Preparing for the Future of Heliospheric Observations

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MOTIVATION

- CME research has undoubtedly progressed in the STEREO era, especially in the heliosphere
- As we transition from cycle 24 to cycle 25, its a good time to take stock of the progress we made and consider what we can do in the future
- Will the tools we developed in cycle 24 continue to be useful? How much more information can we get out of our current data?

OPEN QUESTIONS

- What is a CME? Can we quantitatively define a CME?
- Are all CMEs fundamentally the same? Can we model them all with the same general framework?
- Does a CME maintain its structural coherence as it propagates? How much does the flux rope erode or degrade?
- Where does the CME pile-up mass and is this observable?
- How do the interactions between CMEs work?
- What is the exact nature of the coupling between driver and shock?

OUTLINE

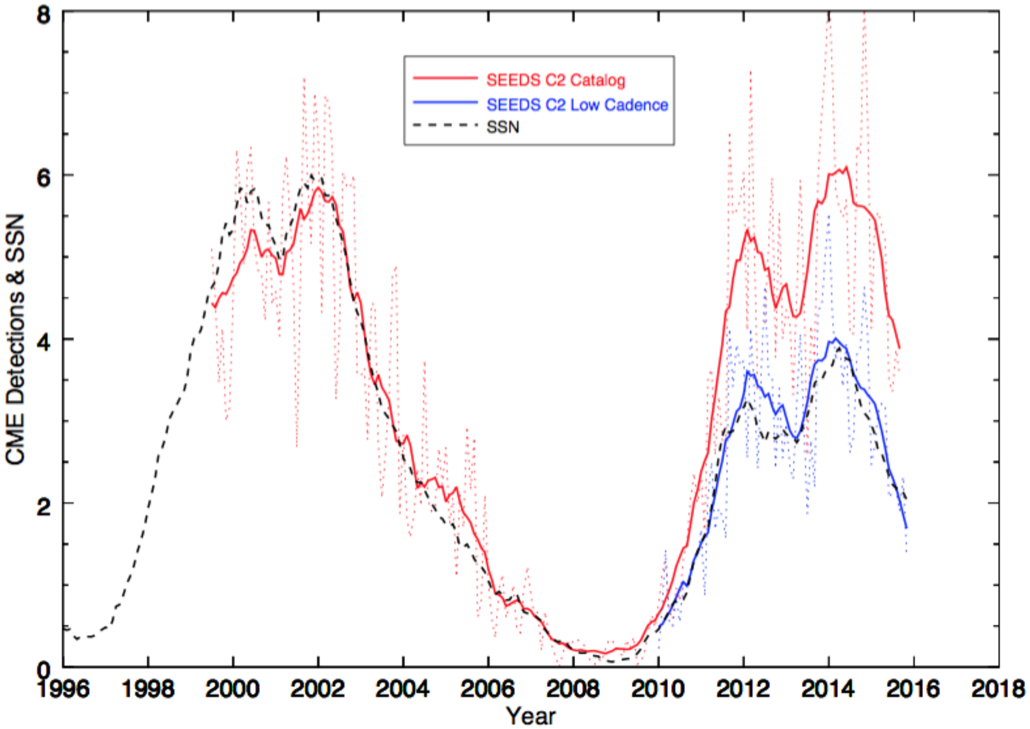
- The coverage of remote sensing data in solar cycle 25
- The limitations of projection effects
- GCS Model
- Propagation Models

DATA IN CYCLE 25

- With the combination of STEREO and SDO, Solar Cycle 24 provided unprecedented remote sensing coverage of the heliosphere
- Multiple viewpoints, extending from the low corona to beyond 1 A.U. allowed for the better imaging of CMEs than ever before
- The upcoming solar cycle will feature far less optimal data availability
- How will this impact our ability to measure CMEs in the heliosphere?

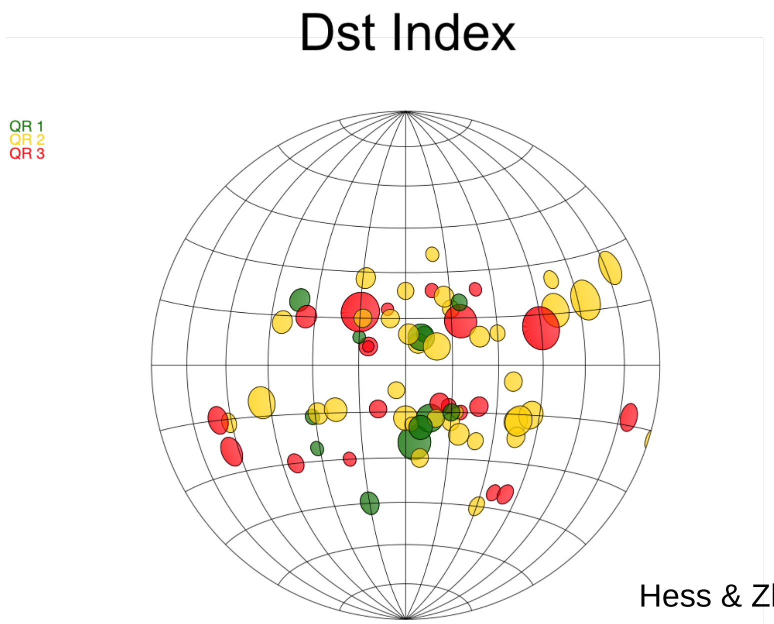
CME FREQUENCY

- Most predictions for cycle 25 show a weaker cycle, similar to cycle 24
- We will likely continue to have relatively fewer events to study
- CME rates are still, despite some arguement, well-correlated with sunspot number (Hess & Colaninno 2017)



CMES IN CYCLE 24

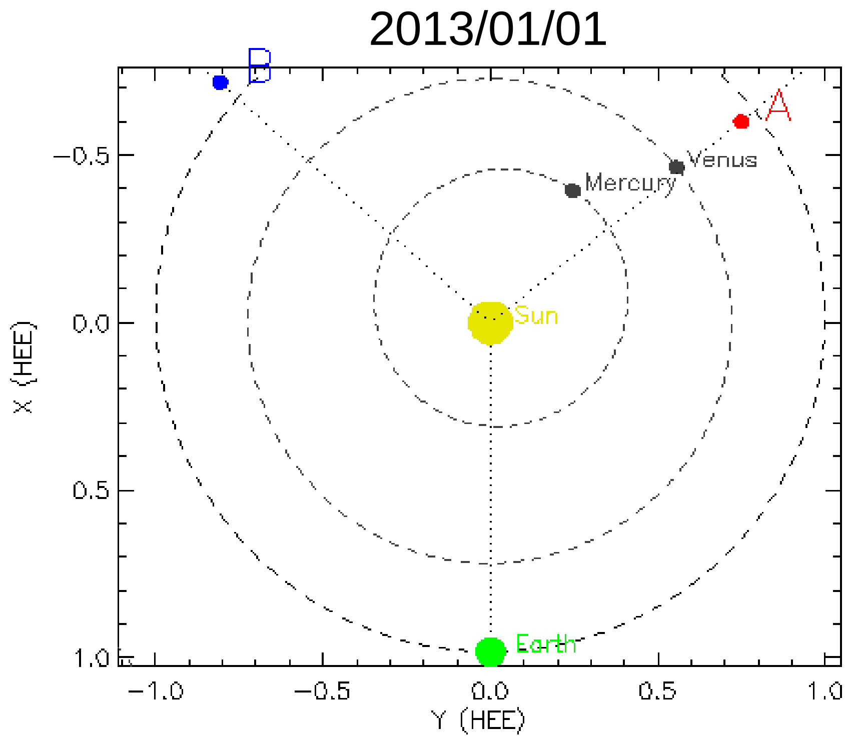
- Despite the weaker solar cycle, there were still a number of strong with noticeable geomagnetic effects

