Solar-C and the Sun-Earth Connection

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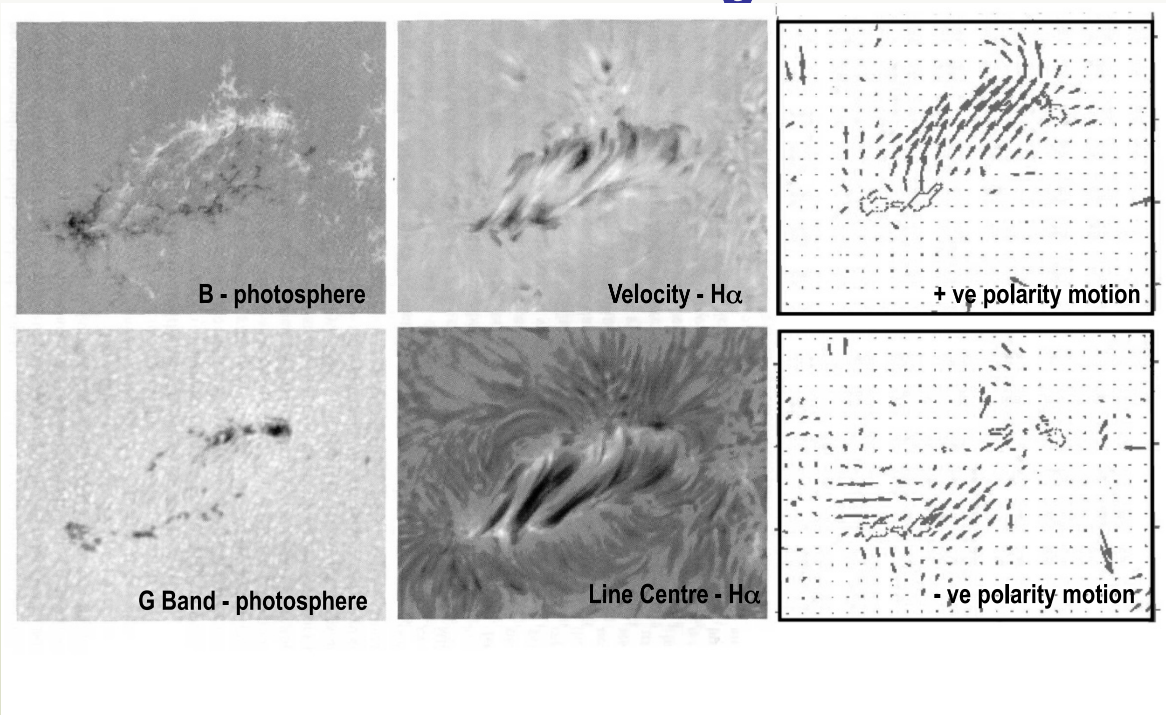
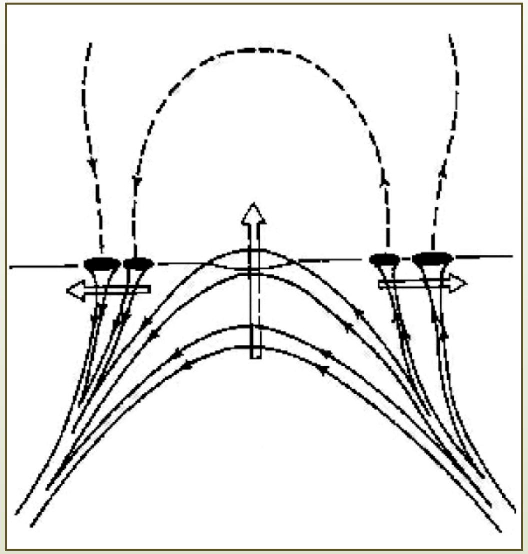
Some Key Areas for the Sun-Earth Connection

- Solar activity, leading to CMEs and flares, and the solar wind are the keys to the Sun-Earth connection – a subset of the Sun's role in the Heliosphere
- Magnetic flux generated at the bottom of the convection zone emerges through the photosphere. Need to:
  - clarify nature of emerged magnetic structures and flux rope formation
  - identify sub-photospheric magnetic structures
- CME launch process and related magnetic configurations must be understood
  - on-disc and coronal signatures (filaments, dimming, EIT waves, sigmoids) are important
- CMEs remove magnetic helicity from the Sun
  - a tool for eruption forecasting?
- Interplanetary CMEs (ICMEs) and Magnetic Clouds (MCs) interact with near-Earth environment
  - clarify their magnetic and compositional relationship to the original CME
- We will briefly outline the above topics in relation to the Solar-C plans

