

STEREO A 07/12/31

EUVI: 03:26:15

COR1: 03:25:18

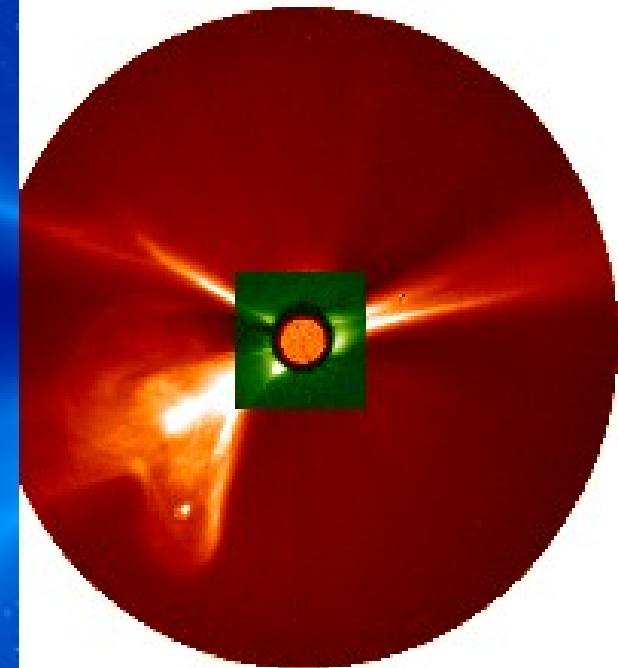
COR2: 03:23:20

HI1: 03:29:01

# Tracking CMEs/Shocks and Predicting Their Arrival Time at the Earth

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# Abstract

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CMEs have been recognized as primary drivers of interplanetary disturbances. Of central importance in space weather forecasting is to track CMEs and their preceding shocks from the Sun continuously out to 1 AU. We will discuss and evaluate three different strategies for this purpose, specifically (1) frequency drift of type II bursts to track CME-driven shocks; (2) MHD propagation of observed solar wind disturbances; and (3) geometric triangulation of white-light features observed by wide-angle coronagraphs and heliospheric imagers from vantage points off the Sun-Earth line. Event studies together with implications for instrumentation will be presented to demonstrate the capabilities with which the impact of a solar storm on the Earth can be predicted with small ambiguities.



# 1, Type II Frequency Drift

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- The frequency drift of type II bursts results from the decrease of the plasma density as the shock moves away from the Sun;
- The height-time profile can be obtained from the frequency drift assuming a density model:

$$f_p \text{ (kHz)} = 9\sqrt{n \text{ (cm}^{-3}\text{)}} \Rightarrow r \text{ (AU)} = \frac{9\sqrt{n_0 \text{ (cm}^{-3}\text{)}}}{f_p \text{ (kHz)}}$$

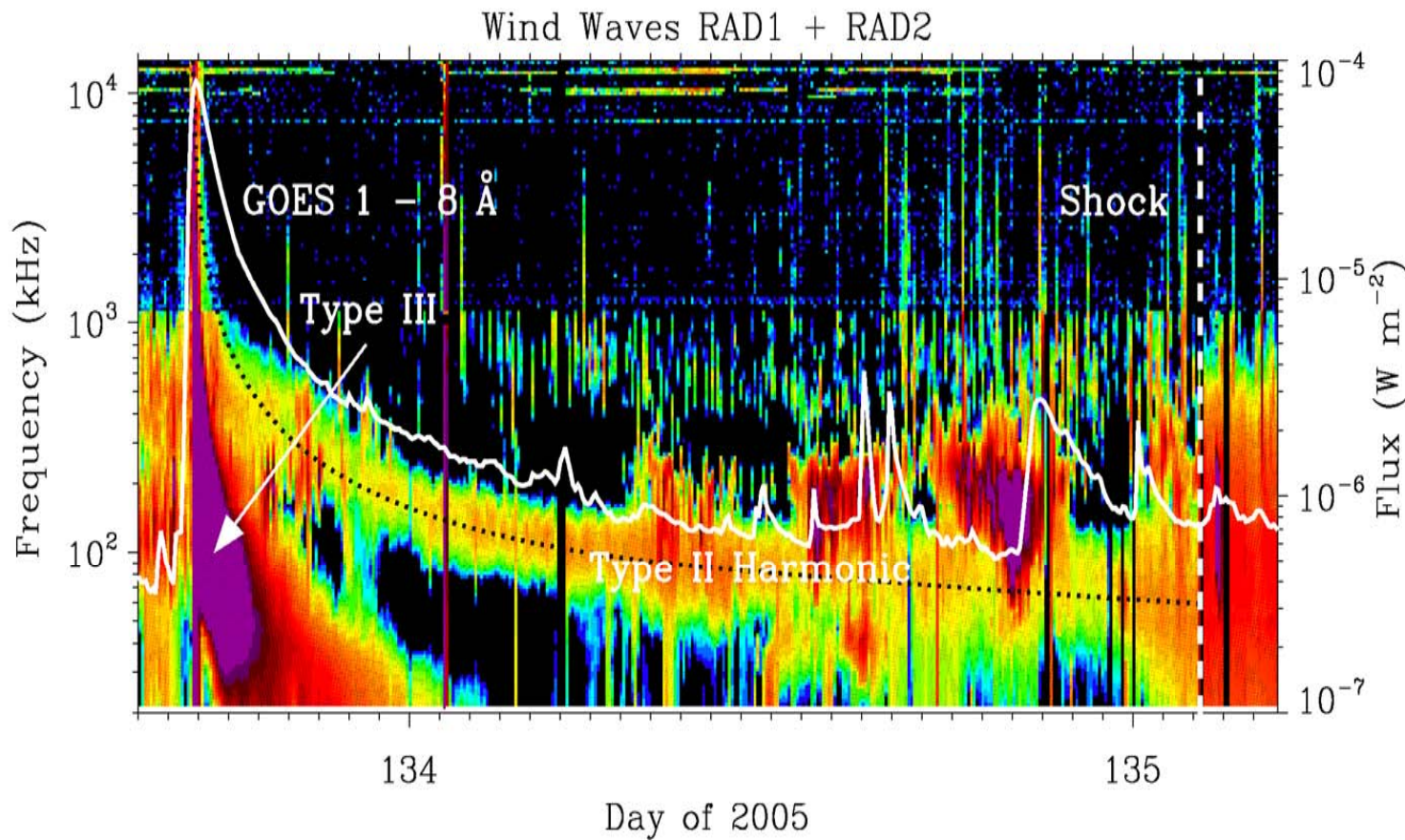
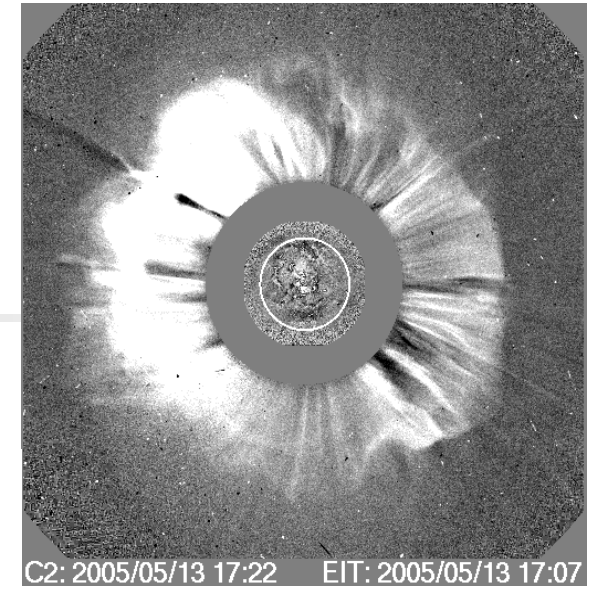


## 2, MHD Propagation of Solar Wind

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- Solar wind measurements can be used as input to an MHD model (assuming spherical symmetry), and we can track the disturbance from MHD model output;
- Solar wind slowdown due to pickup ions is included, so the model can propagate solar wind measurements to any distances in the heliosphere;
- The model uses the piecewise parabolic method (PPM), which can capture shocks with 1-2 grids.

