



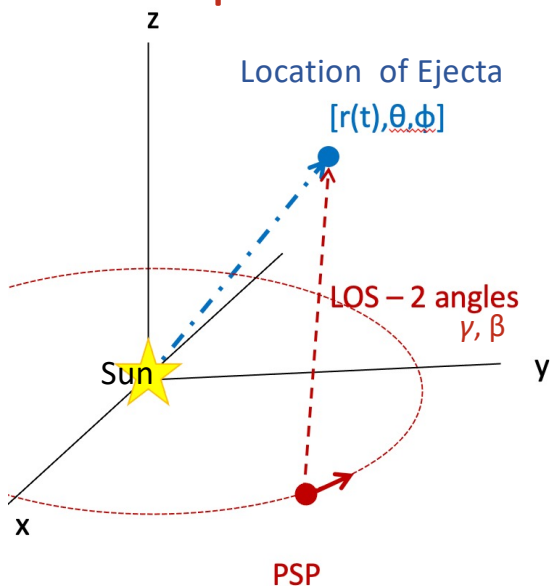
STEREO-A/SECCHI and PSP/WISPR Joint Observations of Solar Minimum CMEs



*P. Liewer, C. Braga, J. R. Hall, P. Hess, R. A. Howard, P. Penteado, J. Qiu, G. Stenborg,
STEREO Team Meeting, 18 January 2022*

- Tracking & Fitting Technique for determining the trajectories of solar eject from WISPR images that takes into account PSP's rapid motion
- CME from Orbit 2 (2019 Apr 2) – STEREO HI-1A data used to verify Tracking & Fitting Technique (*Liewer et al Sol Phys 2020*)
- Streamer Blowout CME from Orbit 4, 25-27 Jan 2020 (*Liewer et al A&A 2021*)
 - Used simultaneous ST/ HI-1A & PSP observation to triangulate to determine CME location
 - Unexpected evolution of magnetic flux rope captured by STA/EUVI – Is it the source?
- CME from Orbit 7 (20 Jan 2021)
 - Evolution of high latitude prominence eruption captured by STA EUVI, COR1, COR2
 - WISPR images suggest a nested flux rope structure of CME

Technique for Tracking & Fitting Ejecta for Trajectory Determination



- Ejecta's pixel location in an image defines a line-of-sight from PSP, described by two angles referenced to WISPR point-of-view
 - We use angles defined relative to PSP orbit plane – in & out of the plane - $\gamma(t)$, $\beta(t)$
 - Assume ejecta moves **radially at constant velocity** => ejecta's longitude and latitude are constant in the Heliocentric Inertia (HCI) frame
 - Derived 2 equations to relate ejecta's HCI coordinates $[r(t), \theta, \phi]$ to image coordinate angles $\gamma(t)$, $\beta(t)$
 - Developed a procedure for fitting measured $\gamma(t)$, $\beta(t)$, obtained from a sequence of images, to the 2 equations
-
- Manually track a feature in a sequence of images to obtain a set $[\gamma(t_i), \beta(t_i)]$
 - Fit the data to the 2 equations to determine the 4 unknown trajectory parameters: longitude, latitude, velocity, and radius (distance from the Sun) at the start of tracking.
 - Tracking & Fitting method described in *Liewer et al, Sol Phys 2020*

3D Trajectory of 2019 April 2 “Skull” CME ($PSP \cong 40 R_{sun}$)

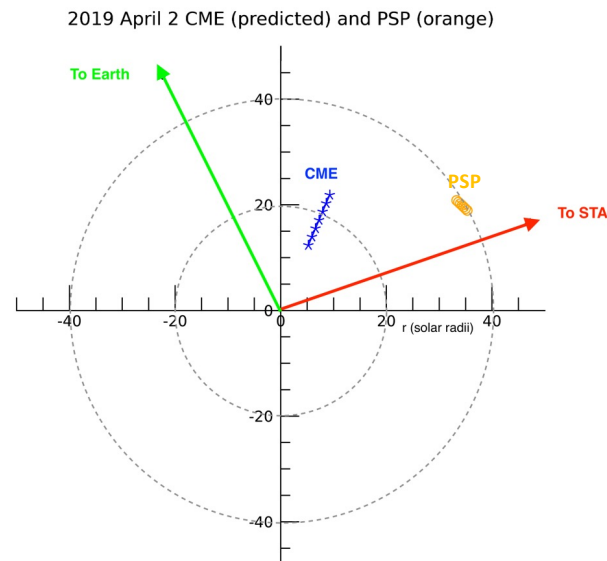
- From Tracking (Lower Eye) and Fitting, we determine the 3D trajectory of a CME feature (Lower Eye) in HCI coordinates (*Liewer et al, Sol Phys 2020*) :