Flux Emergence at Photosphere





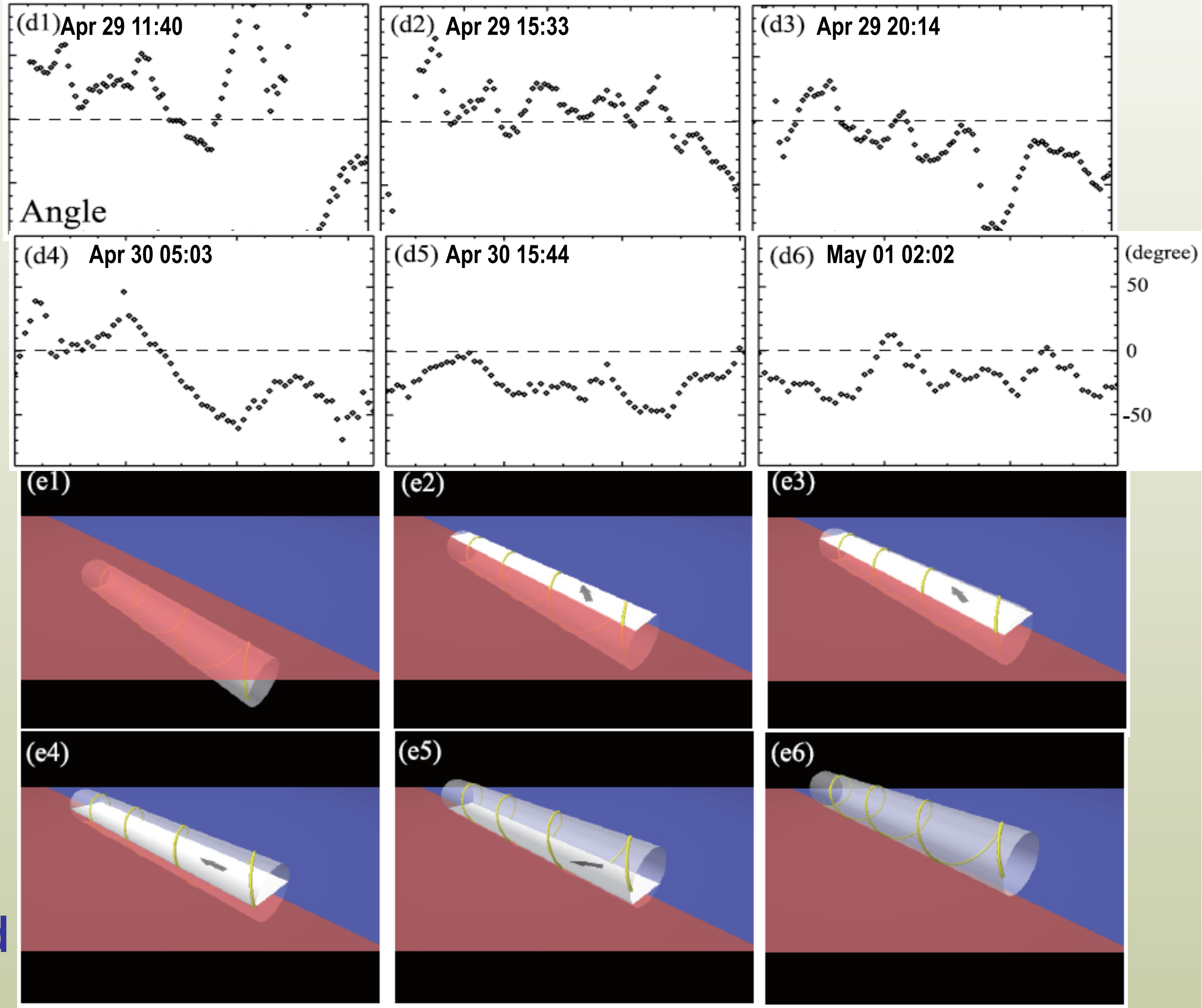
Strauss and Zwann, 1999 courtesy of Lidia van Driel's UCL undergraduate lectures!

- Emergence of a bipolar plage region
  - sequence of polarity emergence
  - Hα filament system: $v_{up} < 10$ km s^{-1}; $v_{down} < 50$ km s^{-1}; 20 min lifetime
  - opposite polarities move apart: $v < 2$ km s^{-1} first half hour; $v \sim 1.3$-0.7 km s^{-1} next six hours
- Scenario consistent with the emergence of a fragmented Ω-shaped loop
  - still connected to the toroidal flux in the dynamo (tachocline) region
- See recent Hinode result by Okamoto et al. 2008