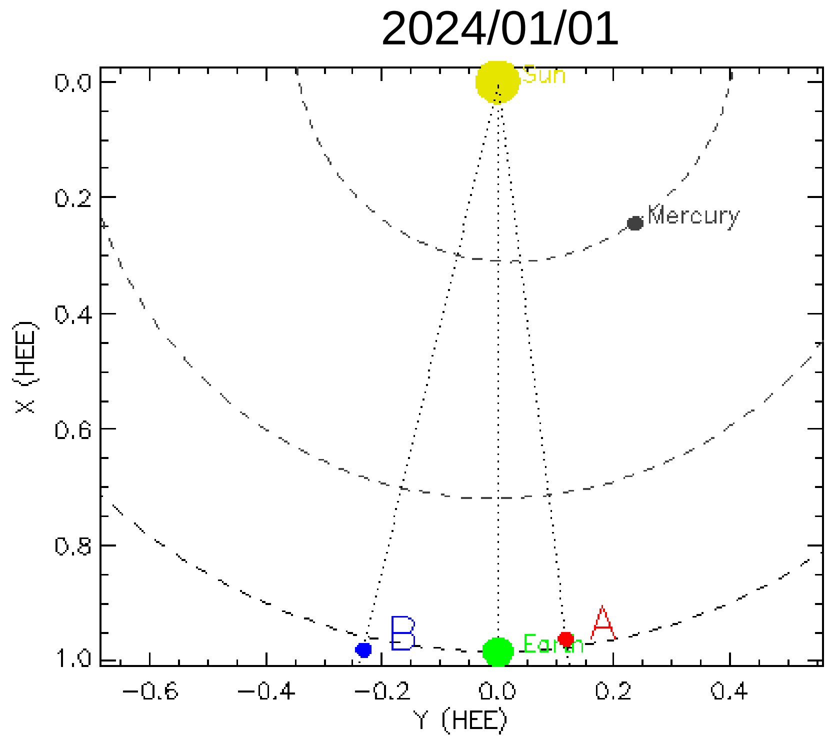


Hess & Zhang (2017)

	Events	Shocks	TT	In-Situ Speed	Transit Speed	CDAW Speed	CDAW Width	|B|	QR
All	70	45	80	400	500	655	258	10.6	2.13
Dst > -40 nT	23	11	90	392	461	549	226	8.3	2.30
-100 nT < Dst < -40 nT	35	21	82	427	492	631	256	10.6	2.09
Dst < -100 nT	12	12	58	460	599	965	331	13.3	1.92

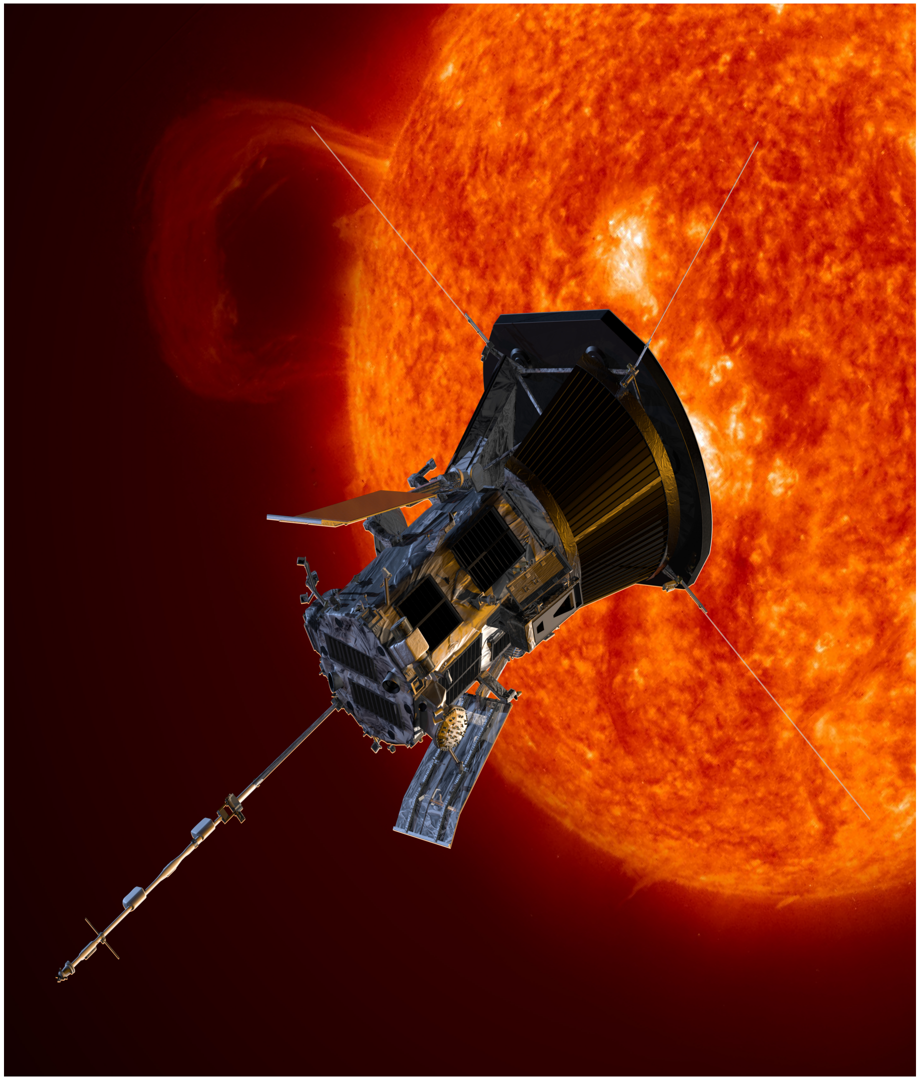
DATA IN SC24 VS SC25





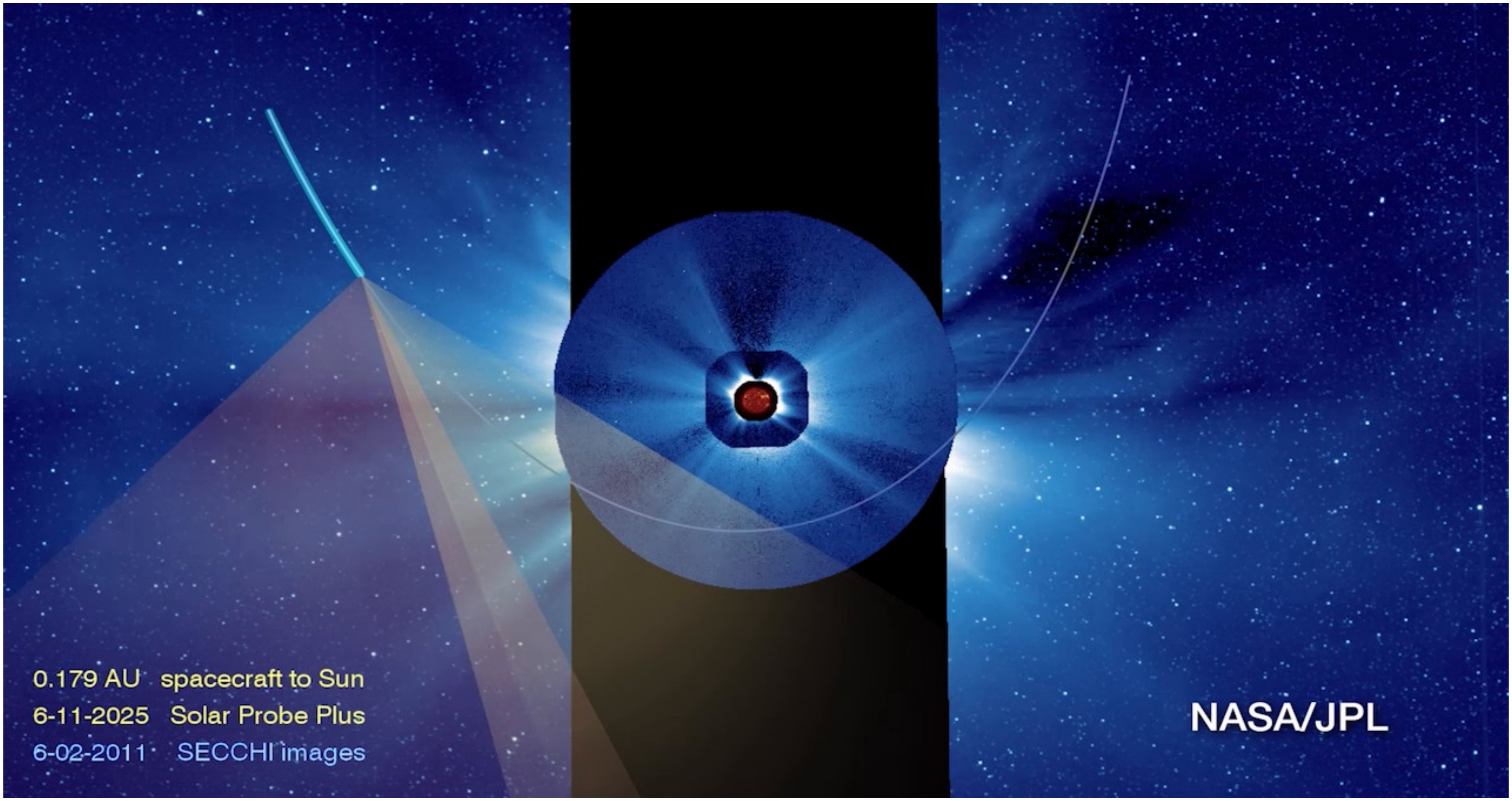
- With the configuration of STEREO, there will be issues of uniqueness, line of sight effects, and SEP impacts