HCI longitude = 66° ; Latitude = 6° , $V = 333 \text{ km/s}$; $R(0)/R_{sun} = 13.4$ @ $t_0=2019 \text{ Apr } 2 \text{ 12:09 UTC}$

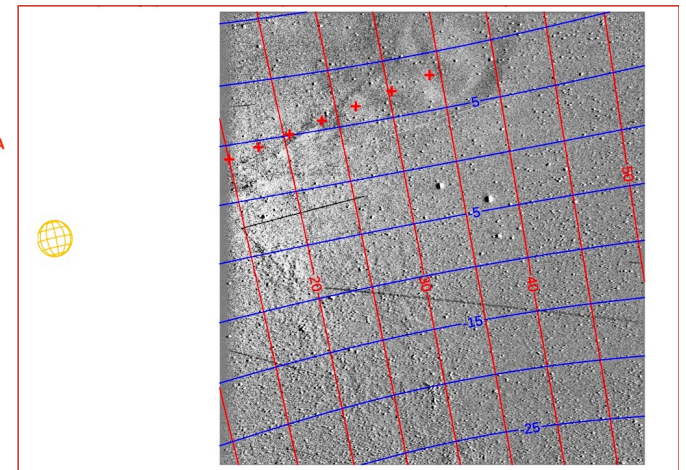
WISPR-I (r-difference)



Polar plot of 3D trajectory points
HCI coordinate system



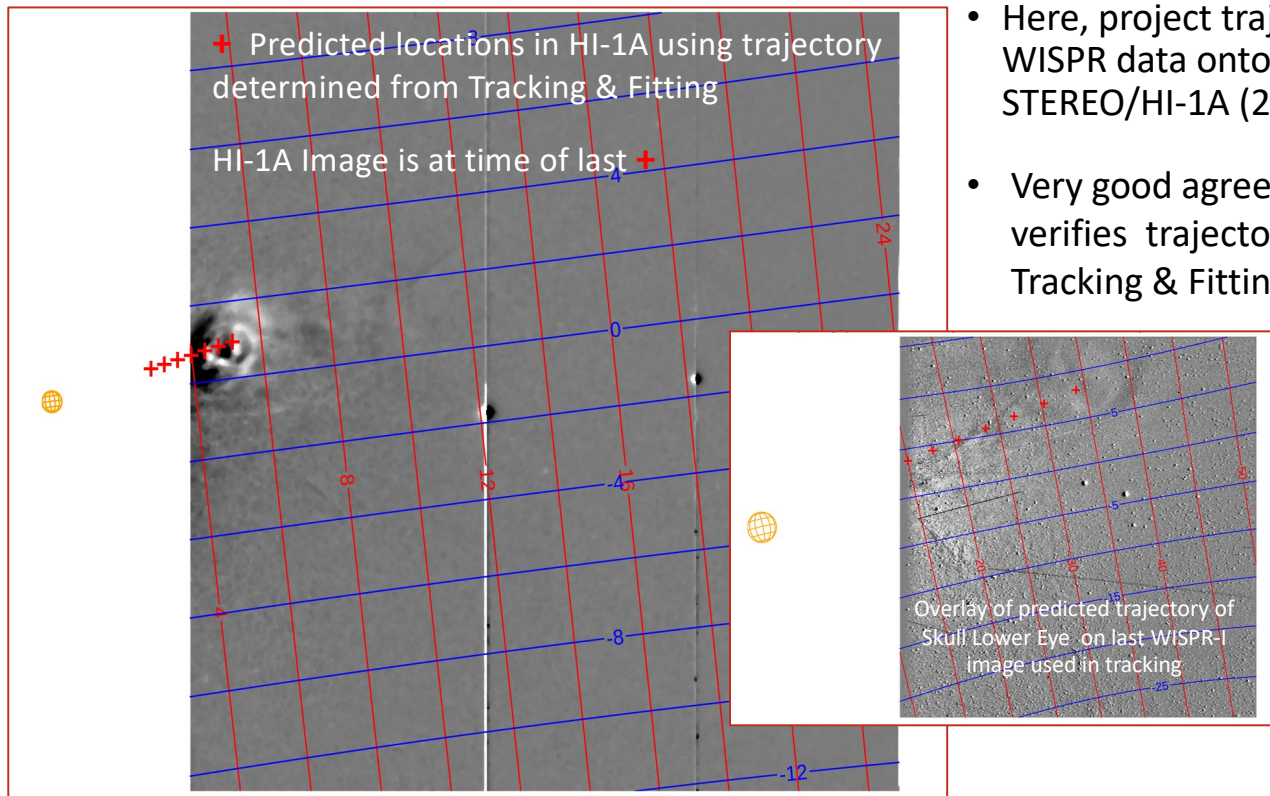
Overlay of predicted trajectory of Skull Lower Eye on last WISPR-I image used in tracking