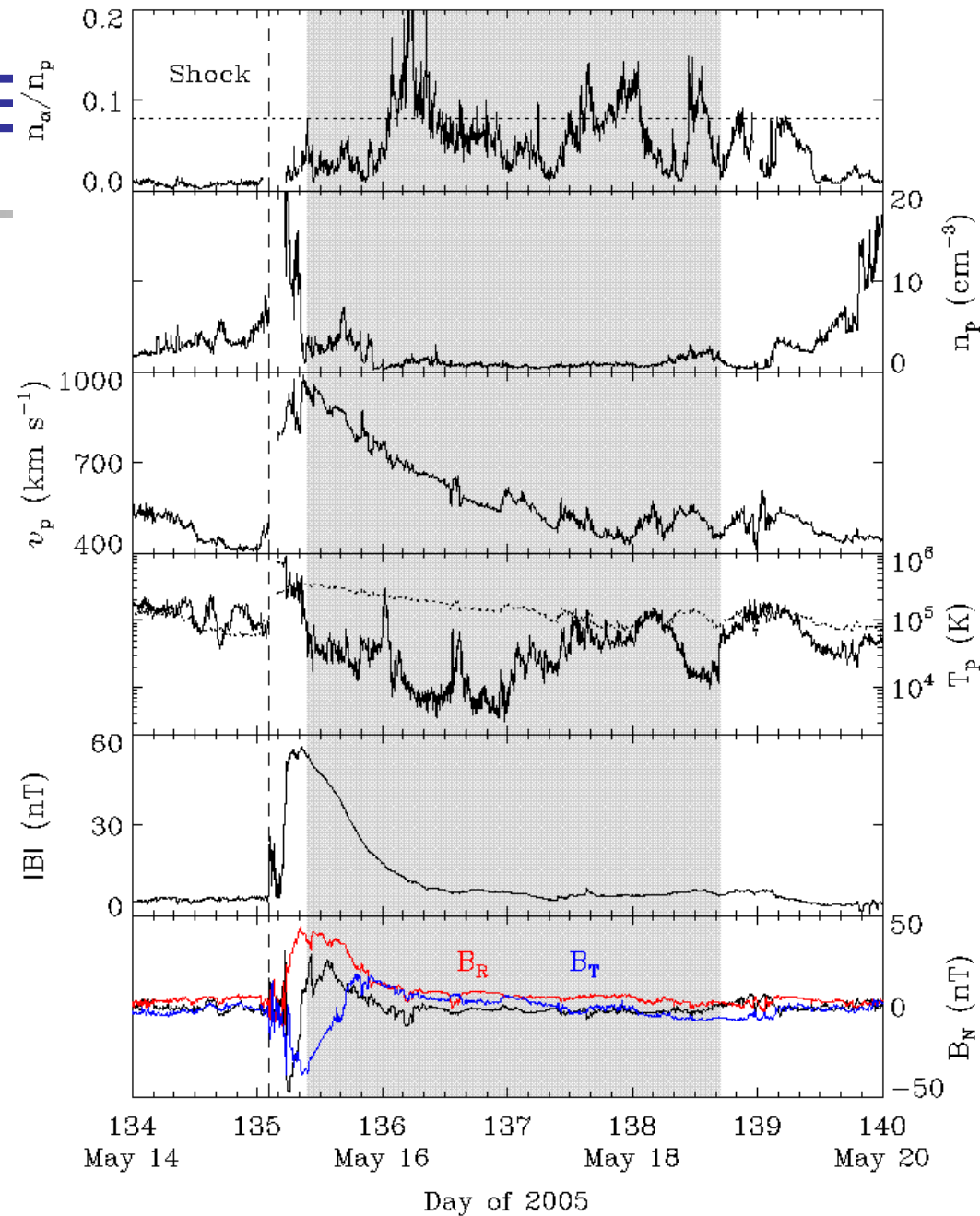
# 2005 May 13 CME



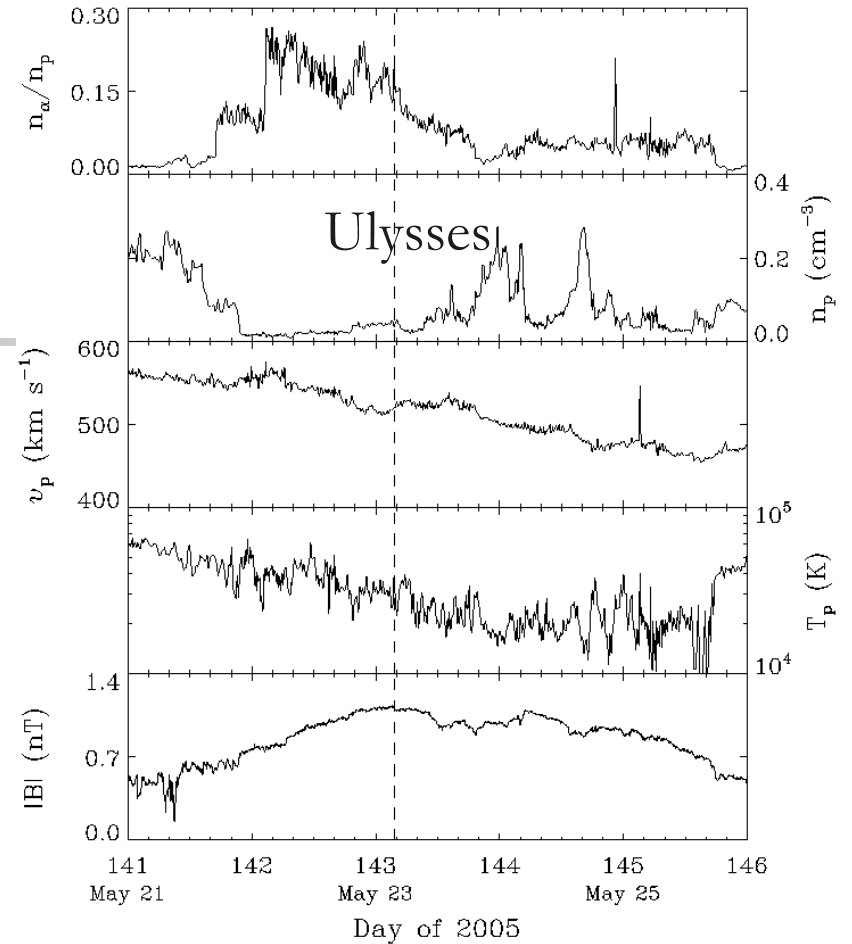
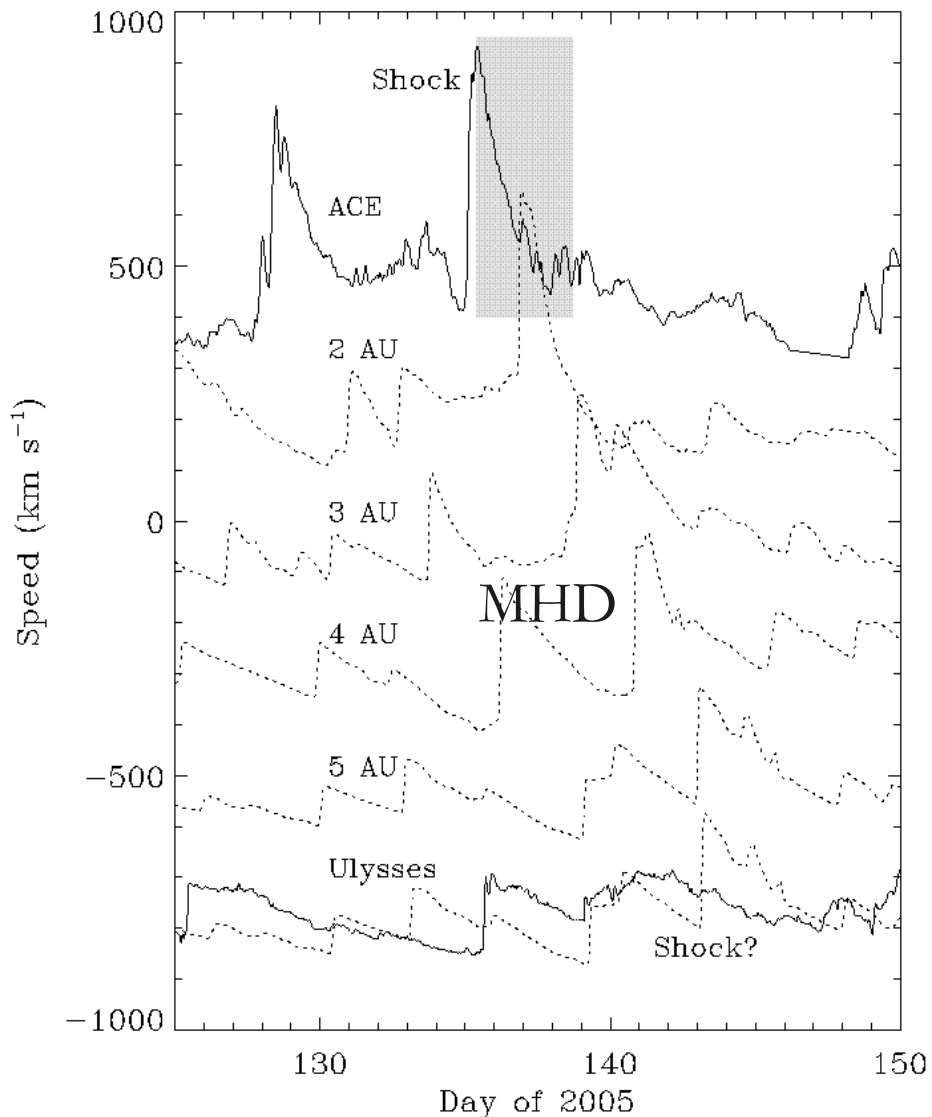
- A large halo CME with a projected speed 1689 km/s;
- The CME-driven shock appears as a weak edge ahead of the CME front;
- A type II burst extends continuously to 1 AU.

# 2005 May 13 CME

- The 2005 May 13 CME produces a large shock and ICME at 1 AU;
- The shock speed at 1 AU is about 950 km/s;
- Use the observed solar wind data as input to the MHD model and track the disturbance from model output.



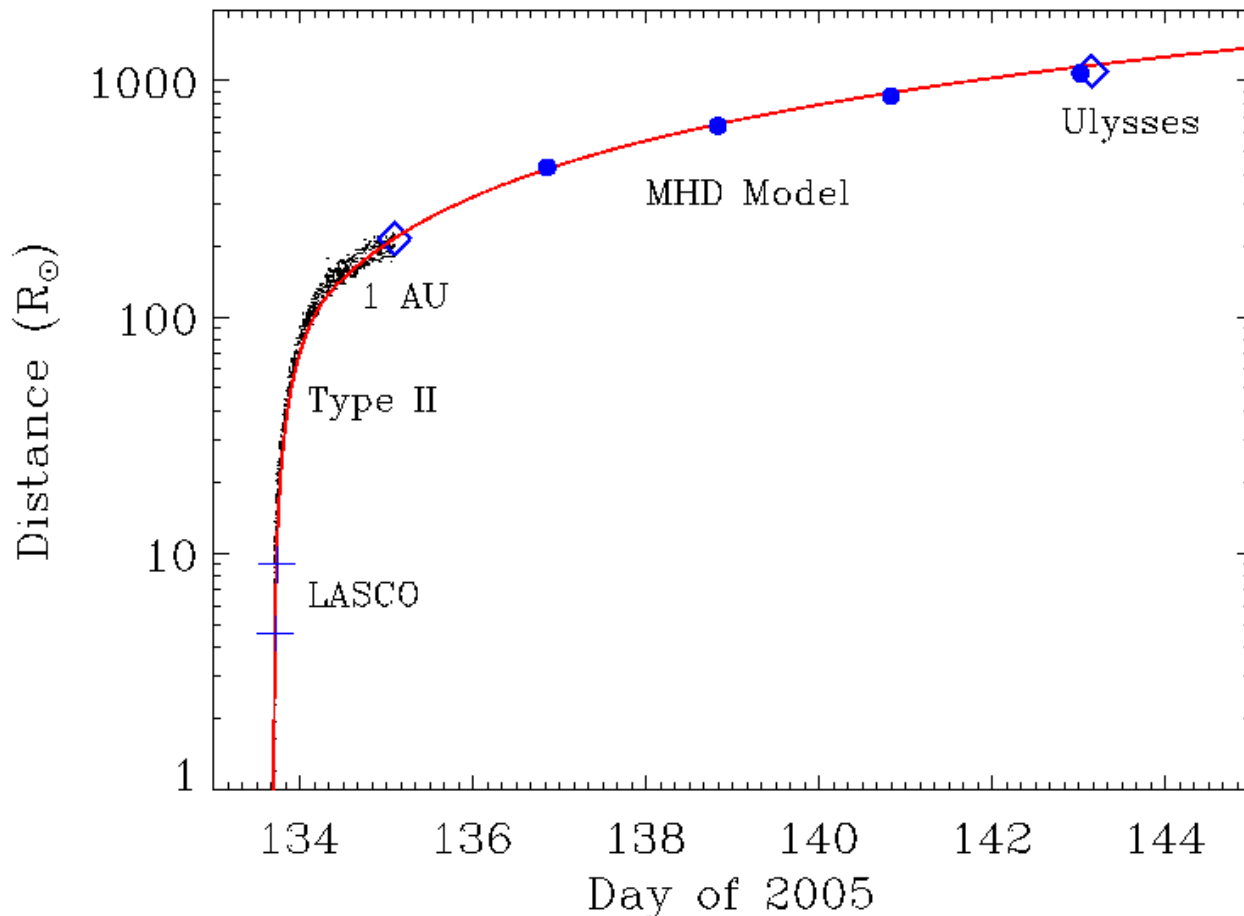
# 2005 May 13 CME



- Ulysses observed a solar wind disturbance at 5.1 AU, 73 deg east and 21 deg south of the Earth, but it does not look like a shock;
- The predicted arrival time at Ulysses is coincident with the observed disturbance.