Hinode Observation of an Emerging Flux-rope

- Okamoto et al., 2008 used a time series of vector fields below a prominence

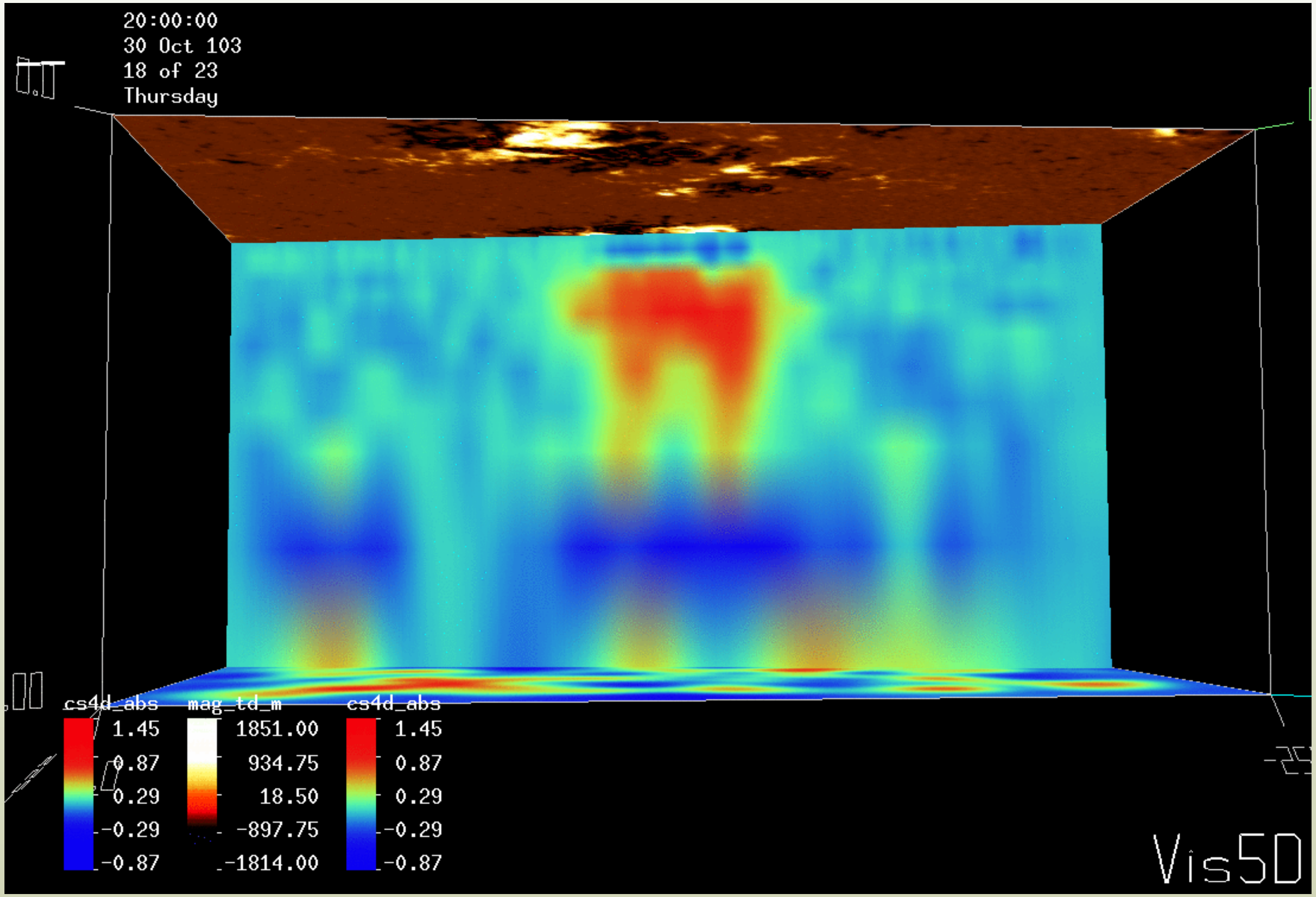
- Horizontal field along polarity inversion line (PIL) changed direction
- Horizontal field region was blueshifted
- Upper panels show angle between PIL and horizontal field
  - θ positive: normal
  - θ negative: inverse
- Lower panels show schematic of emerging flux-rope



- **These are clearly subtle and difficult observations but definitive results are needed**

Flux Emergence Below the Surface (Kosovichev, 2007)