- Can we use STEREO-A view of CME to verify trajectory?

Verify Tracking & Fitting Result using STEREO A Viewpoint

- Developed projection software to take 3D trajectory points $HCI(x, y, z)$ and re-projects them to proper location in image from another spacecraft using WCS information in FITS headers of the image

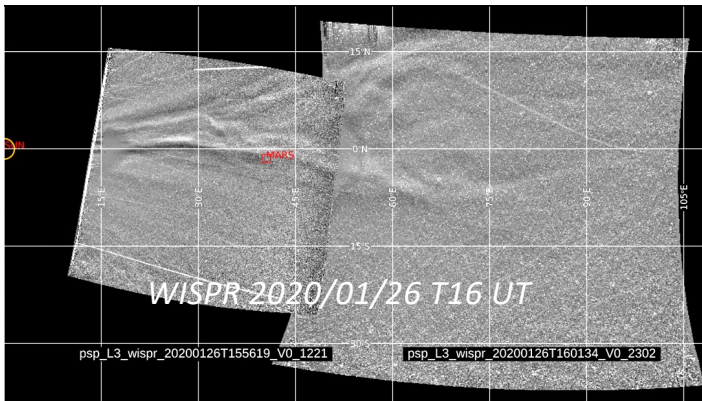


- Here, project trajectory determined from WISPR data onto simultaneous image from STEREO/HI-1A (2019-4-2 T18:09)
- Very good agreement with HI-1A view verifies trajectory determined from Tracking & Fitting

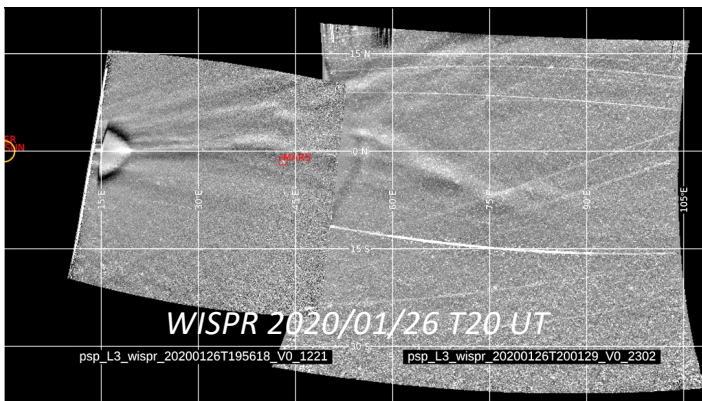
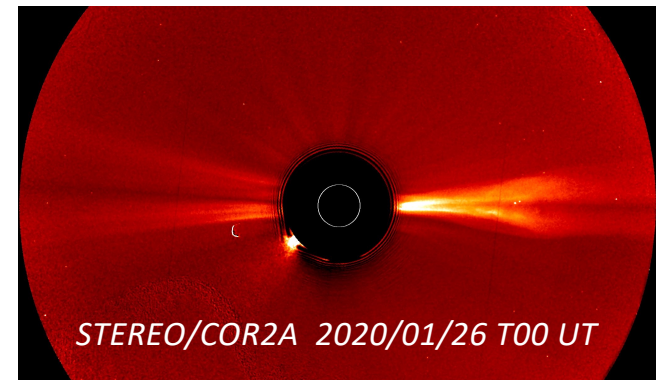
See also Wood et al (ApJ 2021) "Internal Structure of the 2019 April 2 CME"