# 2005 May 13 CME

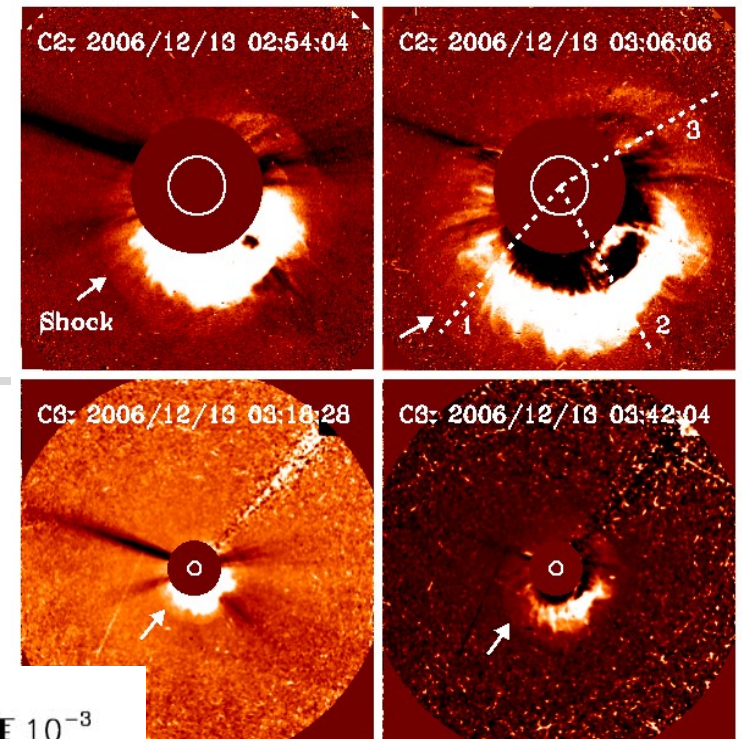
Fit obtained from radio and 1 AU data only



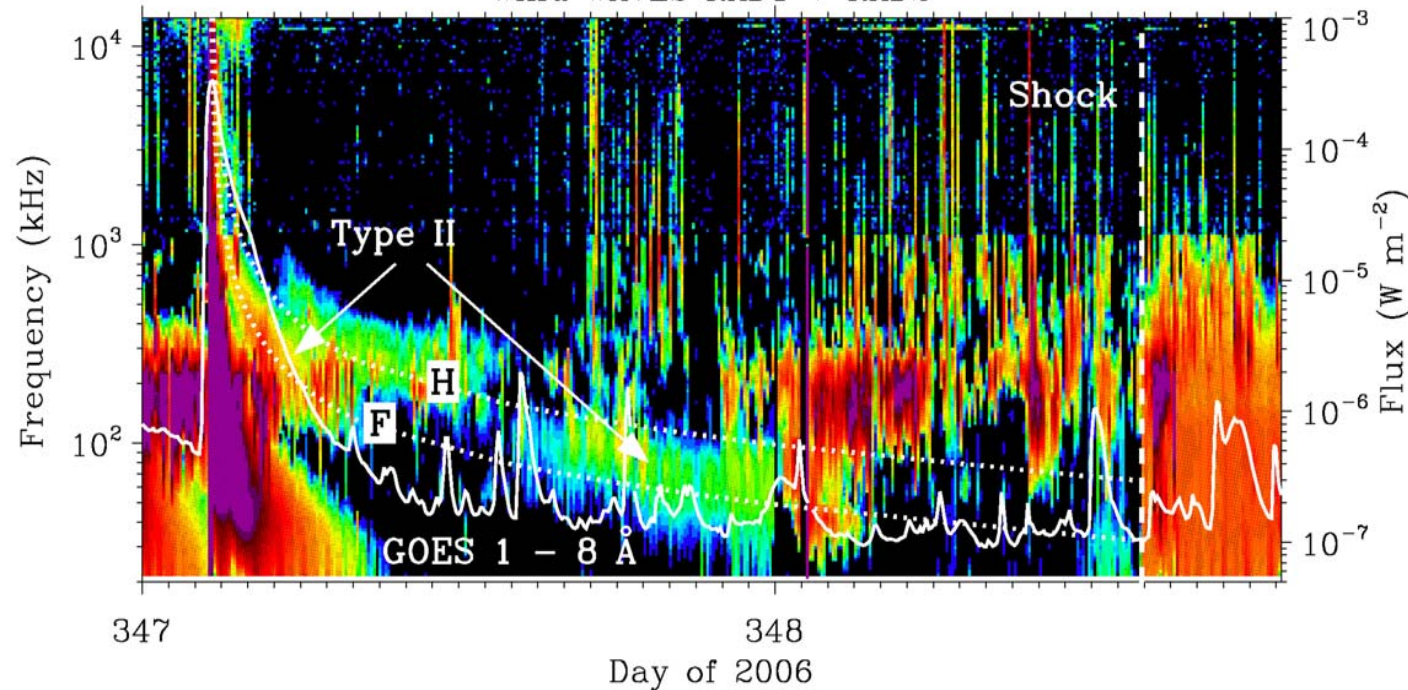
- Shock propagation is obtained from frequency drift and 1 AU data only, and then extend the curve further out;
- Radial speed at the Sun 2100 km/s, larger than projected speed (1689 km/s);
- The fit matches white-light data, the MHD model output at different distances and Ulysses measurement remarkable well.