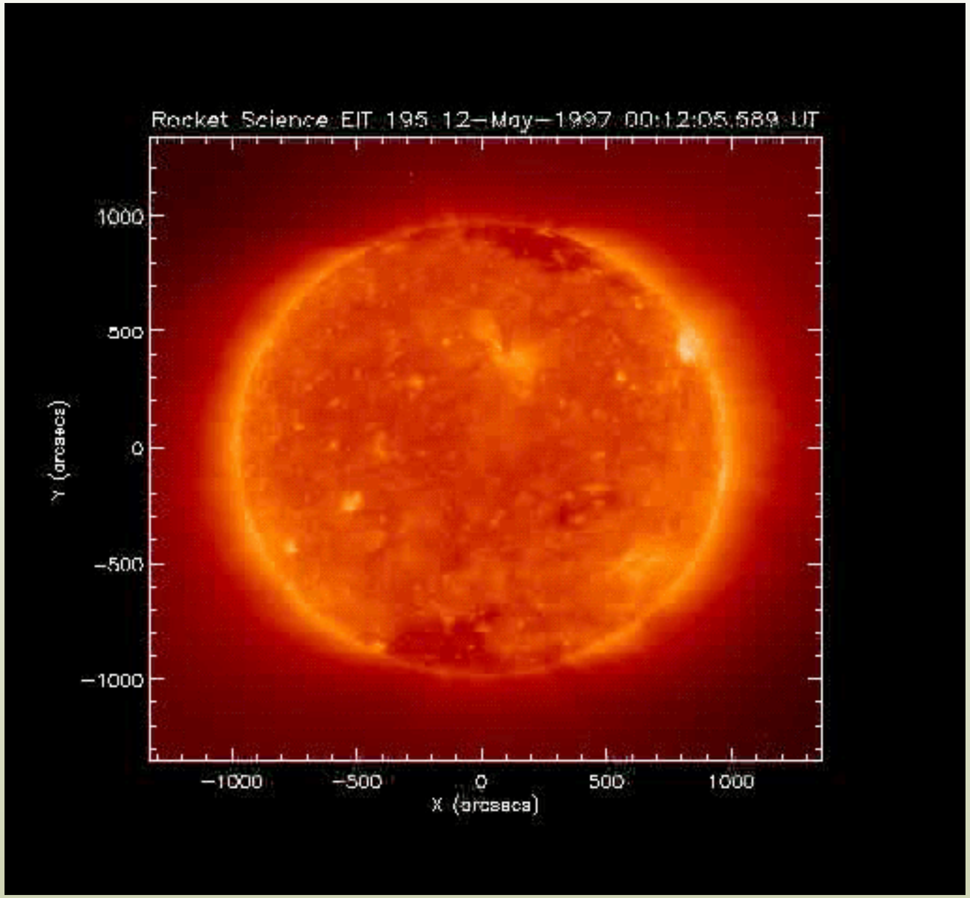
- Subsurface region of anomalous flow velocity suggests emerging Ω loop
- Need to identify flux-rope structures to as great a depth as possible - ideally to tachocline
- Deploy optimum Helioseismology approach



- **Compelling results need to be achieved for the solar activity latitude range**

CME Launching - Dimming Event of 12-May-1997

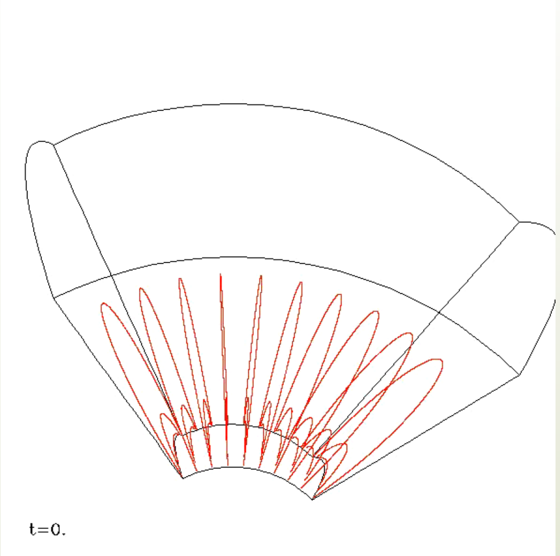
- Features include:
  - twin dimming regions
  - simple magnetic structure
  - LDE flare GOES class C 1.3
  - brightening along and shrinkage of north polar coronal hole boundary
  - fiament eruption
  - coronal wave
  - full Halo CME
  - associated magnetic cloud at Earth



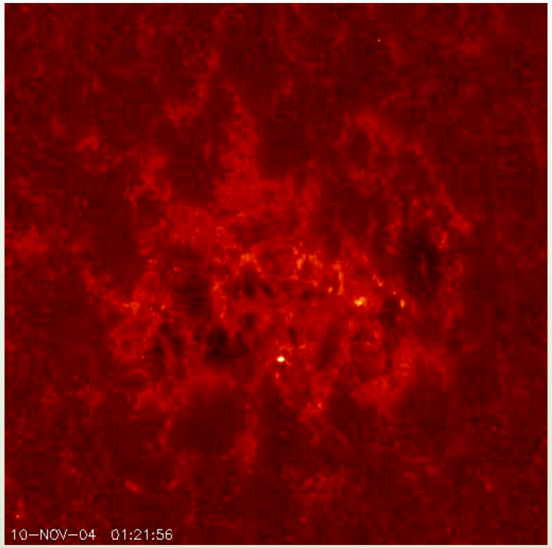
- Well-studied event (Thompson et al., 1998, Webb et al., 2000, Zhukov and Auchére, 2004, Attrill et al., 2006)