UPCOMING MISSIONS


Credit: NASA/Johns Hopkins APL/Steve Gribben

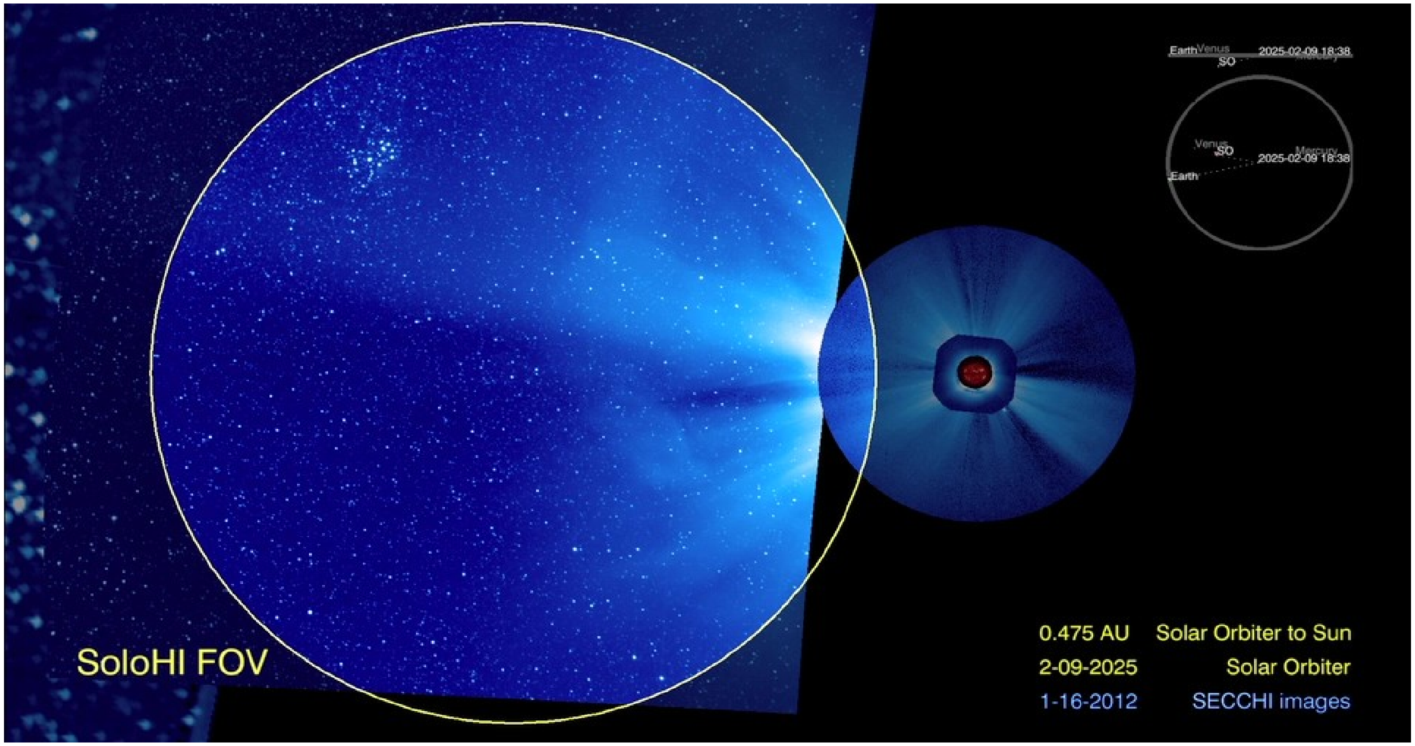
- PSP and Solar Orbiter are going to be extremely illuminating missions for solar and heliophysics
- However, these are encounter missions that will not provide a synoptic viewpoint of CMEs that lends itself to statistical studies
- Much of the WISPR data from PSP will be taken on the backside of the Sun, where any CME that is seen will likely not observed particularly well by any other satellite

PARKER SOLAR PROBE



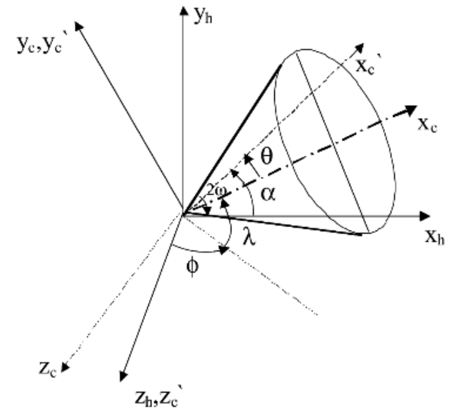
SOLAR ORBITER

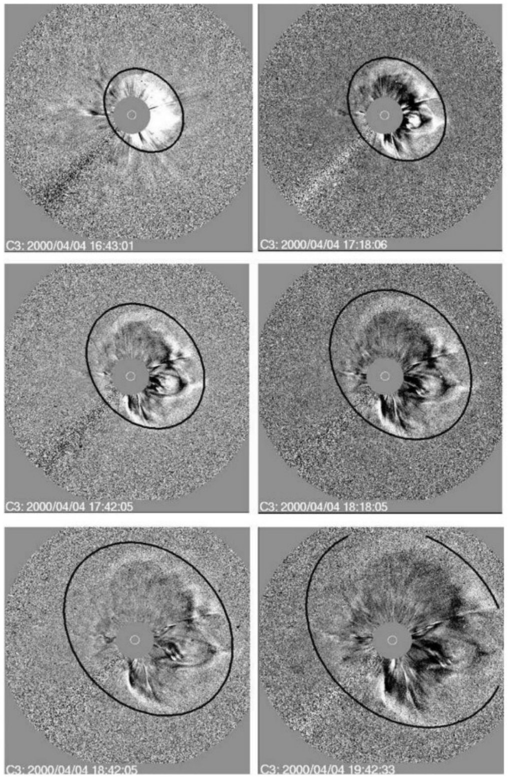
- The SoloHI instrument onboard Solar Orbiter has similar limitations, but does have the ability to provide an out of ecliptic constraint on the CME longitude



BACK TO CYCLE 23?

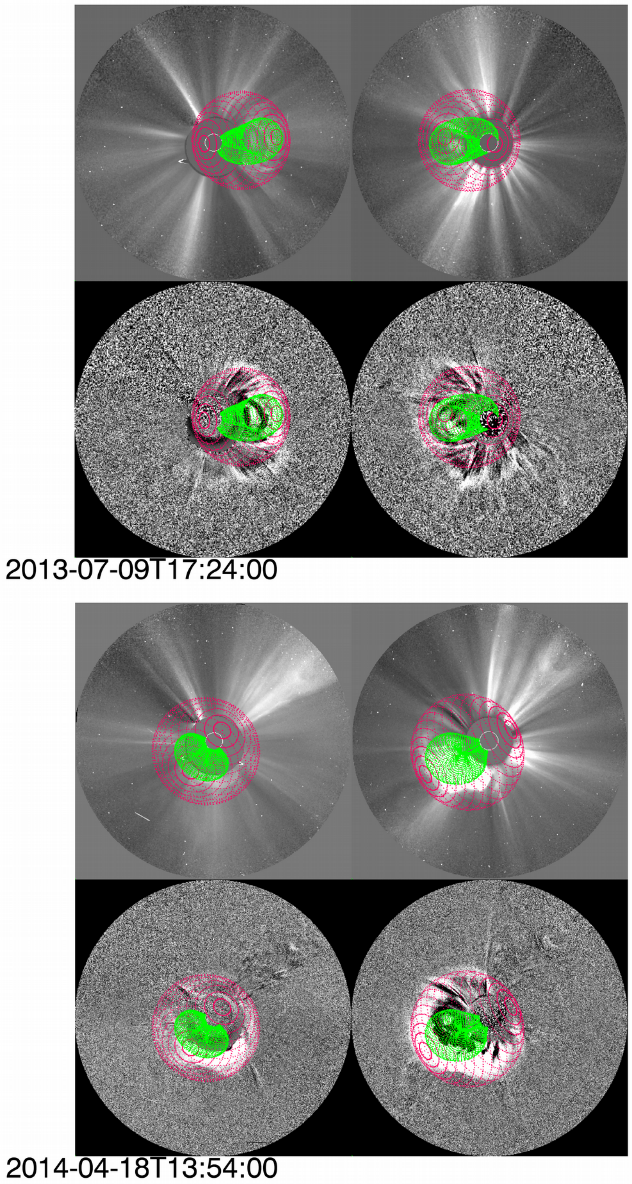
- In the pre-STEREO era, the cone model was widely used for deriving CME heights and speeds
- These are useful but limited by projection effects
- Separating shock from ejecta is very difficult
- For Earth directed CMEs, the lateral expansion of the shock is being measured, not the bulk motion of the ejecta
- Some studies have shown some ability to correlate single viewpoint models to multi-viewpoint results (Lee et al 2015)