# 2006 Dec 13 CME

Liu et al., 2008, ApJ, 689, 563



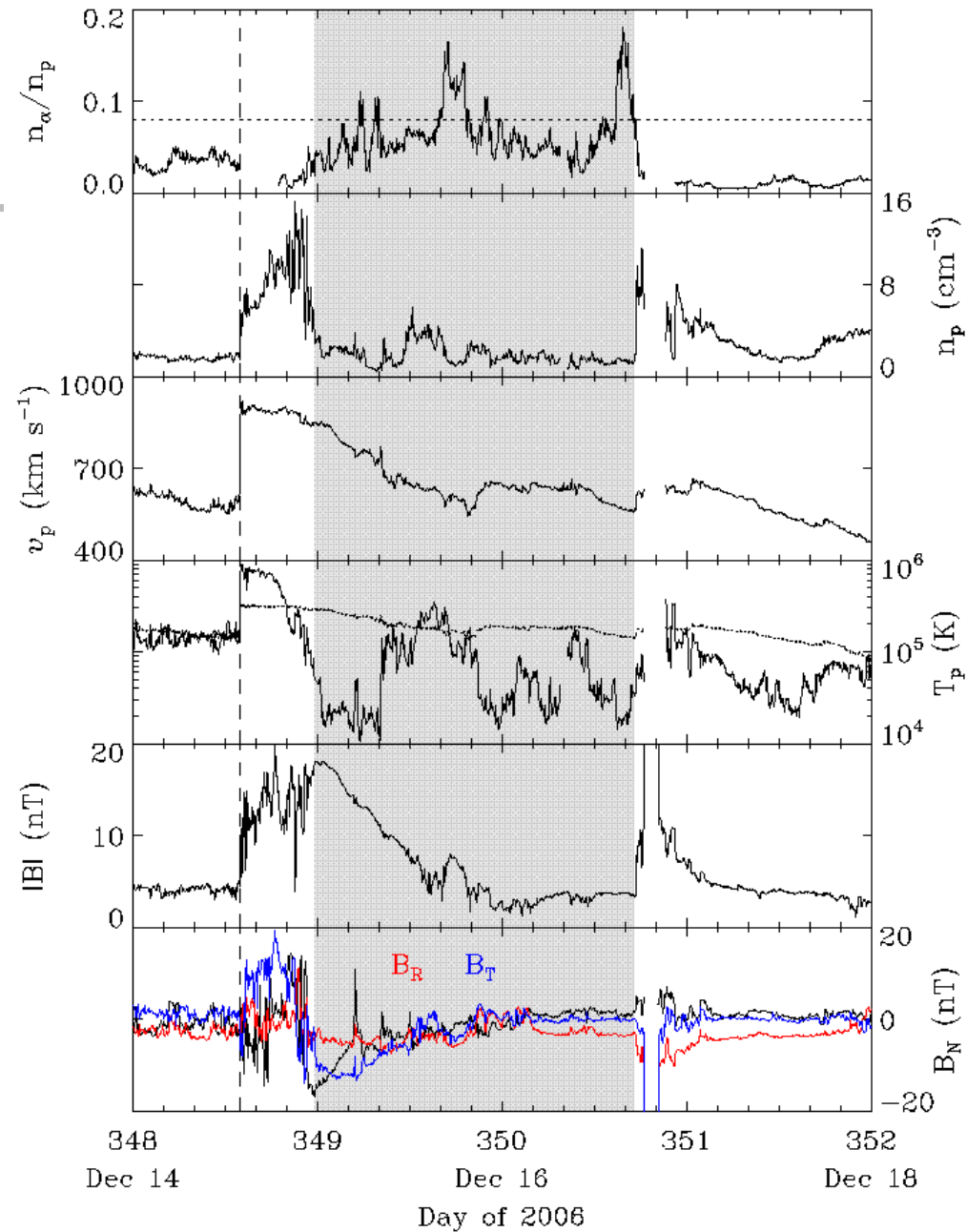
Wind WAVES RAD1 + RAD2



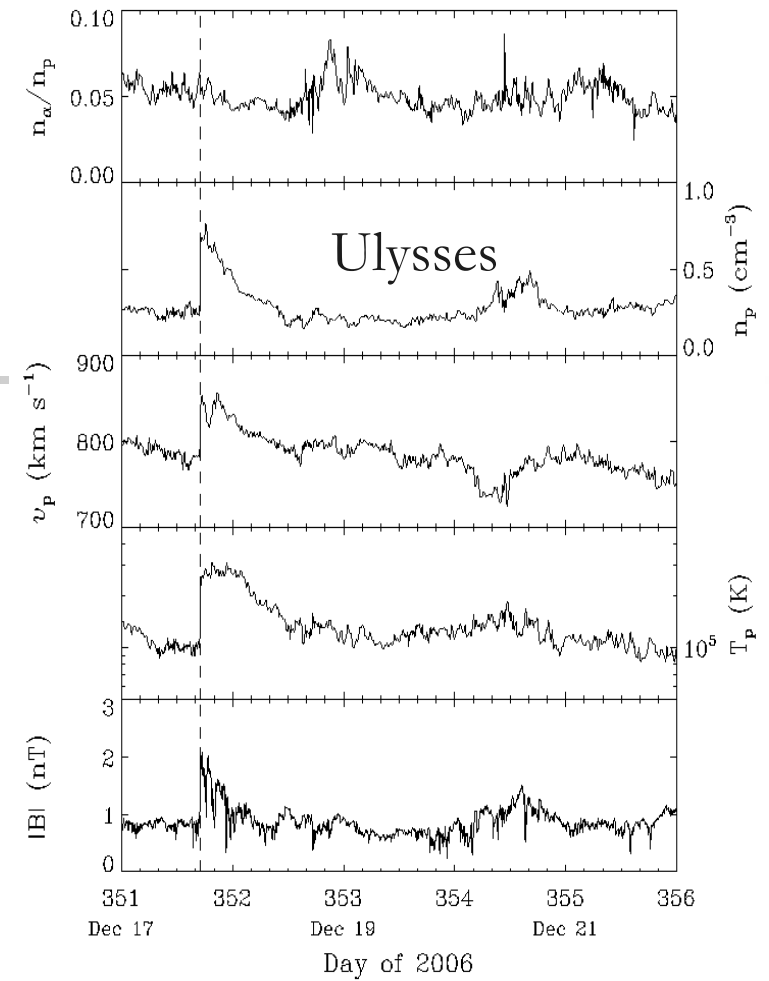
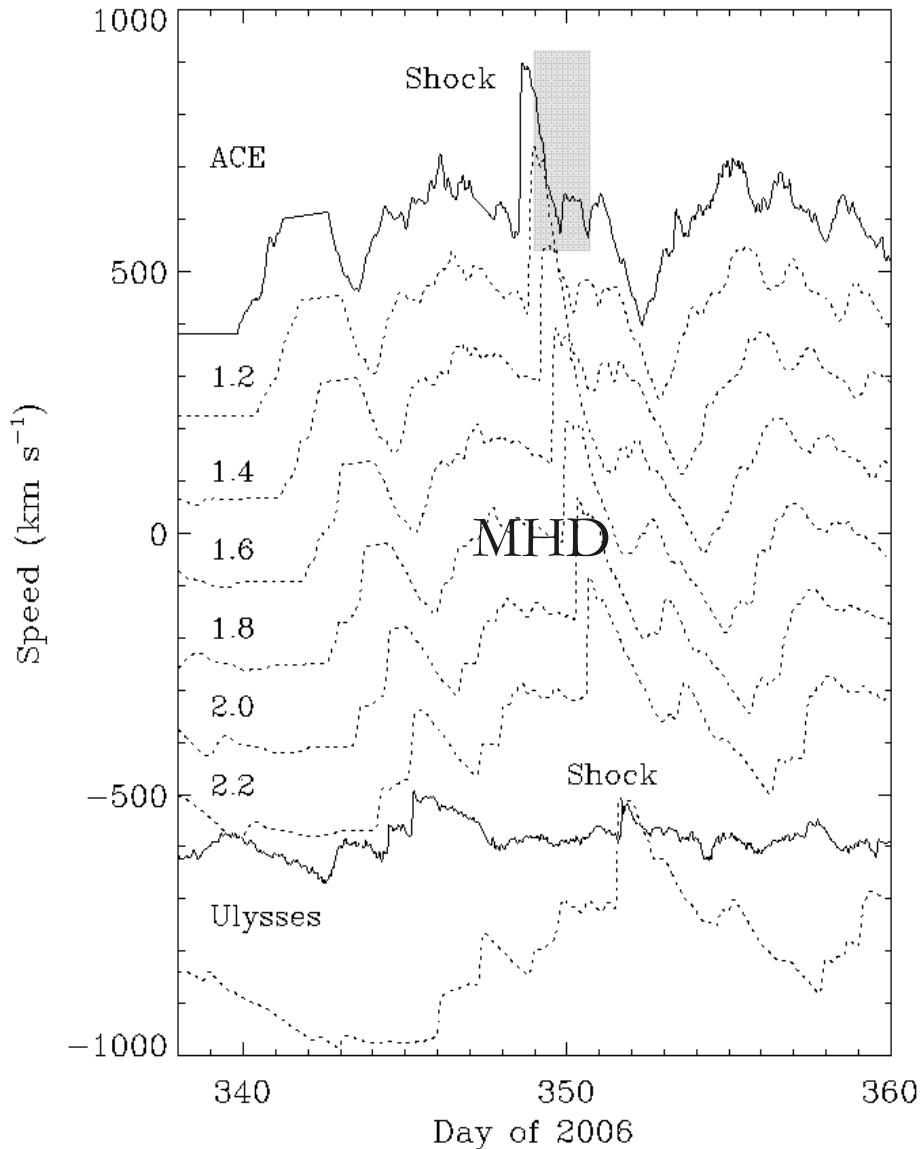
- A large halo CME with a projected speed 1770 km/s;
- The CME-driven shock appears as a weak edge ahead of the CME front;
- A type II burst is also observed.

# 2006 Dec 13 CME

- The CME produces a large shock and ICME at 1 AU;
- The shock speed at 1 AU is about 1030 km/s;
- Use the observed solar wind data as input to the MHD model and track the disturbance from model output.



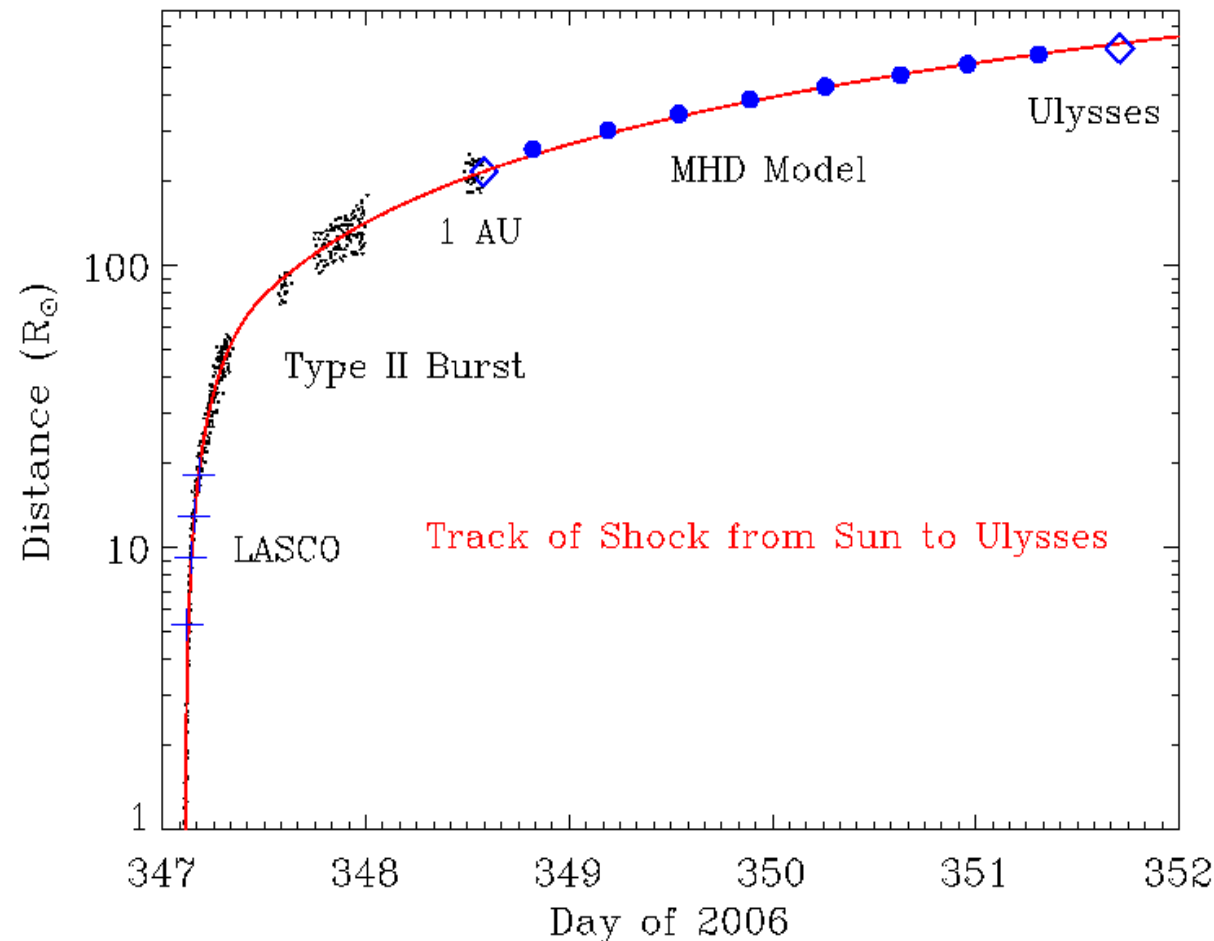
# 2006 Dec 13 CME



- Ulysses also observed the shock (not ICME) at 2.73 AU, 117 deg east and 74 deg south of the Earth, which can be used to test the model;
- The shock arrival time at Ulysses is well predicted with a time difference 3.6 hr, much smaller than the propagation time from 1 AU to Ulysses (75.1 hr).