Orbit 4: CME seen by STEREO A on 25 Jan 2020

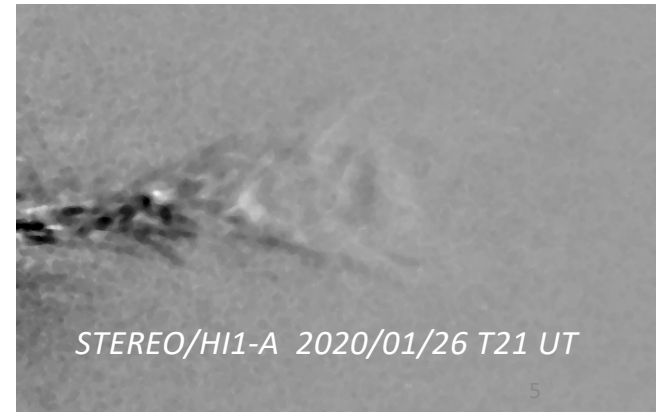
Identified as Streamer Blowout (SBO) CME - Cavity, with no bright leading edge, pushes streamer apart --- CME followed by streamer evacuation



- Both see only cavity – no bright leading edge
- Both see streamer pushed apart by CME cavity

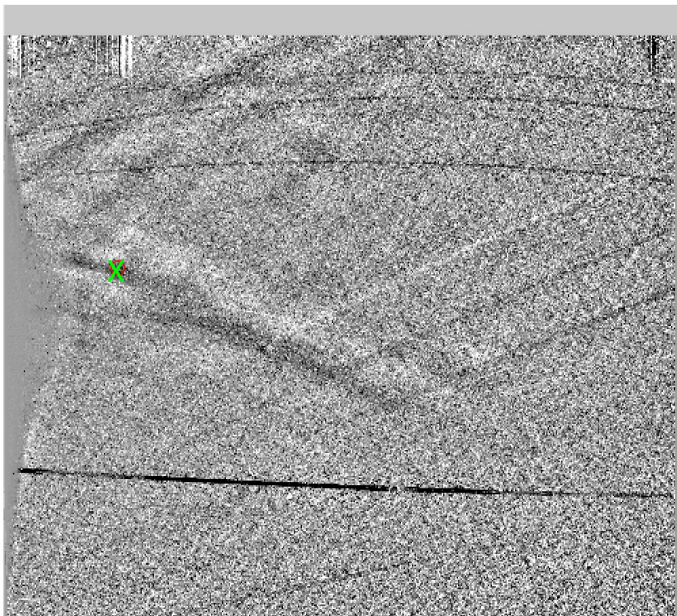


- CME shows similar V-shaped structure in HI-1A
- HI-1 shows more outflow behind CME
- STA/PSP Separation angle $\sim 50^\circ - 60^\circ$



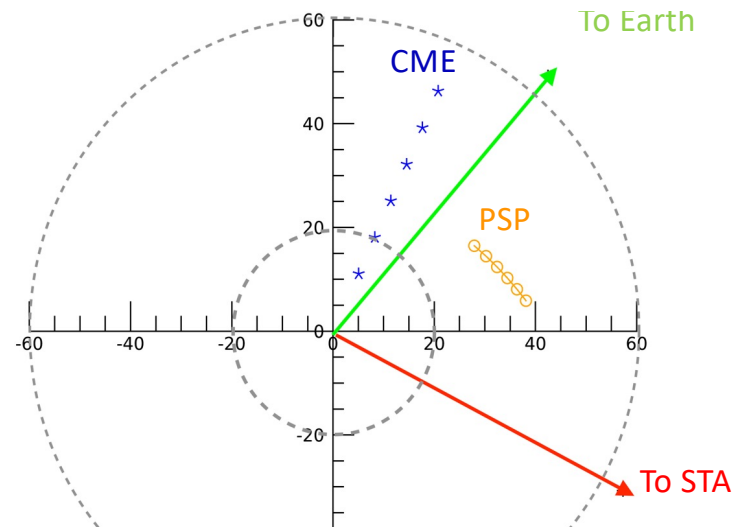
26-27 Jan 2020 CME Trajectory from Tracking & Fitting