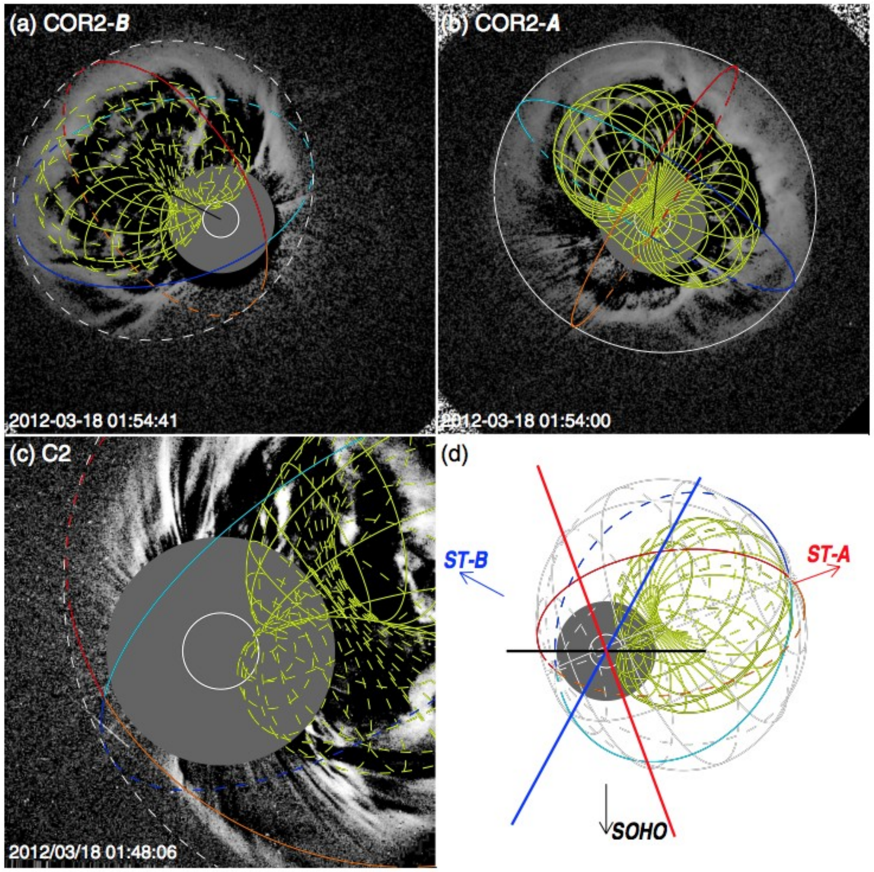
Xie et al 2004

HALO AMBIGUITY



- Halo CMEs are important
  - Geoeffectiveness
  - Best data coverage to compare with other instruments
  - Tend to be fast and powerful to drive shocks
- Observationally, the closer a CME is to the line of sight, the harder it is to observe
- Based on the SC 25 positioning of satellites, most LASCO halos will also be at least partial halos in SECCHI, so they will not be ideally observed by any satellite

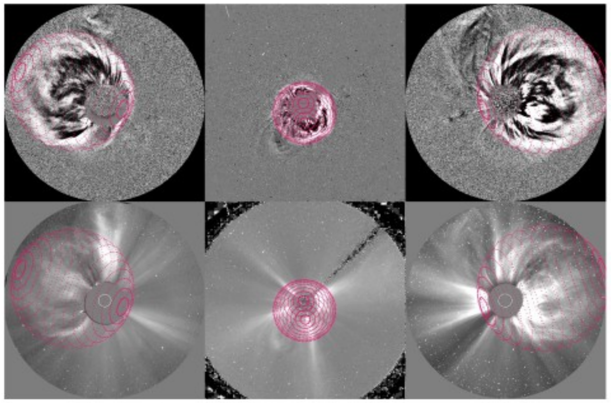
PROGRESS ON SHOCKS



Kwon et al 2015

- Fortunately, we do still have the knowledge that was gained in the STEREO era
- The relationship between halo CMEs and shocks (Kwon et al 2015) is better understood
- Observations have linked shock signatures from EUV, white light and in-situ data

SHOCKS



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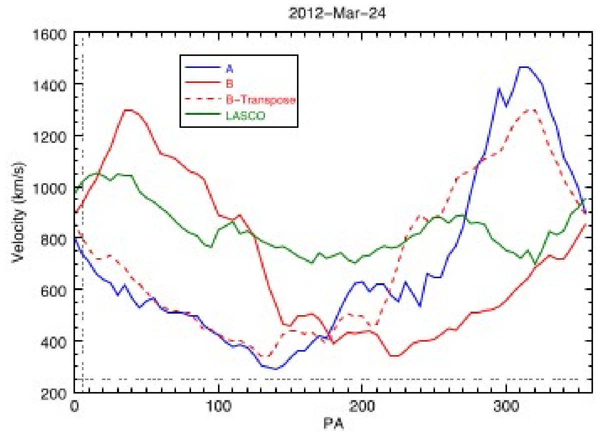
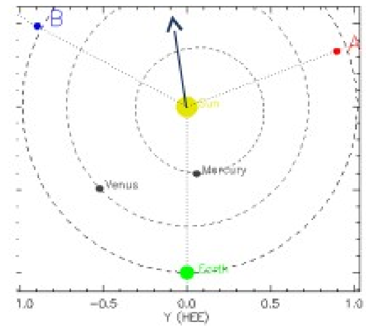
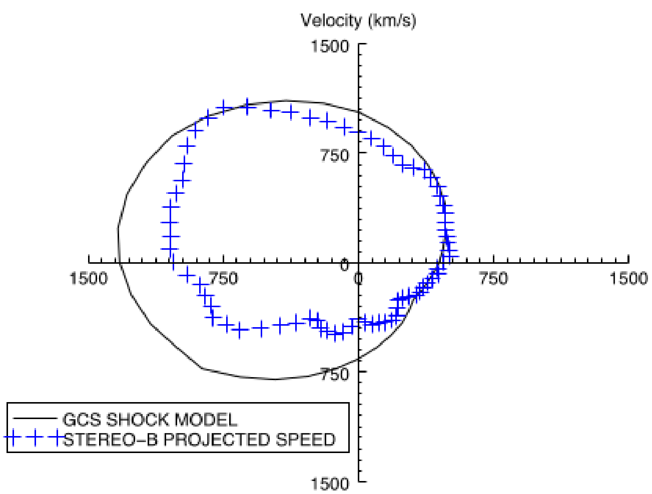
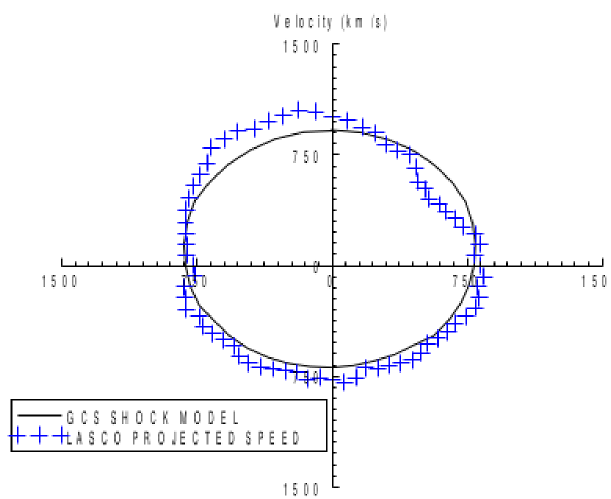
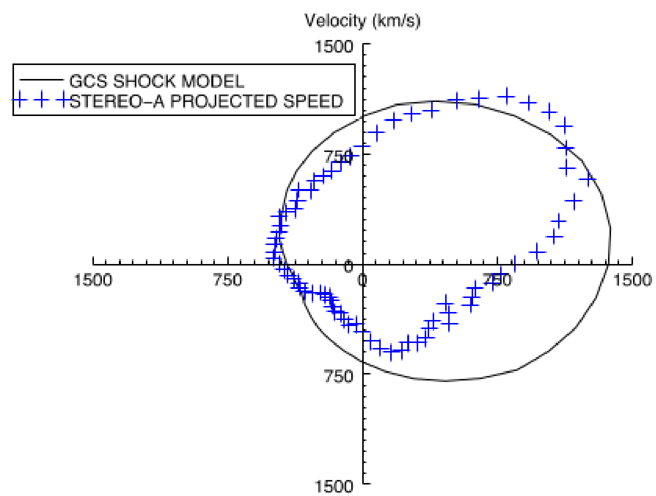