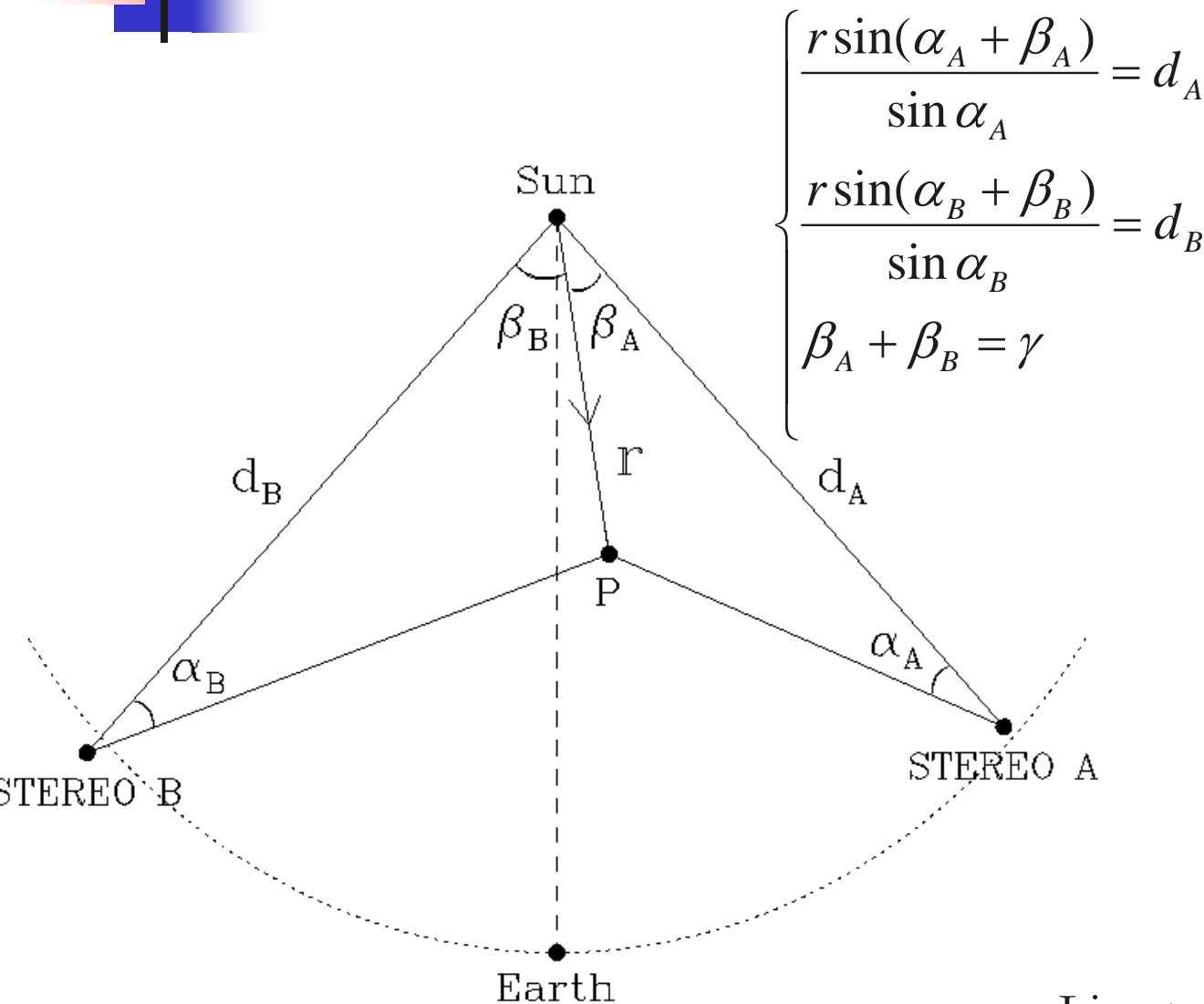
# 2006 Dec 13 CME

Fit obtained from radio and 1 AU data only



- Shock propagation is obtained from frequency drift and 1 AU data only, and then extend the curve further out;
- Radial speed at the Sun 2200 km/s, larger than projected speed (1770 km/s);
- The fit matches white-light data, the MHD model output at different distances and Ulysses measurement remarkable well.

# 3, Geometric Triangulation of Imaging Observations



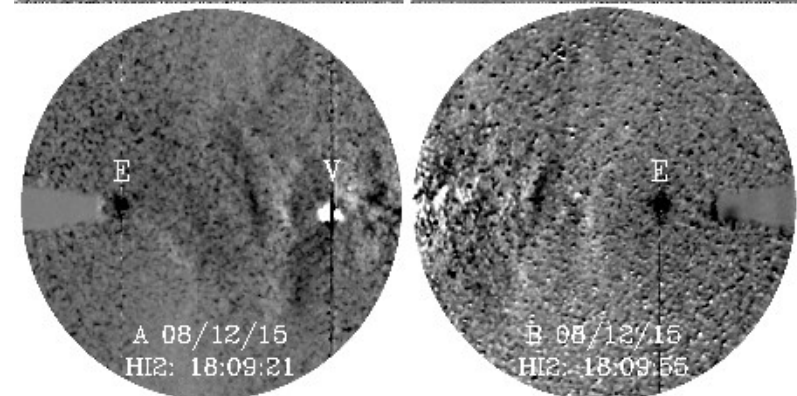
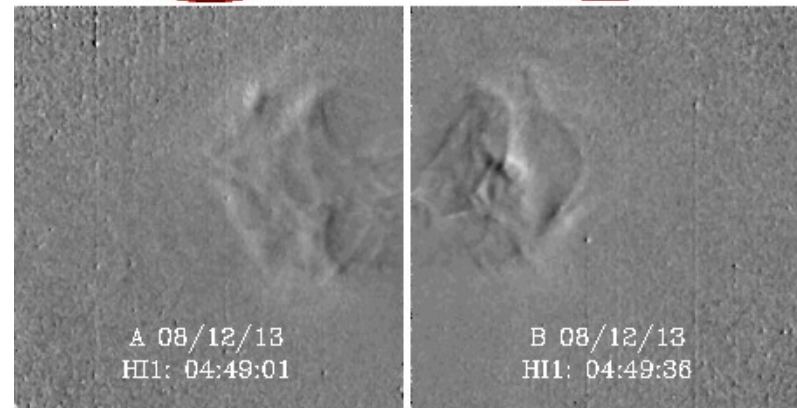
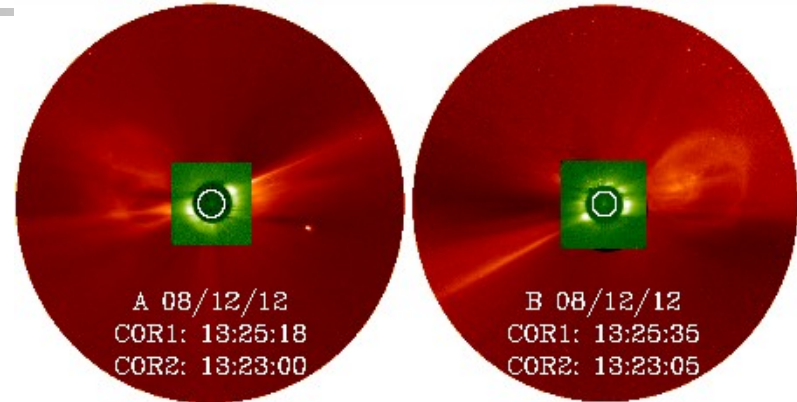
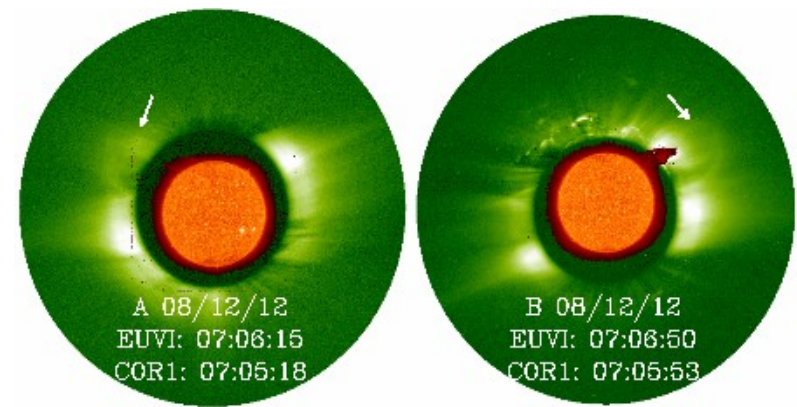
$$\begin{cases} \frac{r \sin(\alpha_A + \beta_A)}{\sin \alpha_A} = d_A \\ \frac{r \sin(\alpha_B + \beta_B)}{\sin \alpha_B} = d_B \\ \beta_A + \beta_B = \gamma \end{cases}$$

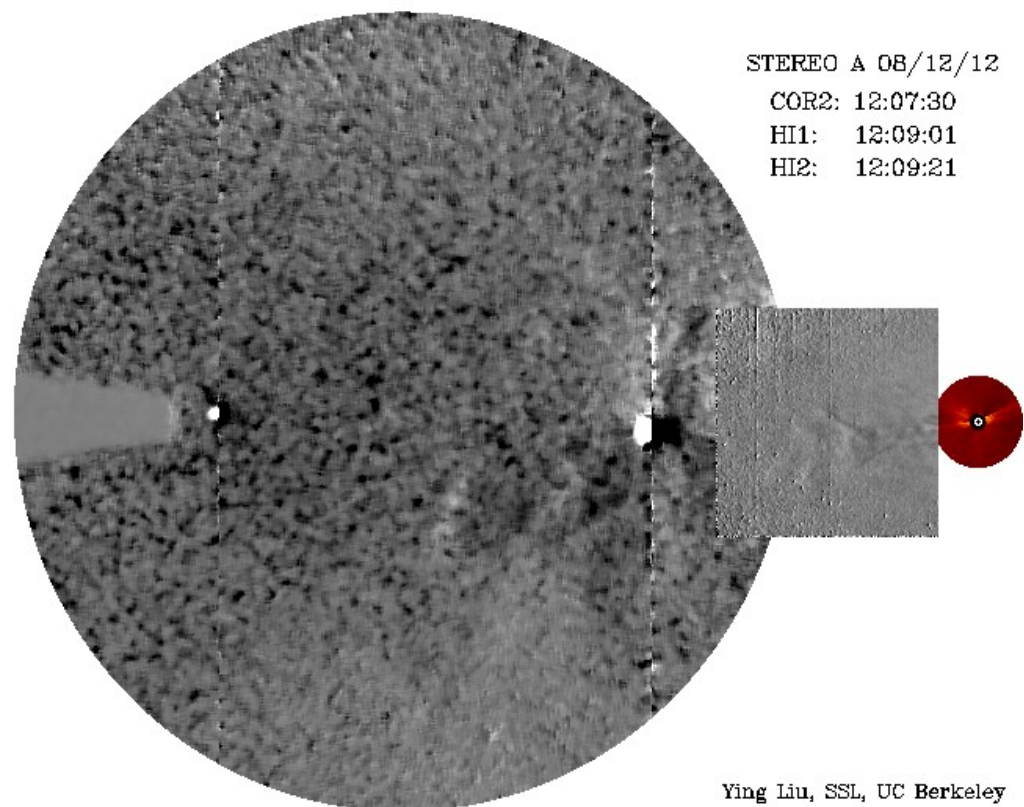
- Can solve these equations to get propagation direction and radial distance in the ecliptic plane;
- Advantages: 1, the triangulation is based on time-elongation plots (J maps), so it can be applied to weak features in HI2; 2, the method does not use any model fit, so the solution is unique; 3, the method can determine the propagation direction and true distance of any white-light features all the way out to 1 AU.