- Here, tracked a dark spot at behind CME cavity in WISPR-O for 10 hrs
- T&F solution for trajectory in HCI coordinates: $(r, \theta, \phi) = (30 R_{\text{sun}}, 65^\circ, 2^\circ)$
 - *Recall, Tracking & Fitting assumes radial motion and a constant velocity*



WISPR-O rdiff image 2020 Jan 26 @ 20:49
PSP $\sim 30 R_{\text{sun}}$ from the Sun

Polar plot of Predicted Trajectory (*) & PSP locations (o)
Heliocentric Inertial frame – Radius in R_{sun}

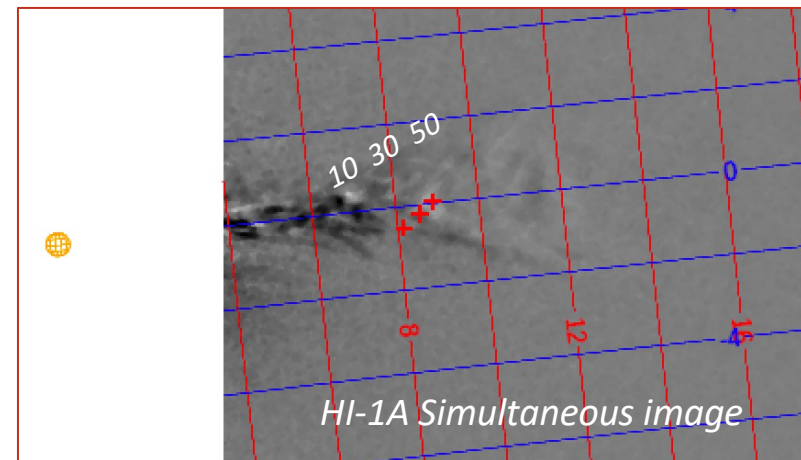
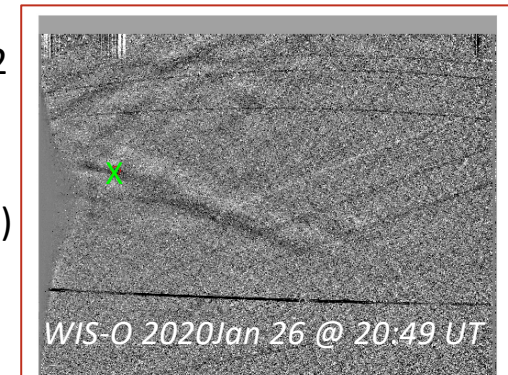


- *STEREO A also saw the CME – 50° separation*
- *Can we verify trajectory using STEREO A?*

Verify CME Trajectory by Triangulation between STA & WISPR

Used projection software to take 3D locations HCI (x, y, z) and re-project onto image from STEREO HI-1A using WCS information in FITS header

- Pixel **X** on CME 's Feature in WISPR image defines a LOS through space (2 angles)
- Feature can be anywhere along the LOS
- Choosing a distance R_{psp} from SC along LOS gives a 3D HCI location (x, y, z)
- Project onto simultaneous FITS image from HI1-A and iterate to find distance R_{psp} such that projected point falls on same feature
- **Right Image:** Location of WISPR feature X projected onto simultaneous HI-1A image for 3 distances R_{psp} from PSP: 10, 30 & 50 R_{sun}
- Point for $R_{\text{psp}} = 30$ falls near same feature in HI-1
- Iterating, found HCI coordinates (R, lon, lat) = $(31 \pm 2, 66^\circ \pm 3, -2^\circ \pm 2)$, in excellent agreement with trajectory found from Tracking & Fitting