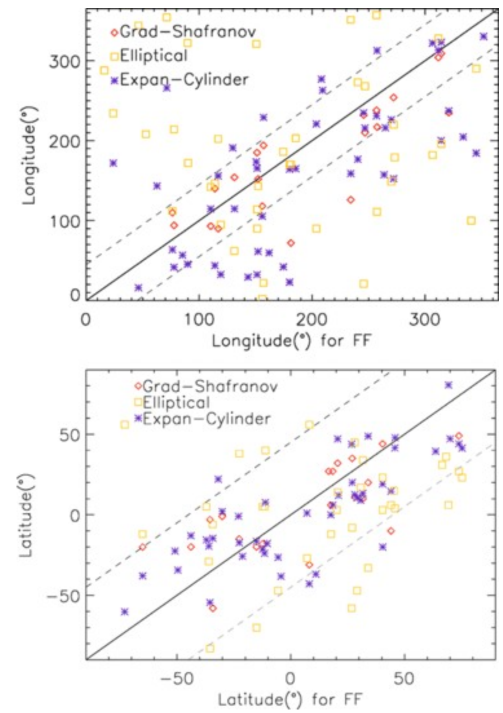




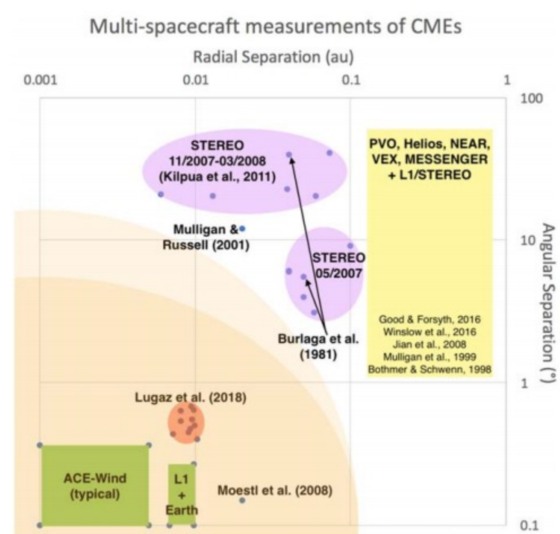
- The spheroid geometry is effective in the low corona, but when the ejecta radial speed >> lateral expansion, the wave loses its symmetry

IN-SITU RECONSTRUCTIONS

- Since Burlaga et al (1981) identified in-situ magnetic clouds, flux rope geometries have been fit to in-situ events to determine the structure
- However, Al-Haddad et al (2013) demonstrated the wide discrepancies between different techniques
- Lugaz et al (2018) found significant differences in orientations for spacecraft separated by very small differences
- Unlike the last time the STEREO satellites were positioned near L1, this will be closer to maximum so there should be many more events to test the coherence of CMEs across small distances



Al-Haddad et al 2013



Lugaz et al 2018

WHAT'S NEXT

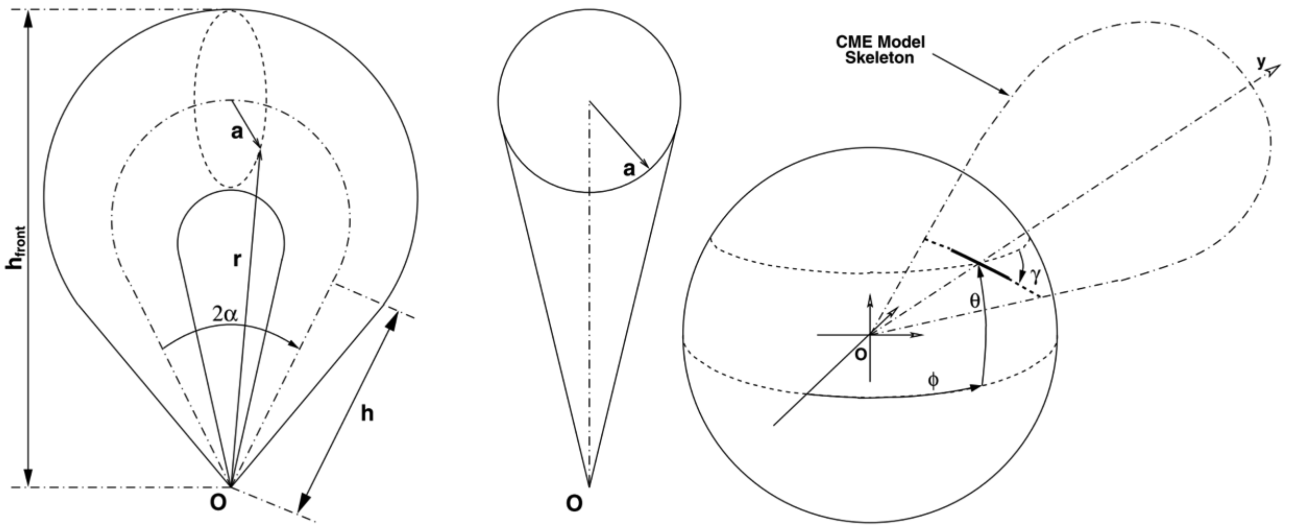
- Based on the knowledge gained in SC 24, forecasting should remain reasonably accurate

- Beyond operations, there are two ways we can hope to improve our fundamental understanding of CMEs
  - Get better data
  - Find new ways to get information from the data we already have

- Can we do more with the events of cycle 24?

CME RECONSTRUCTION

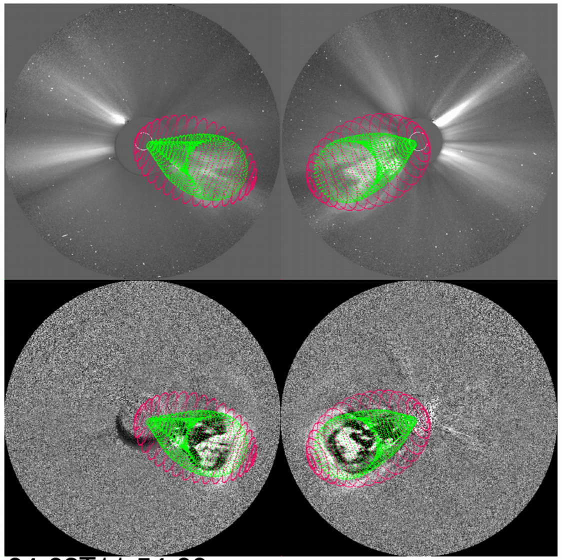
- 3D reconstruction techniques are commonly used to approximate the geometry and propagation of a CME
- A commonly used reconstruction technique is the Graduated Cylindrical Shell (GCS) model for the ejecta but many other similar models exist



(a) (b) (c)