# 3, Geometric Triangulation

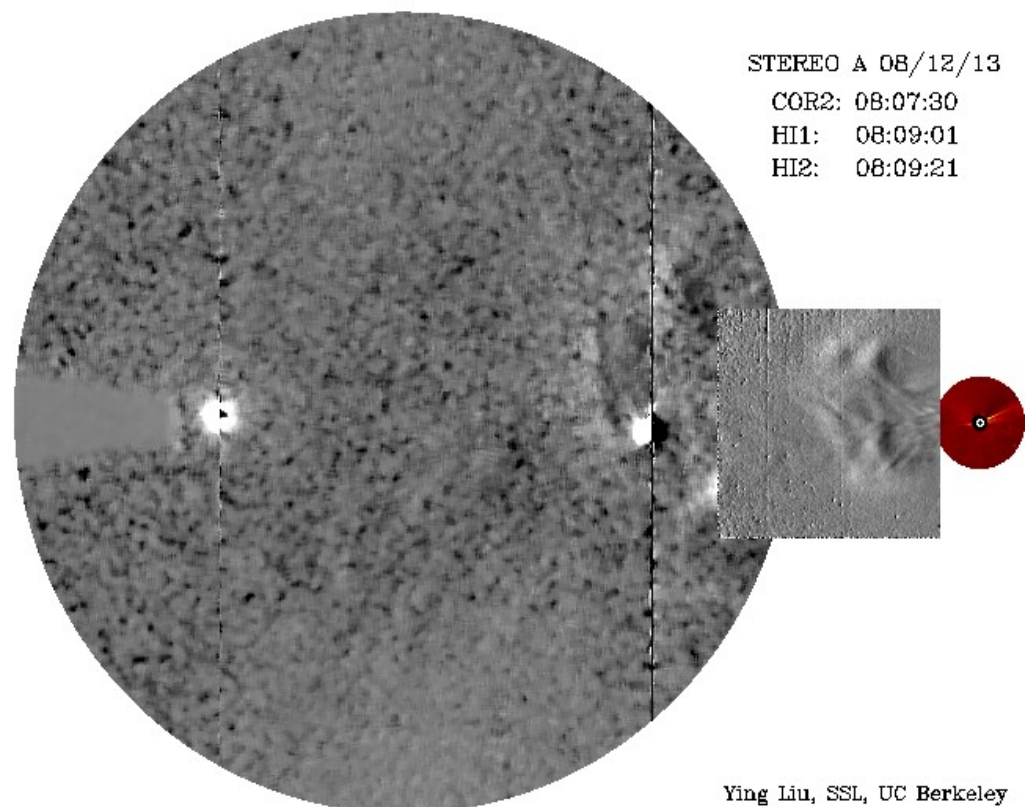
Two views of the 2008 Dec 12 CME from STEREO A and B (movies are available):

- Separation between A and B is about 86.3 deg;
- The CME is induced by a prominence eruption;
- The CME can be seen all the way to large distances;
- The CME produces wave-like structures in HI2.

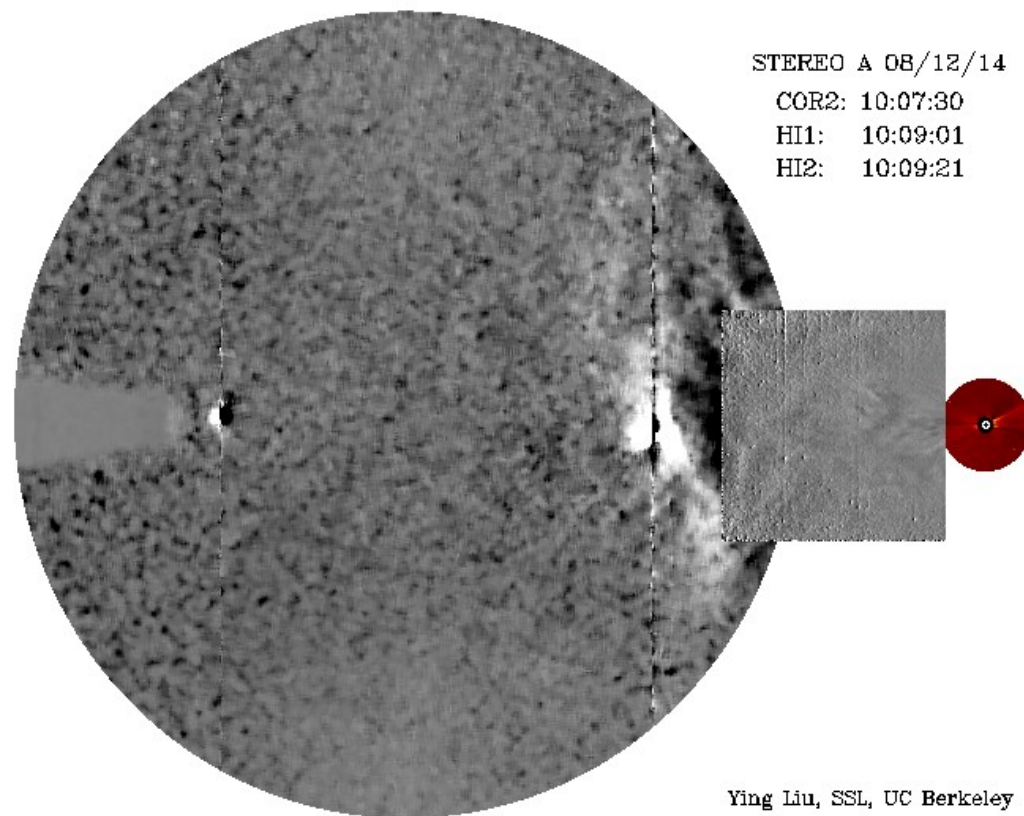




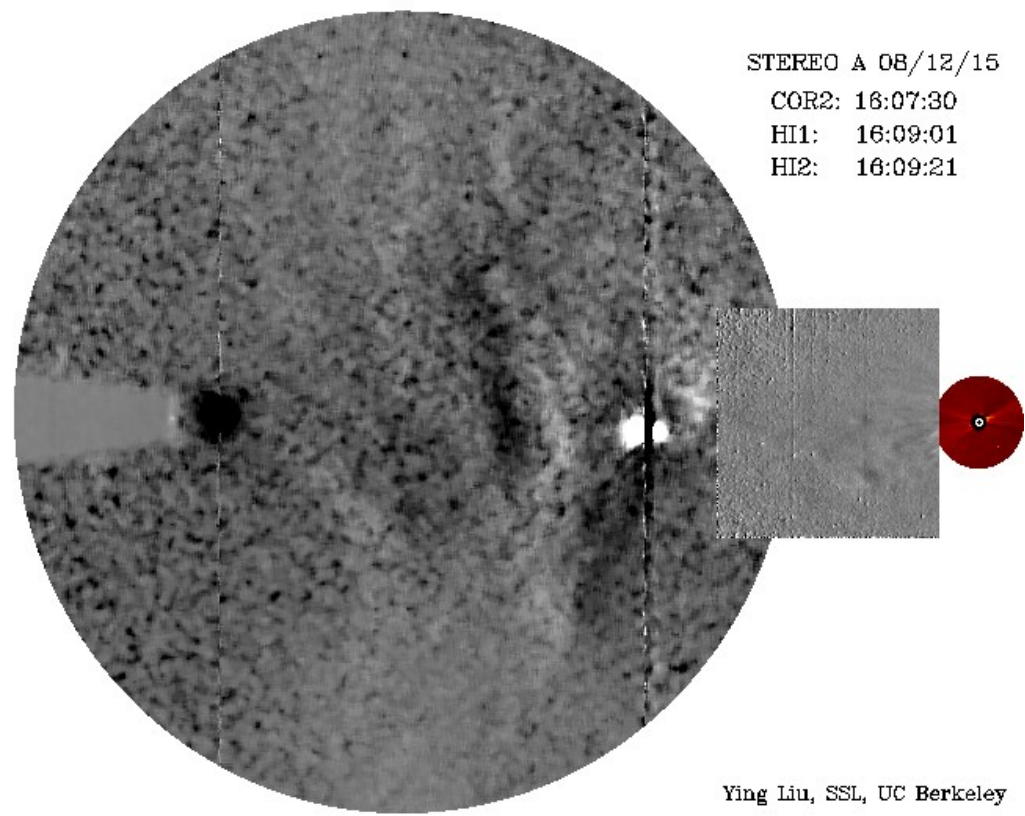
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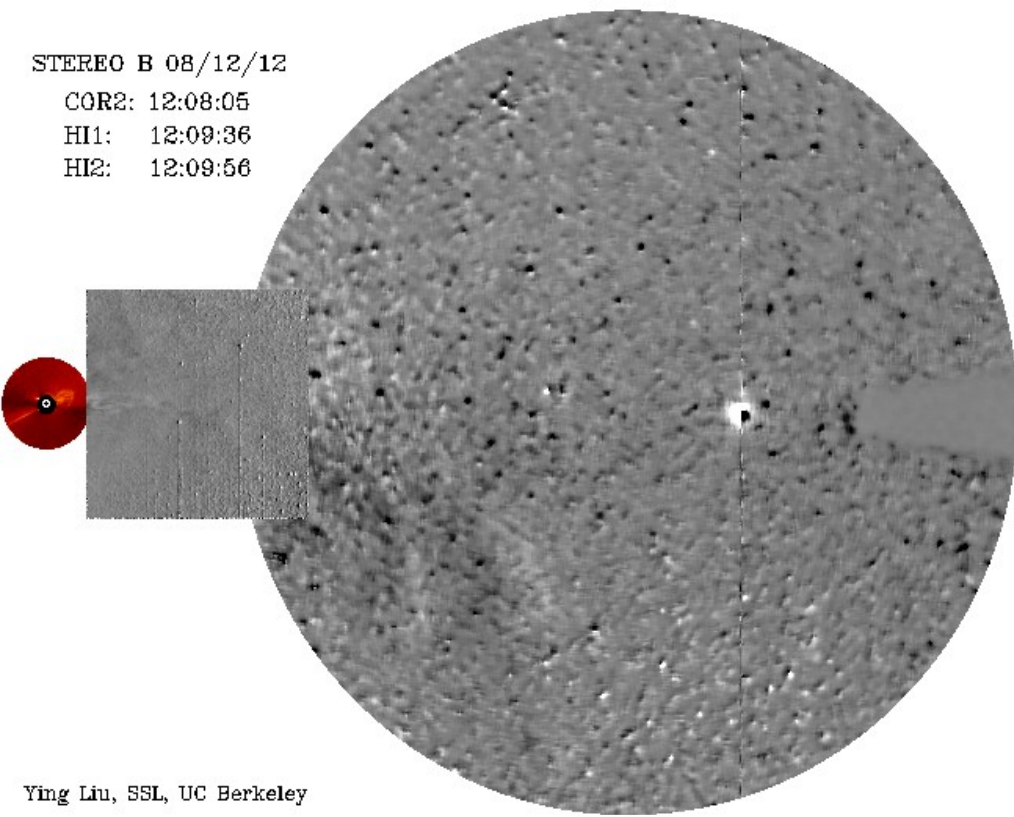
Ying Liu, SSL, UC Berkeley