CME Models

- Single class of models discussed here
  - ideal MHD instabilities
- Many other energy storage and release models exist

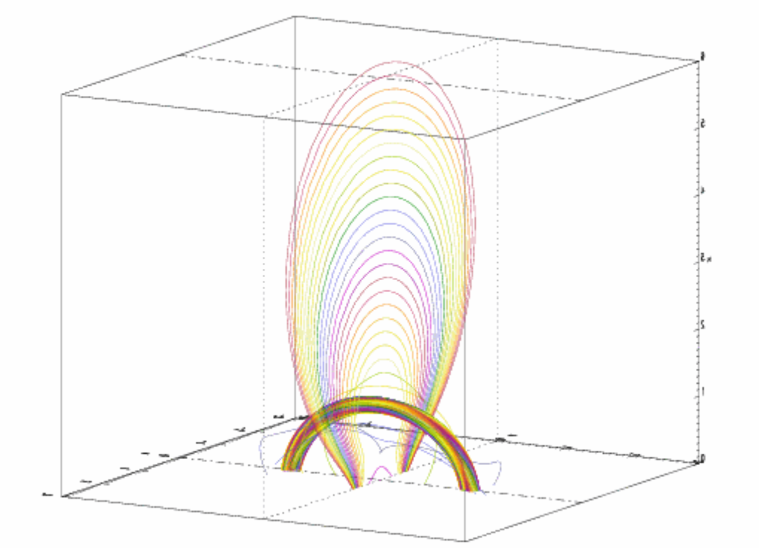


Fan (2005)



Williams et al., (2005)

- Kink Instability
  - occurs when twist in flux rope exceeds a critical value of 2.5 π (Priest & Hood, 1979)
  - driven by conversion of *twist* into *writhe*
  - example observed by TRACE in 2004,Nov 10
- Torus instability
  - occurs if the overlying field drops sufficiently fast with height.
  - driven by hoop force of a flux rope (Lorentz force of a current ring)
- Kink instability may precede Torus eruption



Török & Kliem, (2007)

CME Models

- All the models require understanding the competition between magnetic pressure forces (expansion) and magnetic tension forces (restraining)
- Difficult to tell which model is correct
  - combination of different models involved?
- Expected observational differences between the models are subtle
- Hard to distinguish between e.g. a pre-eruption flux rope (flux cancellation; Linker et al., 2003) and a collection of strongly sheared field lines (breakout; Antiochos et al., 1999)
- After eruption both models have a flux rope
- Flux ropes may also emerge from below the photosphere
- Models are not yet able to predict observable quantities
- **Require study of CME acceleration sites, pre-CME structures, pre flare indicators**
  - **clarify energy buildup**
  - **understand energy release mechanism**

Role of Magnetic Helicity

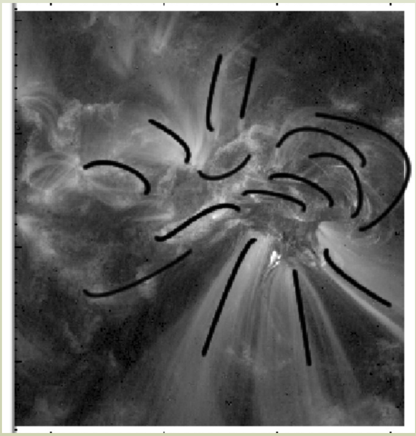
- Magnetic Helicity, H is a globally conserved quantity that can describe the stress present in a complex magnetic configuration

- Helicity is removed from the corona to the Interplanetary Medium (IPM) by CMEs
  - total helicity content of an Active Region may indicate CME productivity or even show threshold behaviour

- Determine H_r by e.g. linear force-free extrapolation of photospheric field to the corona

$$\vec{\nabla} \times \vec{B} = \alpha \vec{B}, \qquad \alpha = \text{constant}$$

where α is determined from a best fit to coronal loops



- H_r is then determined from the relation

$$H = \alpha \sum_{n_x=0}^{N_x} \sum_{n_y=0}^{N_y} \frac{|\widetilde{B}^2_{n_x,n_y}|}{(k_x^2 + k_y^2)^{3/2}}$$

