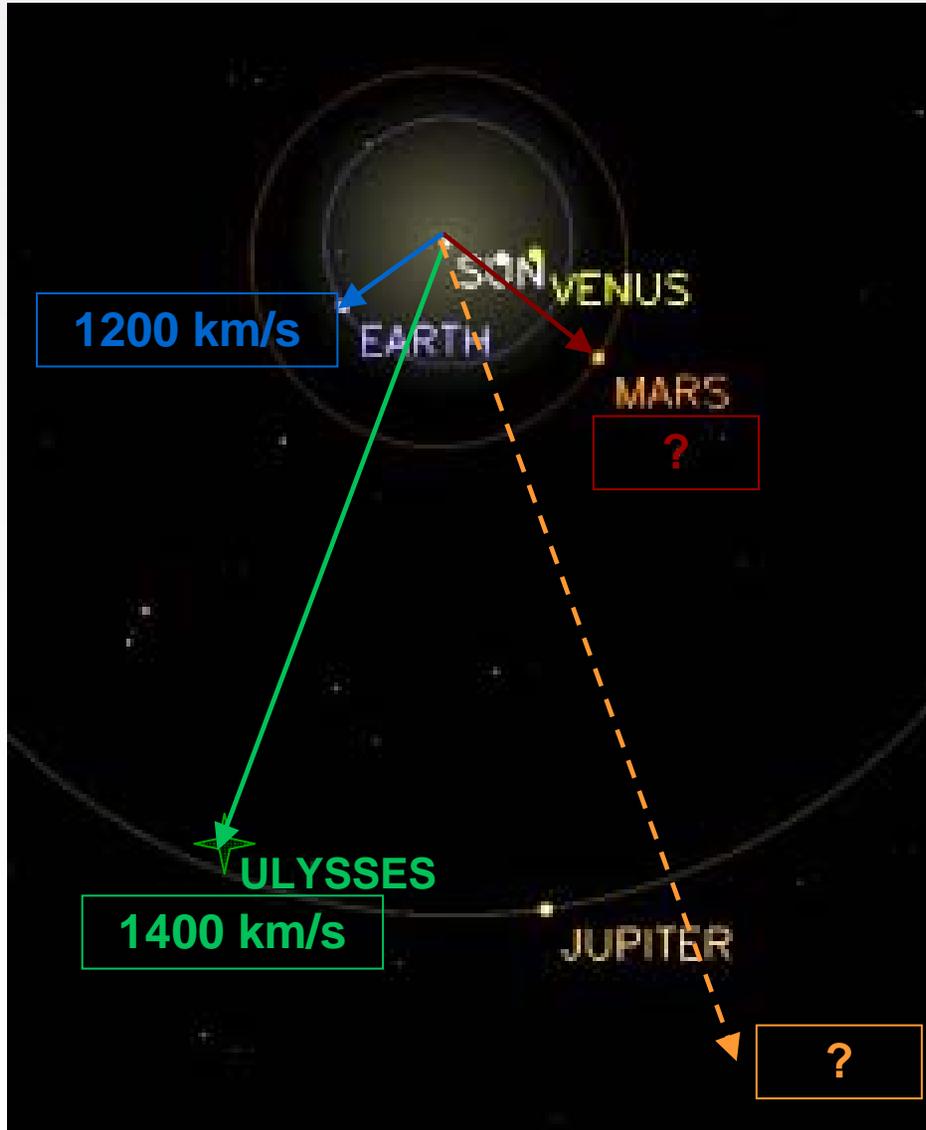
Ejecta 798-837 km/s

Transit speeds

At **ACE**, 21 Jan 18:20 UT
1200 km/s: slow down

At **Ulysses**, 26 Jan 19 UT
1400 km/s: closer to the
primary direction of travel.

2. Speeds and expansion

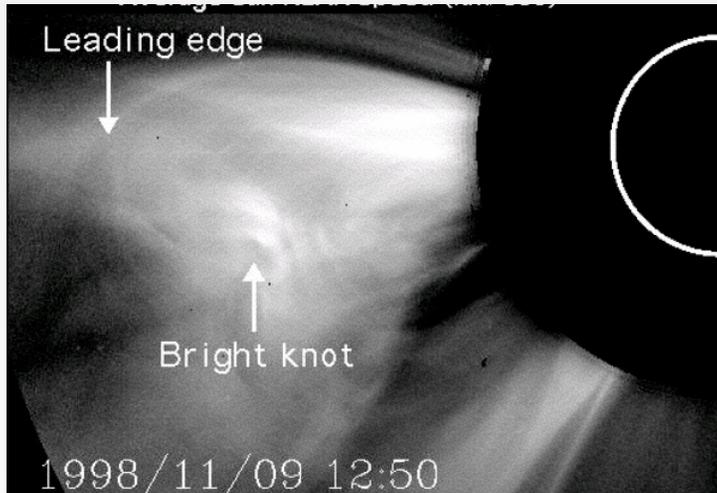


- IP Scintillation suggests ICME reached **3000 km/s**
- Other possible investigations at Mars (MExpress, MGS) and at Saturn (Cassini, shock front particles).