Thernisien et al 2009

GCS EXAMPLES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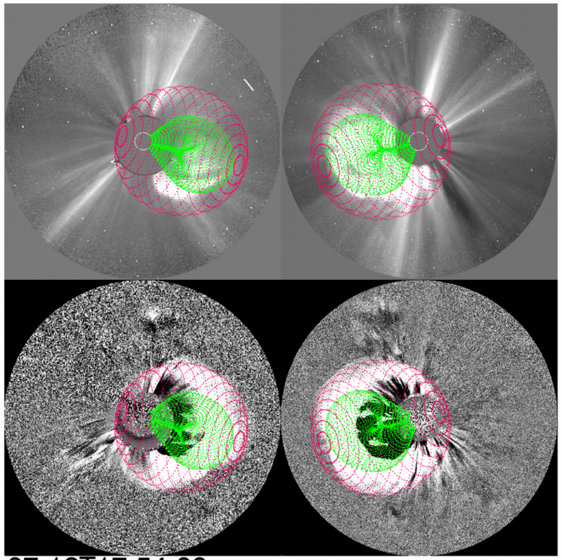
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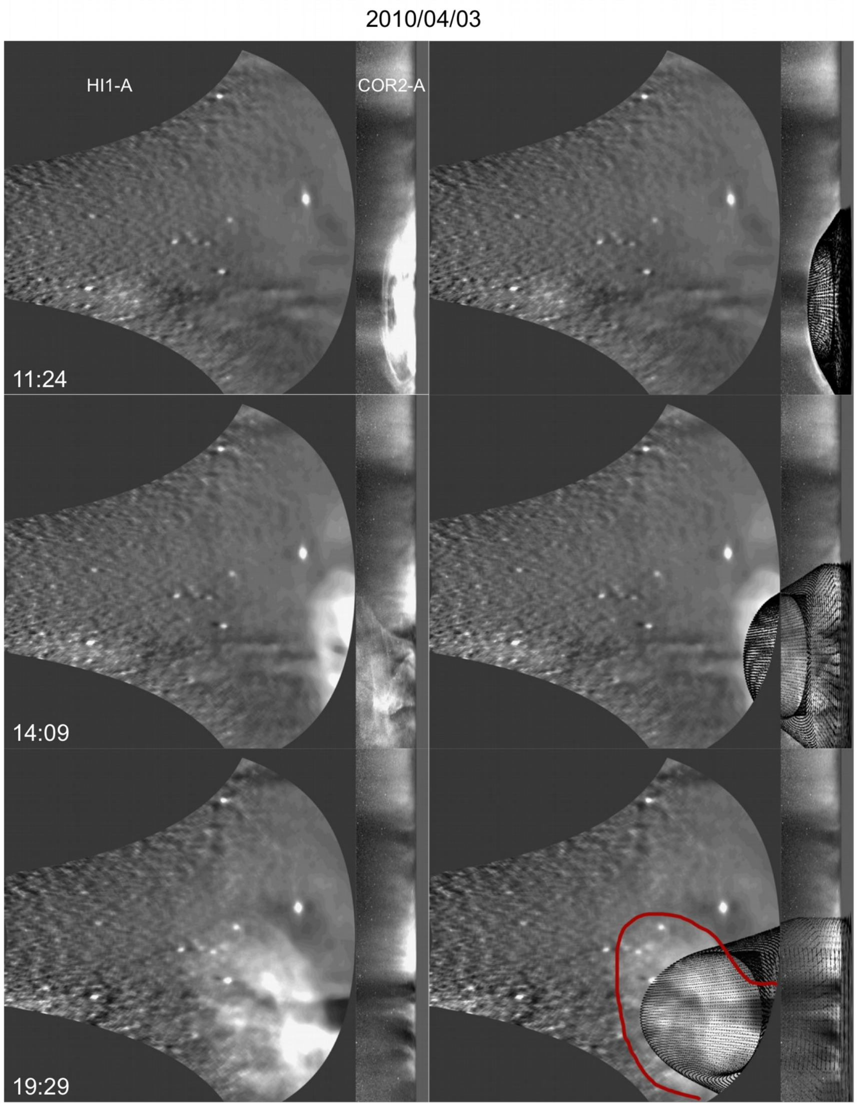
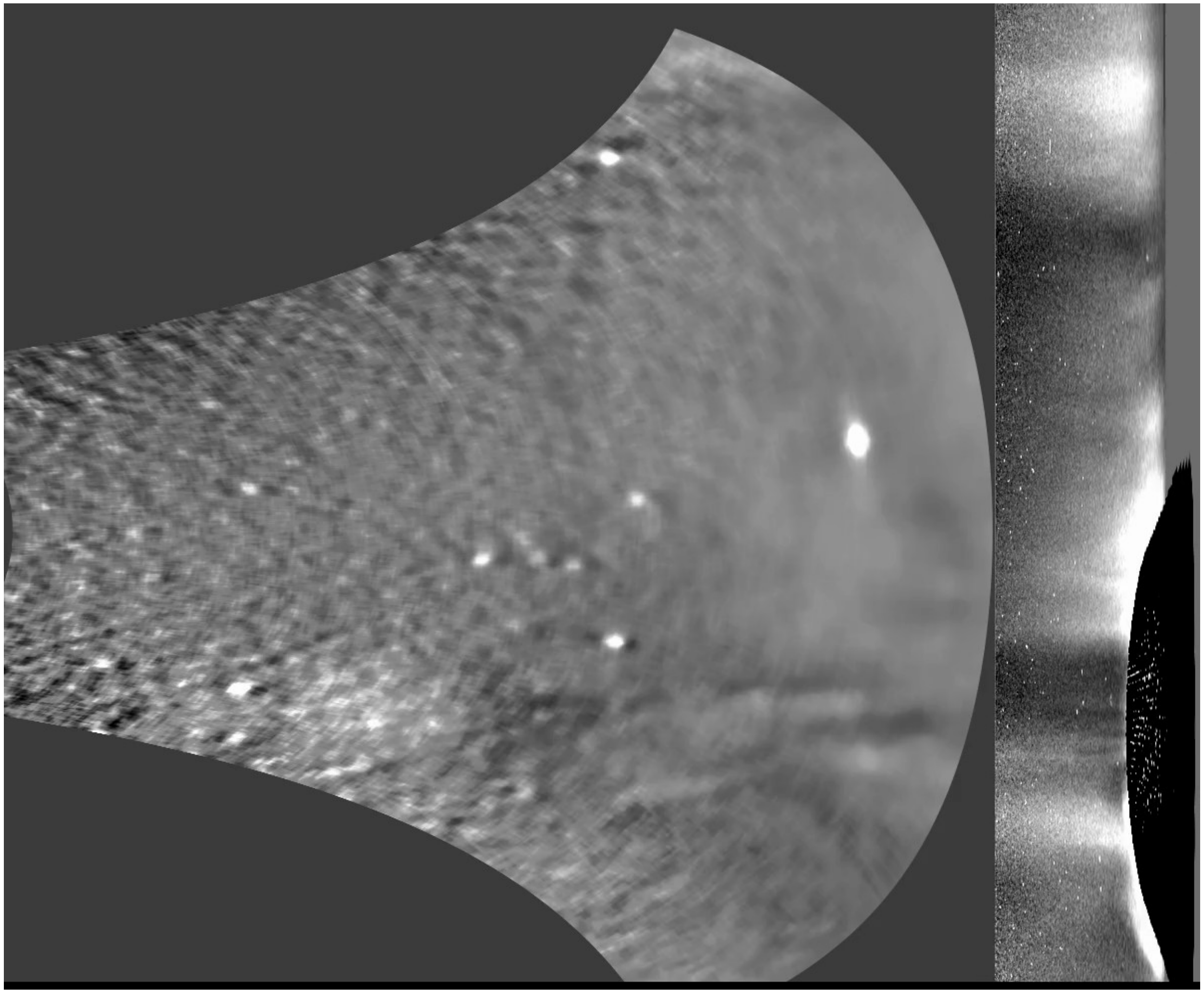
- **GCS fittings are not measurements**
- These models depend entirely on the ability to compare the geometry of the same event observed from multiple viewpoints
- At least two viewpoints are needed for this, and the fittings are far less ambiguous if the CME is propagating close to the plane of the sky of one