STEREO B 08/12/12

COR2: 12:08:05

HI1: 12:09:36

HI2: 12:09:56

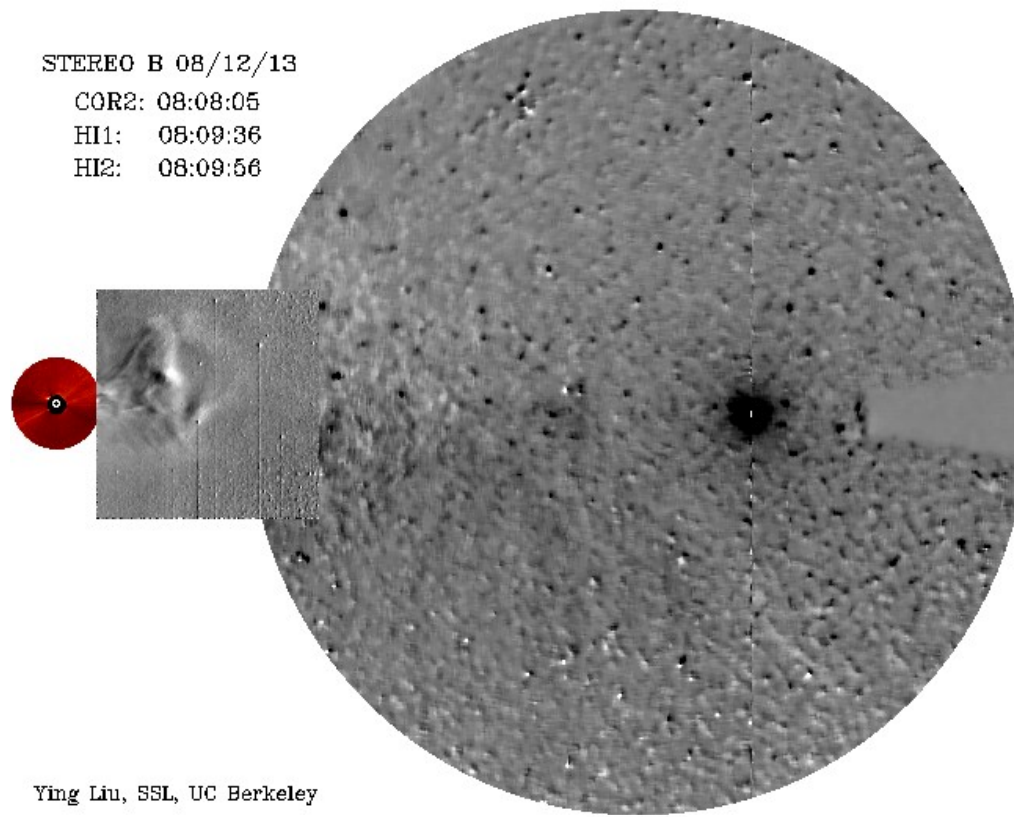


STEREO B 08/12/13

COR2: 08:08:05

HI1: 08:09:36

HI2: 08:09:56



Ying Liu, SSL, UC Berkeley

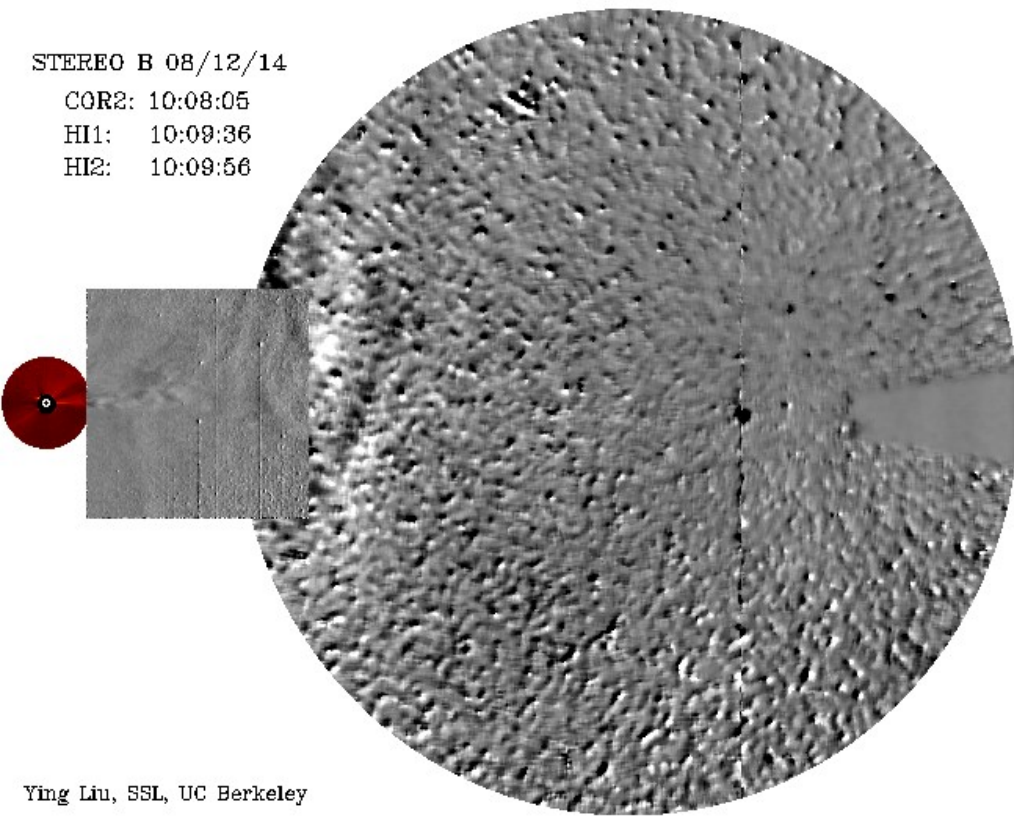
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STEREO B 08/12/14

COR2: 10:08:05

HI1: 10:09:36

HI2: 10:09:56

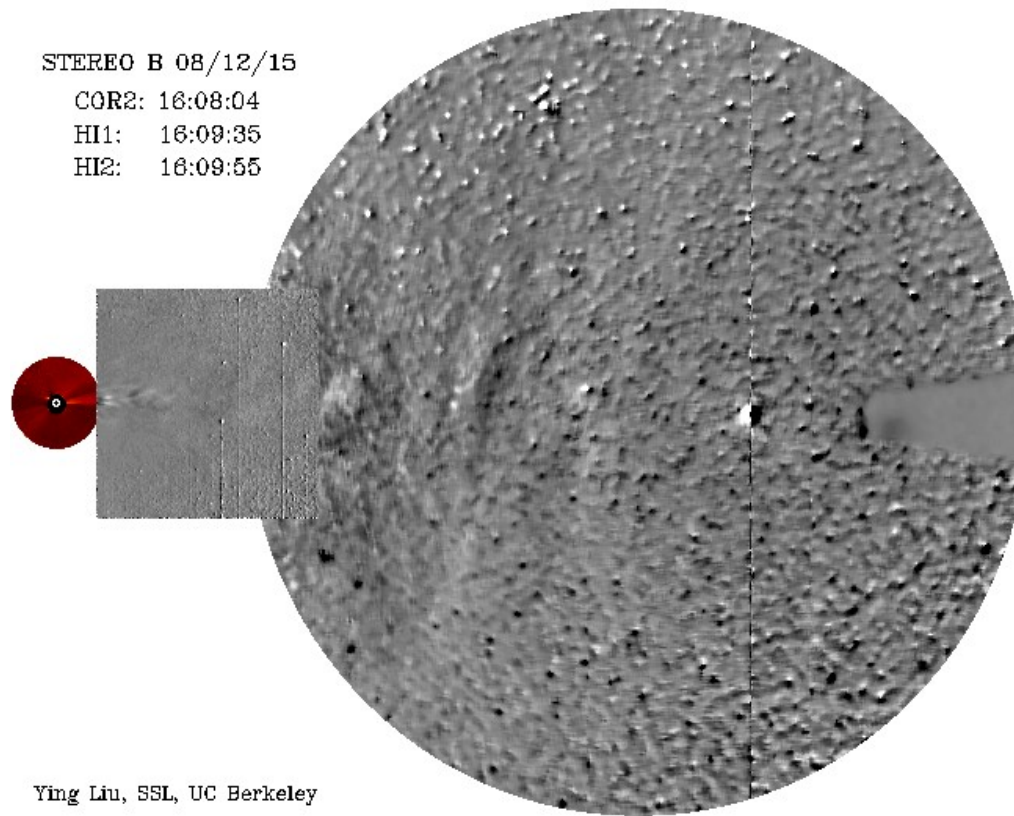


STEREO B 08/12/15

COR2: 16:08:04

HI1: 16:09:35

HI2: 16:09:55



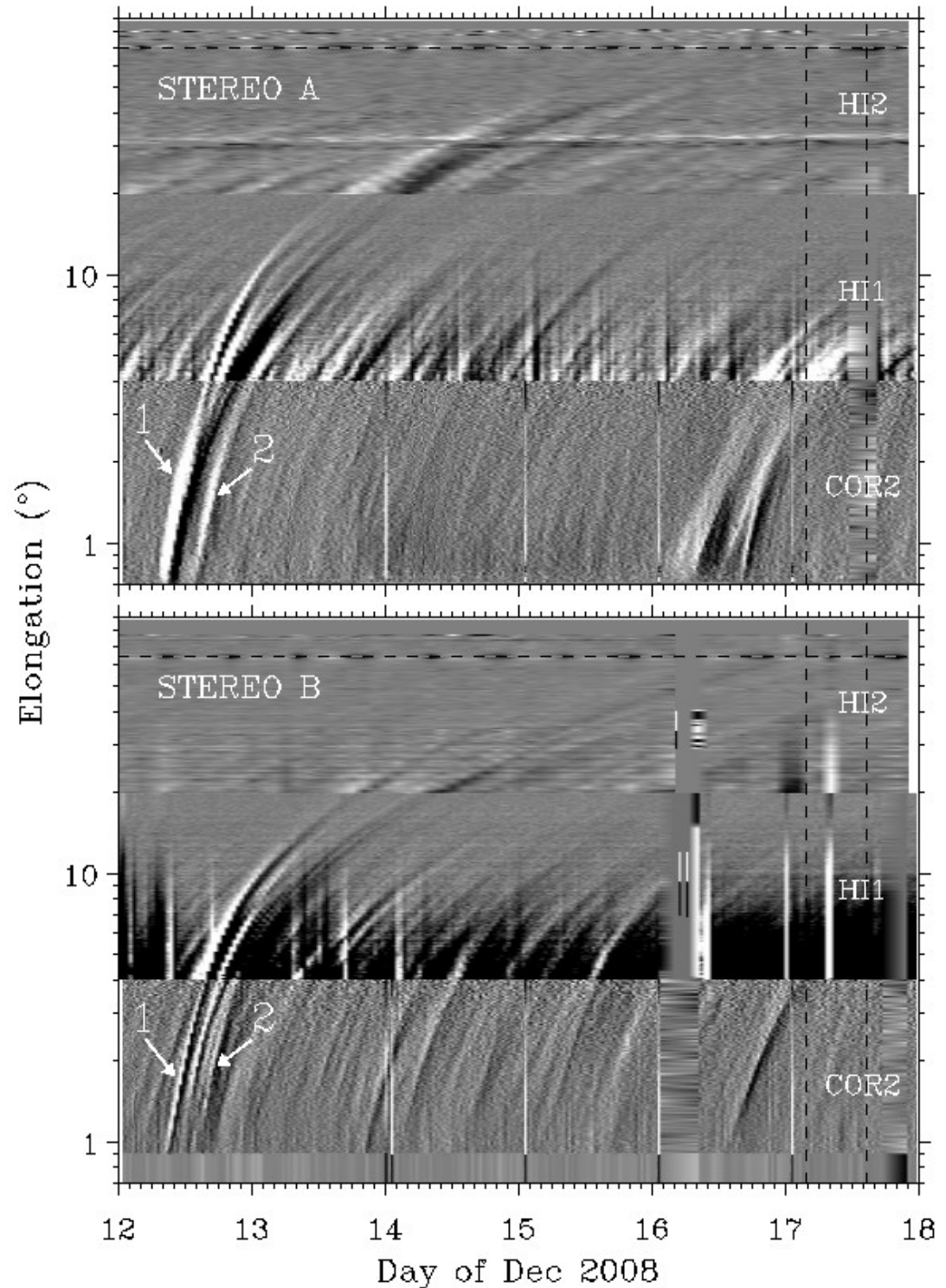
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# 3, Geometric Triangulation