Transit speeds

At **ACE**, 21 Jan 18:20 UT
1200 km/s: slow down

At **Ulysses**, 26 Jan 19 UT
1400 km/s: closer to the primary direction of travel.



[Rust et al. 2006]

Sideway expansion

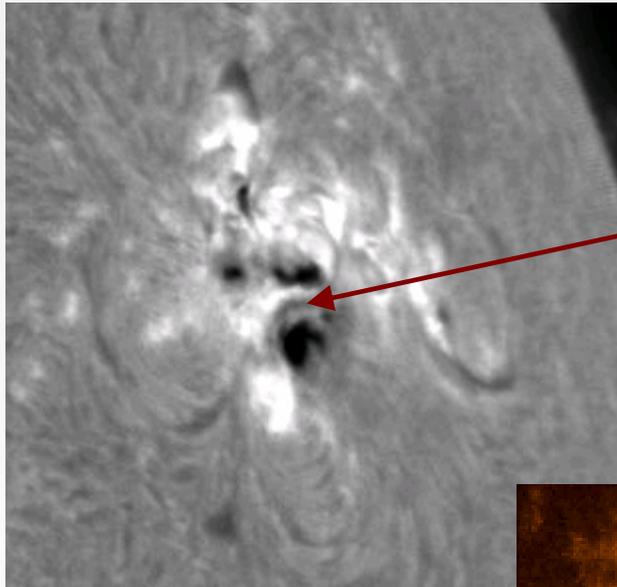
Ejecta front: overlying canopy of field lines from background corona – connected to flow deflections.

Swept up into motion by rising **flux rope** – primary direction of the cloud.

Corroborates **differences** in acceleration between overlying loops and flux ropes

[Rust et al. 2006; Illing & Hundhausen, 1985]