GCS LIMITATIONS

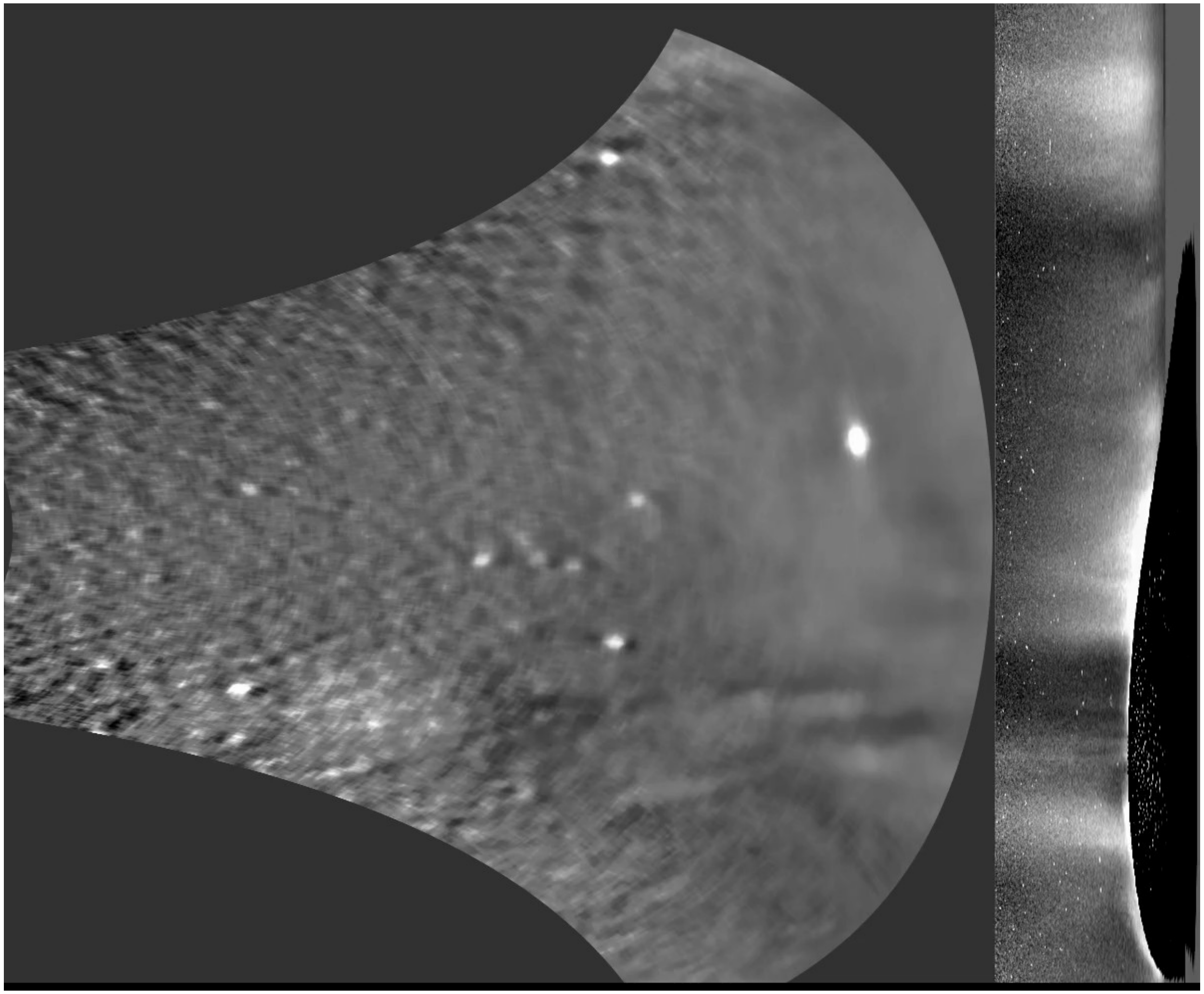
- The GCS model imposes a strict, inflexible structure on the data defined by assumptions
- Without having any sort of ground truth with which to compare a fitting it is impossible quantify its accuracy
- These models are geometric descriptions that largely ignore physical processes for the sake of consistency
- Keep the structure too rigid and small-scale changes to a CME are ignored; too much and the data is over-constrained, rendering the obtained heights useless