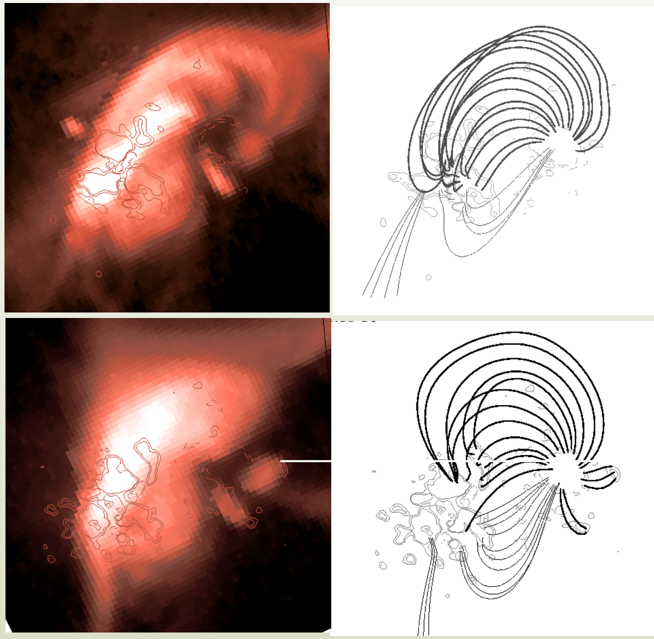
with summation over the spatial Fourier modes of the extrapolated field

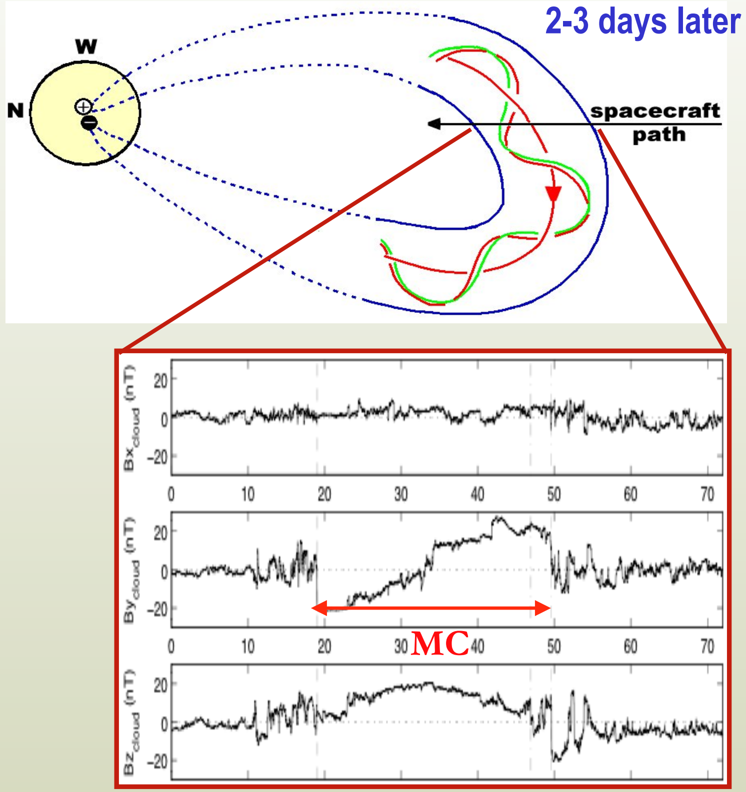
Compare ΔH_{corona} with $H_{Magnetic\ Cloud}$