3. Flux rope and overlying loops

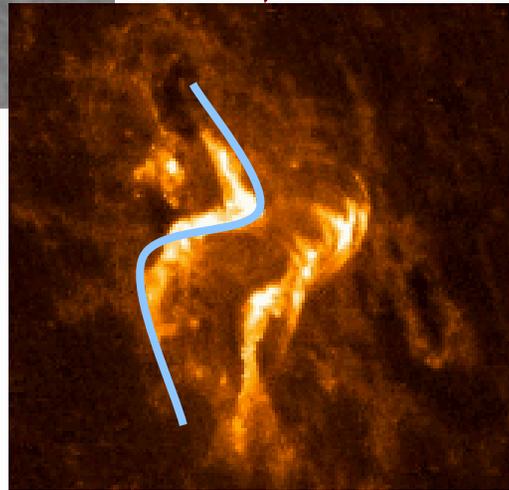


BBSO Halpha 2005/01/19 17:45

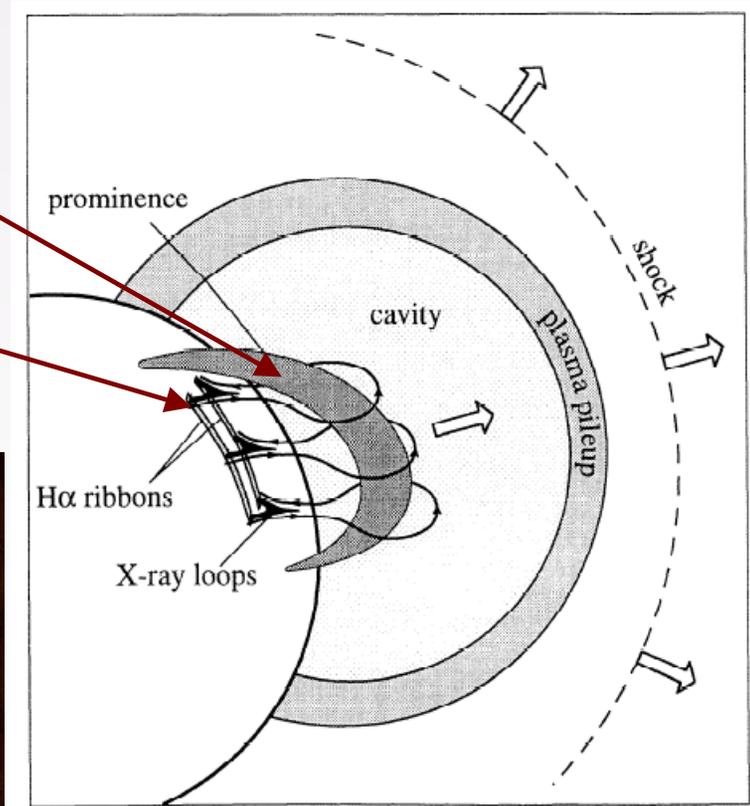
Filament

Two-ribbon flare

Reverse 'S' shape



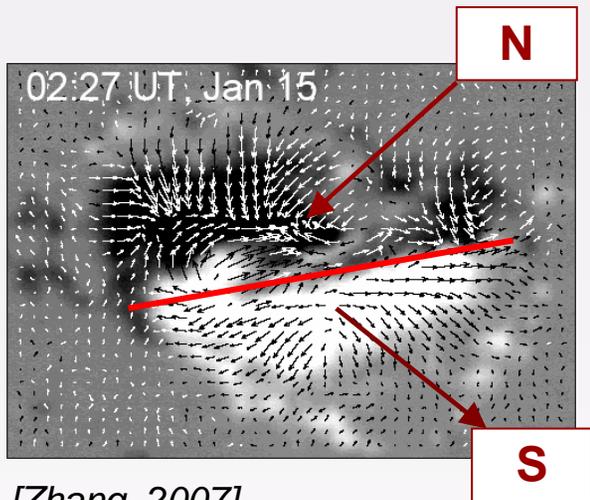
TRACE 1600 A 2005/01/20 ~07:00



[Forbes 2000]

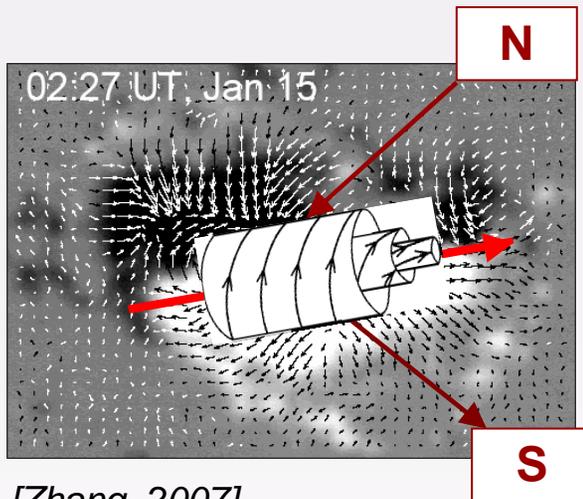
Two inconsistencies between solar and IP observations:

- Ejecta southern flank with inward IMF
- Large difference in flux rope orientation



[Zhang, 2007]

- Predominant bipolar fields connected to inward/outward IMF
- Filament along curved neutral line (E-W, $10 \pm 15^\circ$)



[Zhang, 2007]

Negative magnetic helicity

- From magnetograms:

$$H_m \sim -2 \times 10^{43} \text{ Mx}^2$$

[12-18 January, Zhang, 2007]

- Reverse 'S' shape in EUV ribbons

[Titov & Démoulin, 1999]

Two inconsistencies between solar and IP observations:

- Ejecta southern flank with inward IMF
- Large difference in flux rope orientation