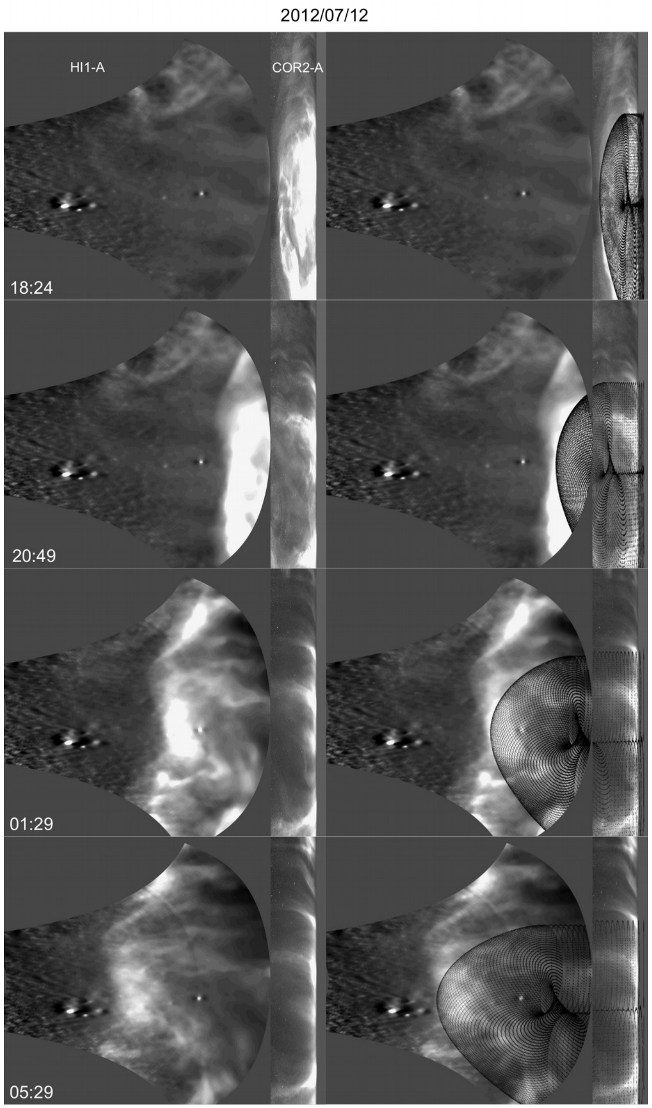
GCS LIMITATIONS



GCS LIMITATIONS

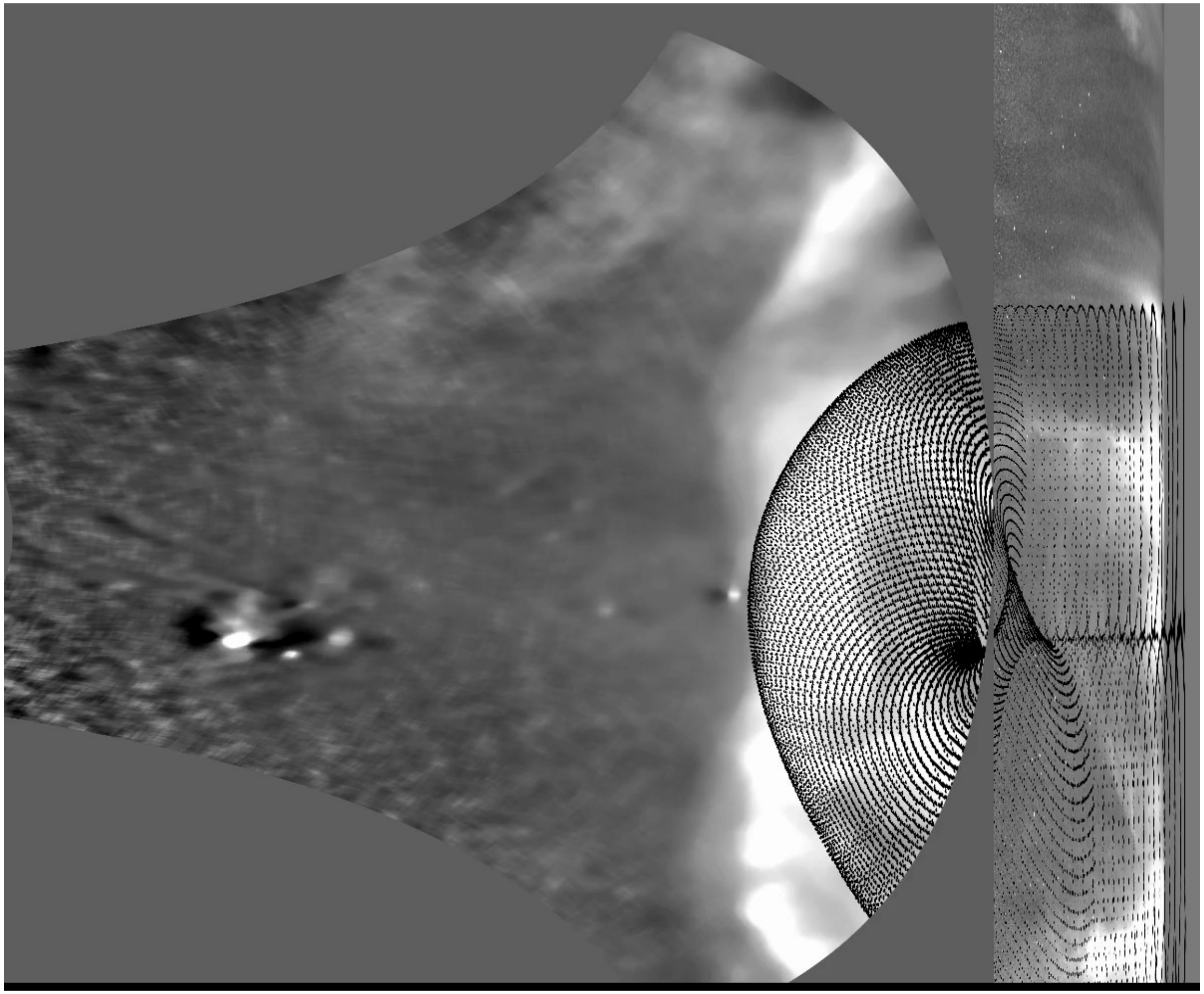


IDENTIFYING THE EJECTA

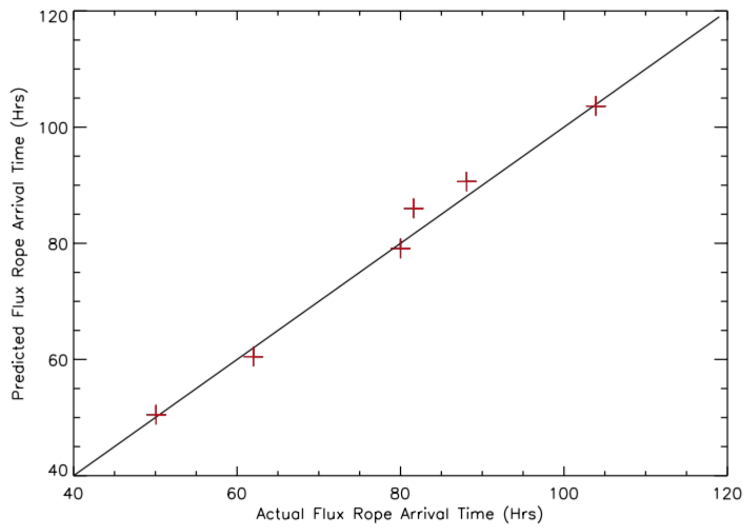


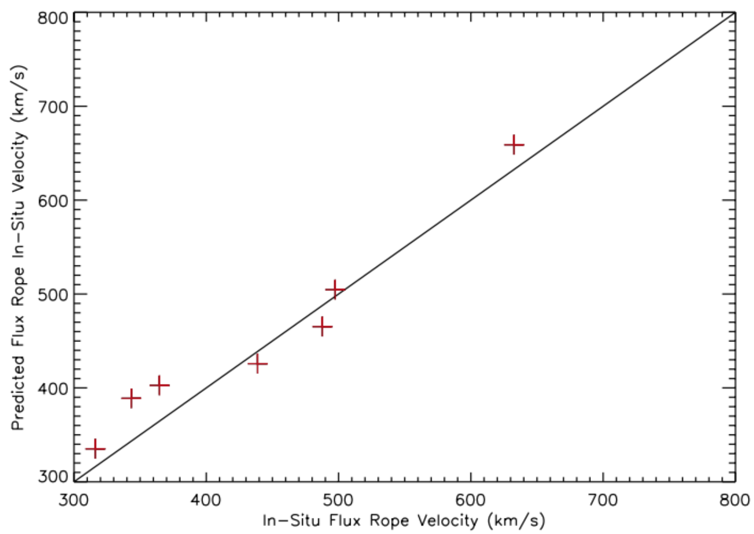
- Running difference techniques can be used to identify shocks, but wash out too much of the ejecta
- In a COR2 base difference, the ejecta is identifiably brighter than the sheath
- Inevitably in the HI-1 FOV, the ejecta will expand and dim and be indistinguishable from the sheath, rendering the GCS useless

IDENTIFYING THE EJECTA



DO THESE LIMITATIONS MATTER?





Hess & Zhang 2015

- GCS model has been shown by many studies to effectively estimate CME geometry
- GCS model has successfully been used to provide inputs into models that have been able to reconstruct the heights and speeds of CME events
- This approach likely is sufficient for forecasting arrival times within ~10 hrs
- Without adding in more complexity, how much better can we make these models? Have we already approached the point of diminishing returns?

THE FUTURE OF THE GCS MODEL

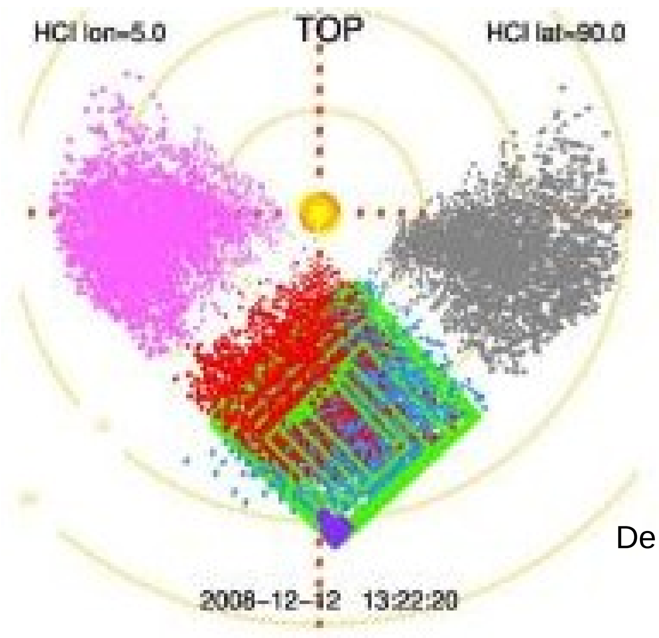
- How effective will the model be without separate views ~90° apart?

- Even with optimal data, can we improve the model to make it more realistic without making it overly complicated?

- Will we ever develop a means of comparing and assessing fits performed by multiple observers?

GENERALIZED RECONSTRUCTIONS

- Utilizing STEREO spacecraft and determining mass that overlaps the observations of each, De Koning (2014) attempted to determine the mass distribution of a CME without imposing a strict structure
- This requires polarized data from multiple observers



De Koning 2014

PROPAGATION MODELS

- Propagation models operate under the same general framework depending on a peak initial speed, a solar wind speed and the relationship between the two
- The initial speed can be based on measurement
- Solar wind speed can be modeled/observed upstream
- The largest unknowns exist in the transition to v_{sw} and the momentum transfer between the CME and solar wind
- Most of this process occurs in HI1, where the ejecta is not well observed

RELATING THIS TO MODELS

- The most common means of estimating propagation reduce the CME to a rigid ballistic object propagating through a fluid
- This assumes that the CME maintains its internal structure as it propagates. If the CME expands non-uniformly, this assumption may break down
- The ambient medium into which the CME propagates can vary. How this will affect the momentum transfer is not well understood. This will definitely impact shocks.
- We can estimate the propagation based on statistical studies of large events, this can provide average propagation characteristics
- But we care the most about the abnormal events

CME PROPAGATION

- We are trying to understand a physically complex process in the heliosphere from 2 to 3 viewpoints
- We care about magnetic field but observe mass
- Have we gotten all there is to get out of STEREO? Are there physical gaps we can fill in without a significant increase in data coverage in the heliopshere

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CONCLUSIONS

- Solar Cycle 25 will almost assuredly have less optimal data for observing CMEs in the heliosphere
- We may be able to do rough approximations of similar techniques used in cycle 24, but this will likely not lead to any real, new insight. At best we will be treading water
- The only way to push our understanding of CMEs forward is to do more with the data we already have
- Better image processing, better models (both for structure and for propagation) can achieve this
- It is important to use the right tool for the right job
- The alignment of spacecraft should allow for a better understanding of CME coherence based on comparison of different in-situ signatures