AR 7912, 14 Oct. 1995

before CME

after CME





- Remote sensing but global observation

  - magnetograms + coronal loops + extrapolation

    -> ΔH_{corona}

- Results so far are suggestive but qualitative

- In situ but local observation

  - measure three B components + flux rope model

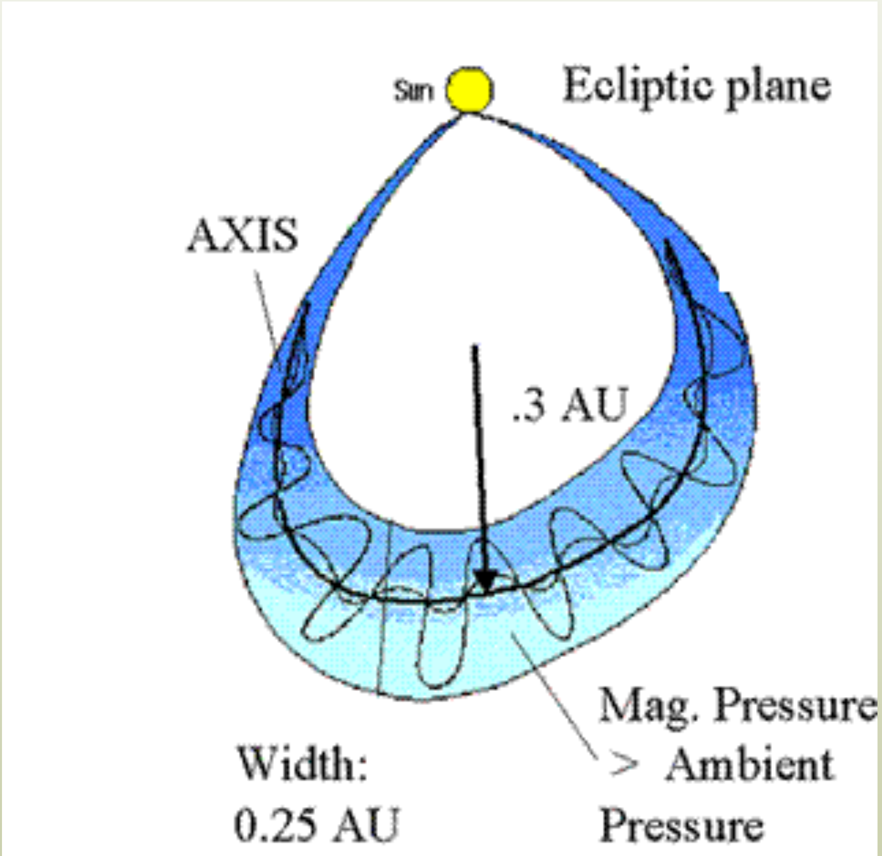
    -> H_{MC}

- **For future, use non-linear force-free extrapolation with vector B-field measurements**

In-Situ Observations of ICMEs

- CMEs are called ICMEs in Interplanetary space

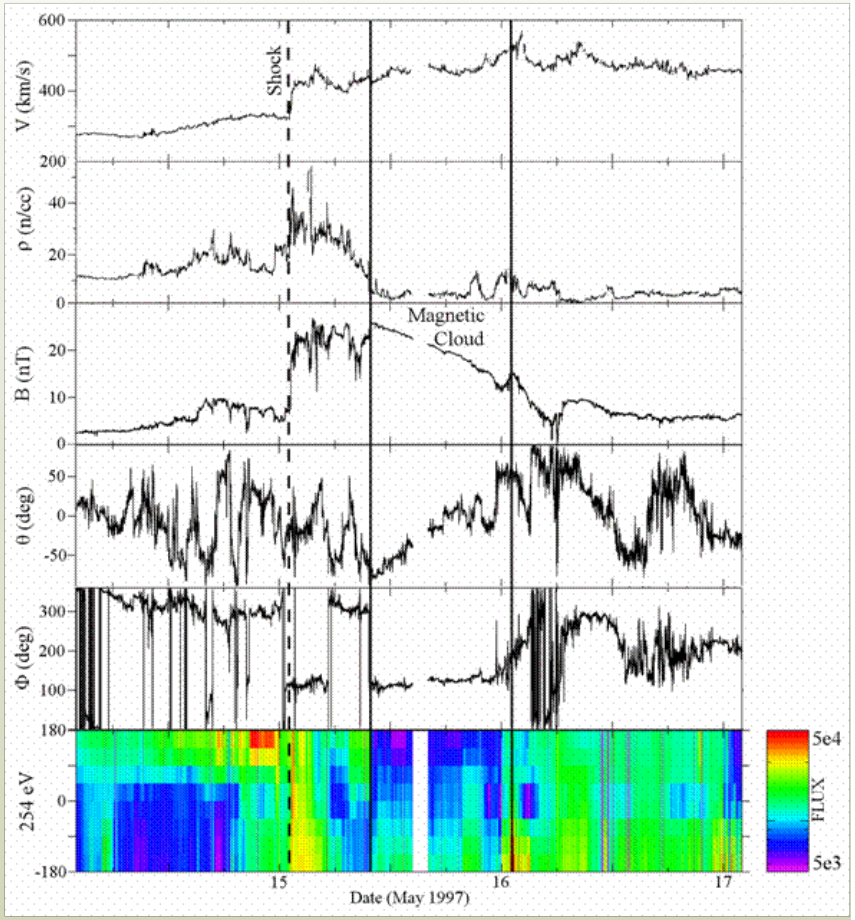
- CMEs are observed in situ as transients in IP space with changes to ambient physical parameters:
  - ***stronger magnetic field*** showing a twisted flux rope structure
  - ***higher density*** and ***lower temperature*** than the surrounding solar wind.



In-Situ Observations of ICMEs

- **Magnetic Field**

- **Strength increase** >10 nT.
  (Hirshberg & Colburn, 1969)
- **Smooth rotation** of the magnetic field direction
  (Klein & Burlaga,1982)
- **Lack of fluctuations**
  (Pudovkin et al., 1979)
- **Discontinuities** at ICME boundaries
  (Janoo et al., 1998)



- **Plasma**

- ~ 50% of ICMEs are associated with IP **shocks**
- Extreme **density decrease** ≤ 1cm^{-3} (Richardson et al., 2000)
- Proton **temperature decrease** (Gosling et al., 1973)
- **Low plasma β** (ratio of gas to magnetic pressure)

- **Magnetic Cloud (MC)**

- Specialist title given to an ICME when the core can be unambiguously identified (Klein & Burlaga, 1982)

In-Situ Observations of ICMEs

- **Composition**

- The abundances of elements and their charge states tend to rise within ICMEs
  - characteristic of having originated in the Sun's Corona.