Time-elongation plot from STEREO A and B:

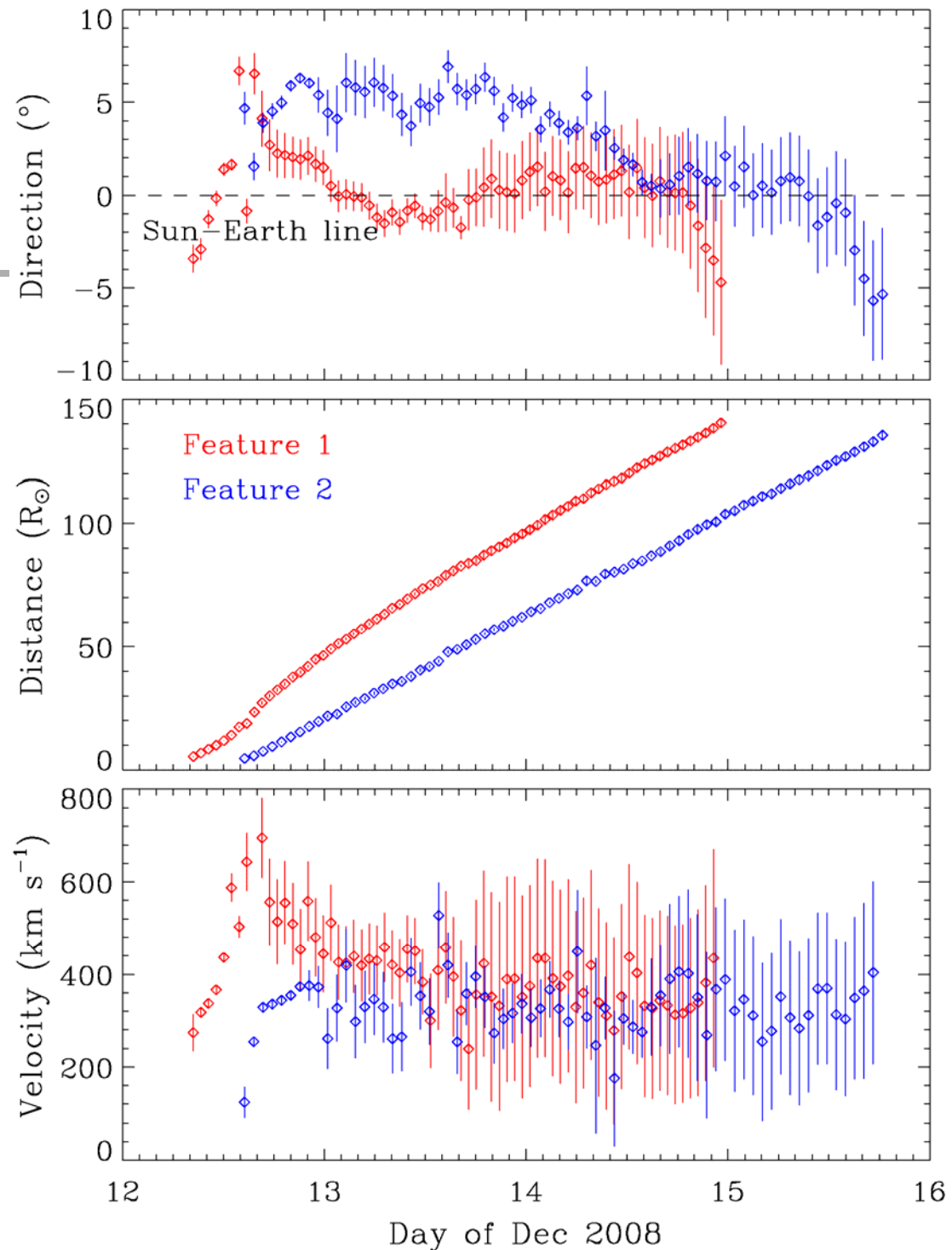
- COR2, HI1 and HI2 are included;
- Two features coincident with the CME can be identified up to 50 deg;
- Earth is at 70 deg for A and 64 deg for B;
- Elongation angles from the tracks can be used to calculate propagation direction and radial distances.



# 3, Geometric Triangulation

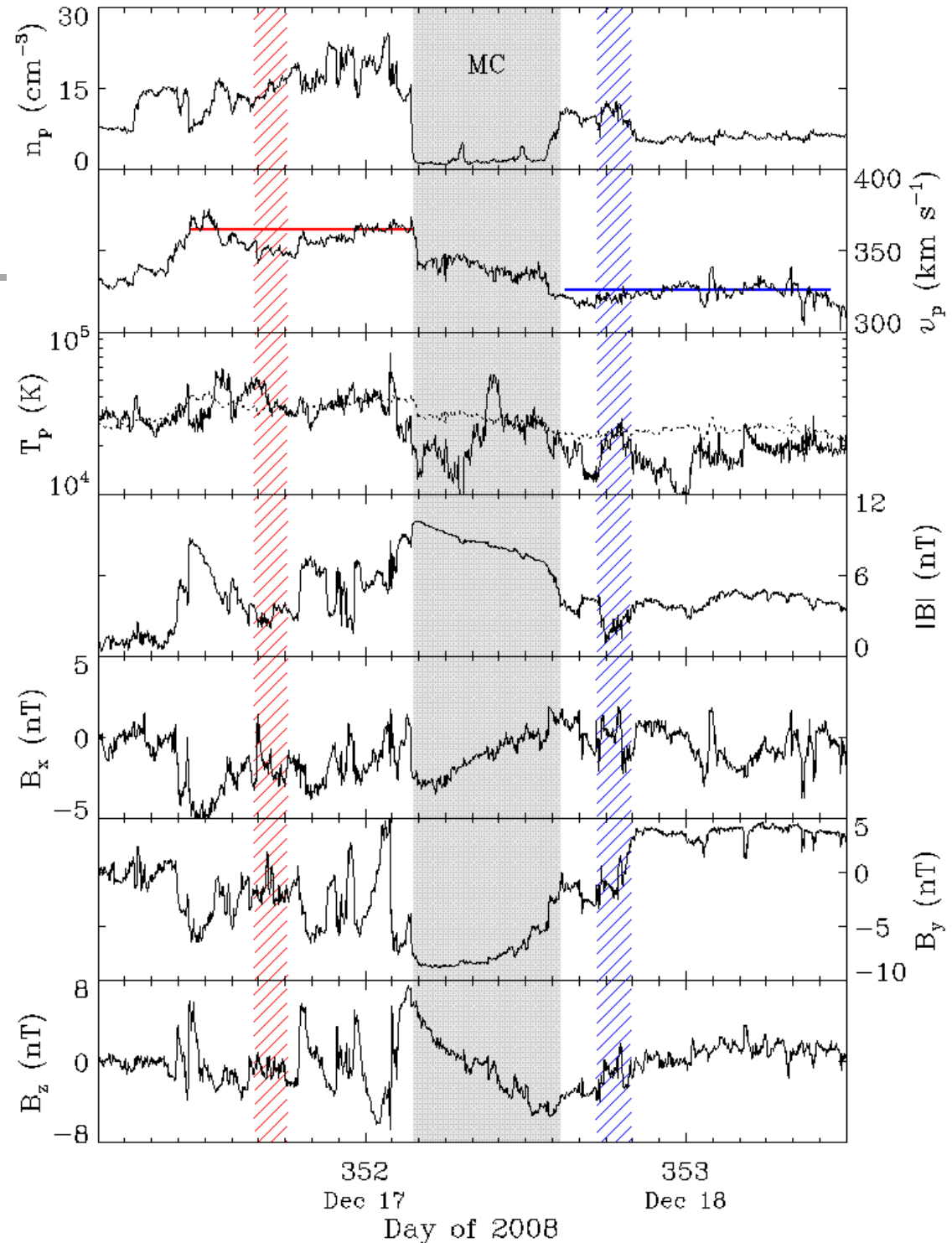
- Propagation direction shows a small variation but is generally within 5 deg of the Sun-Earth line, so the CME will impact Earth;
- The features can be continuously tracked up to 150 solar radii (without projection);
- Radial velocity also shows a variation with distance and is about 363 km/s for feature 1 and 326 km/s for feature 2 close to Earth.

Note: no model fit is used, so the solution is unique!



# 3, Geometric Triangulation

- A magnetic cloud is observed at Earth;
- Predicted arrival times of features 1 and 2 (hatched area) bracket the MC and are coincident with enhanced density regions;
- Predicted radial velocities are also well confirmed by in situ measurements.





# Conclusions

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- Frequency drift of type II bursts can be used to track CME-driven shocks, but in situ measurements is needed to constrain the frequency drift;
- CMEs/shocks can also be tracked by MHD propagation of observed solar wind disturbances, indicating a technique to predict the arrival time of solar storms at Earth when in situ measurements closer to the Sun are available (say, from Solar Orbiter and Sentinels);
- Geometric triangulation of imaging observations can track CMEs remarkably well all the way out to 1 AU (both propagation direction and radial distance);
- Combination of these techniques indicates a coming era when space weather forecasting can be made in real time and with small ambiguities!