Helical kink instability

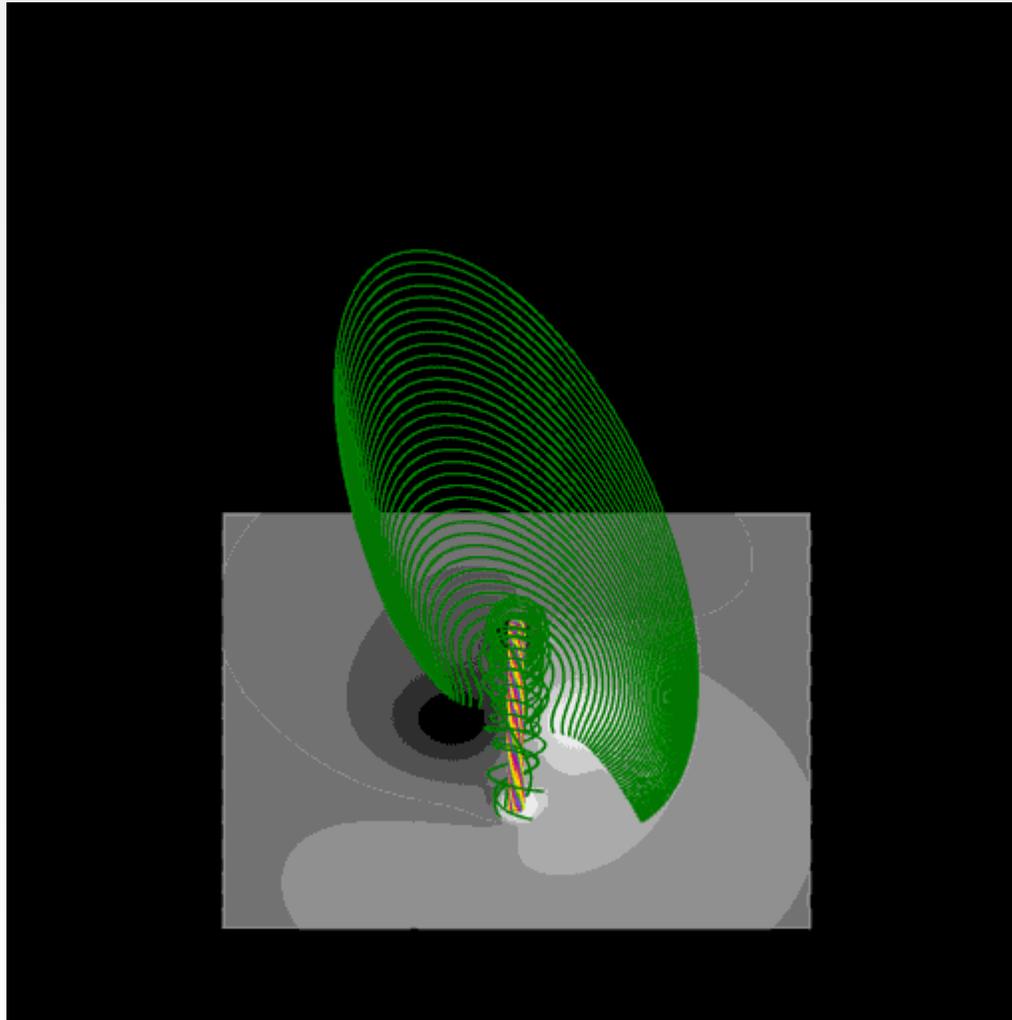
Direction of rotation depends on the sign of magnetic helicity (sense of twist in flux rope)

Left-handed (-) → counter-clockwise

Right-handed (+) → clockwise

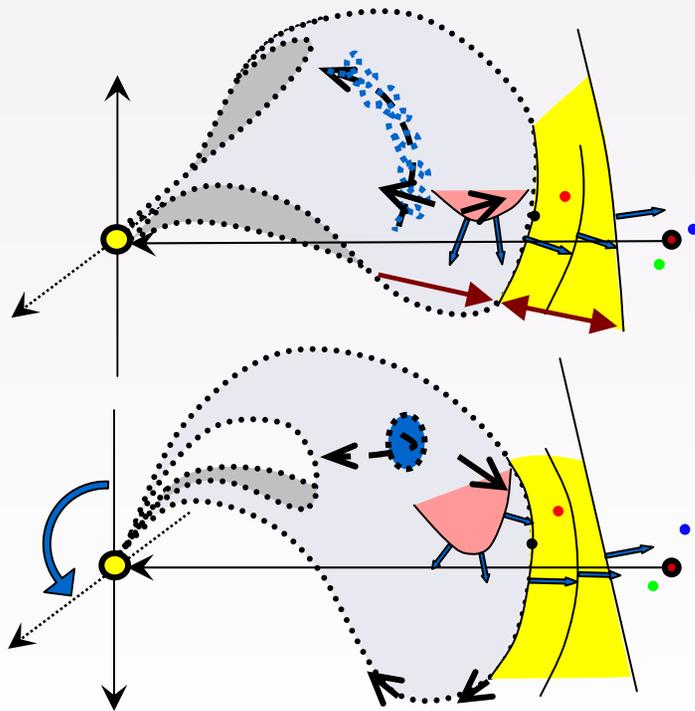
Same left-handed chirality as IP flux rope, consistent with helicity conservation.

Flux rope directed towards west
→ counter-clockwise rotation of 80°



Ejective eruption of a kink-unstable flux rope
[Török and Kliem, 2005]

Conclusions: main features



Foullon et al. 2007, Solar Physics, 'Sun-Earth Events' Topical Issue, in press

- Rare identification of a MC on its flank (longitudinal half-extent $\sim 67^\circ$)
- Differences between the shock and ejecta front normals \longleftrightarrow expansion of the cloud on its flank
- NCDE caused by enrichment in helium at the ejecta front
- Current sheet substructure dragged along between the cloud core (flux rope) and the overlying cloud canopy.
- Large ($\sim 80^\circ$) rotation of the flux rope and overlying arcade (cloud canopy) \longleftrightarrow flux rope being subject to the helical kink instability at the Sun.