→ Enhanced α/proton ratio: $He^{2+}/H^{+} > 8\%$

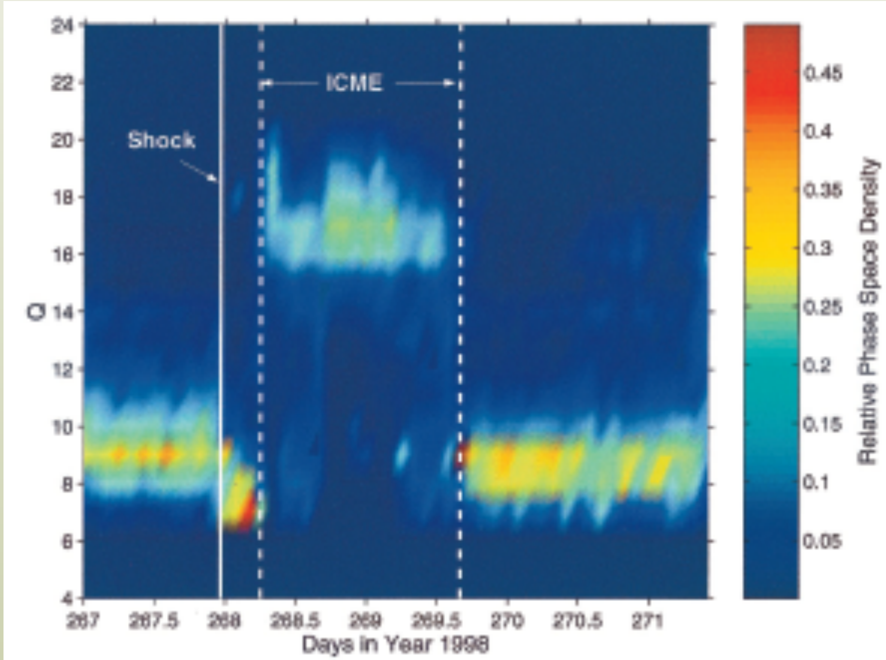
→ Over 80% of MCs have elevated O and Fe charge states: e.g. $O^{7+}/O^{6+} > 1$

→ Occurrence of He^{+}: $He^{+}/He^{2+} > 0.01$

→ Enhancements of Fe/O

→ Unusually high ratios of $^{3}He/^{4}He$

Fe Charge State Distributions observed with ACE



Lepri et al., (2001)

- ACE example for near-Earth MC shows:
  - highest ion stages at front, lower at rear
  - coronal followed by chromospheric material

- However this is a simple example
  - exact composition can be unique (Gloeckler et al., 2005)

Relevance of Solar-C

- Subset of Sun-Earth connection topics has been reviewed that includes
  - Search for evidence of existence of flux tubes – above and below the photosphere
  - CME Launch processes
  - Measurement and use of magnetic helicity
  - In-situ registration *of arriving* ICMEs/MCs

- Emerging flux rope studies require high quality vector magnetograms with good cadence and a field of view greater than AR size to be available in the AR latitude range

- **No clear advantage for Plan A**

- Formation of flux ropes at the tachocline **and** their passage through the convection zone
  - high latitude observations **may** allow flow and anomalous velocity studies to tachocline

- **Posible Plan A advantage; SDO/HMI and Plan B abilities to be quantified**

Relevance of Solar-C (continued)

- CME launch process needs
  - understanding of the flux rope formation process
  - identification of role of pre-launch phenomena
  - observation of the associated disc and low corona signatures
  - multiple views of CME expansion

    → implies a heliospheric imager or coronagraph for Plan A
- **Plan A and Plan B both have role**
  - **Plan A allows CME tracking by contributing to multiple views**
  - **Plan B allows detailed views of the pre-launch processes**

Relevance of Solar-C (continued)

- Quantitative magnetic helicity measurements require high quality vector magnetic field measurements good cadence and a field of view significantly greater than AR size to be available in the AR latitude range

- Automated NLFF magnetic field extrapolation code also required

- **Assuming SDO AIA/HMI capability exists, no advantage for Plan A**
  - **need better understanding of Plan B capabilities**

- In-situ sampling of ICMEs/MCs at range of latitudes requires
  - Sensitive magnetometer measurements
  - Solar wind and ICME electron/proton plasma analyser
  - Plasma composition measurements by ion mass spectrometer

- **Plan A sampling advantage if spacecraft has these instruments**

Thank You