Triangulation makes NO assumption about the motion, but limited by ability to identify same feature in both images

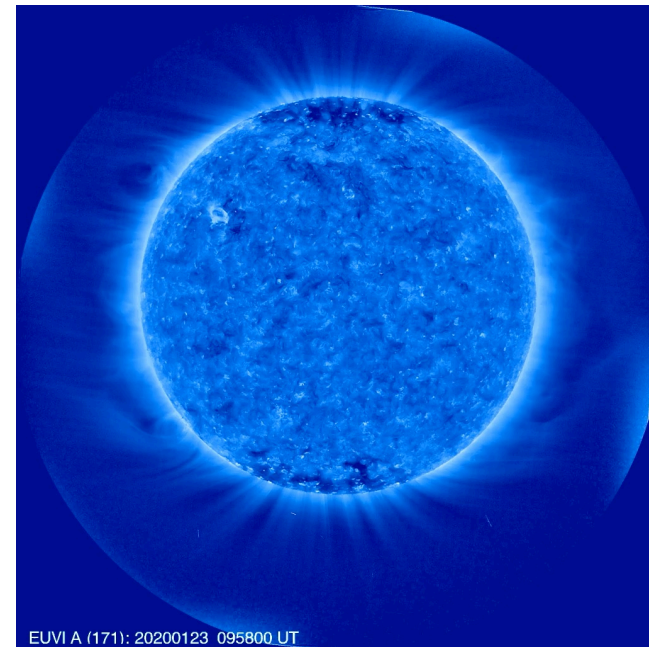
What was the source of 2020 Jan SBO CME?

STEREO-A Observations of Flux Rope Evolution

- EUVI 171 shows evidence of Flux Rope formation & rise 23 Jan 12-24 UT
- STA Data gap 24 Jan (pause in movie)
- Structure in same location leaves EUVI FOV 25 Jan ~6 UT.
- SBO CME seen in COR2A ~13 UT
- Exhaustive search of LASCO, WISPR shows no sign of ejection on 24 Jan
- Search of HI-1&2 for 25 Jan showed no suggestion of CME having left Sun on 24 Jan

Conclude:

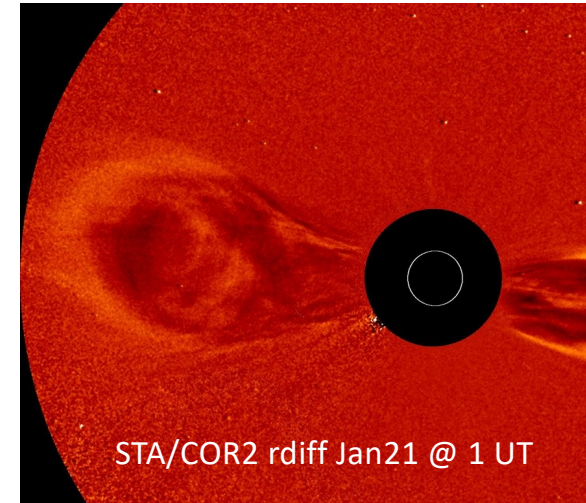
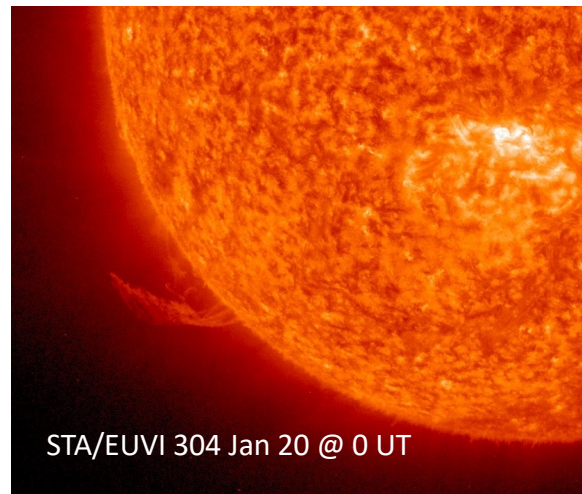
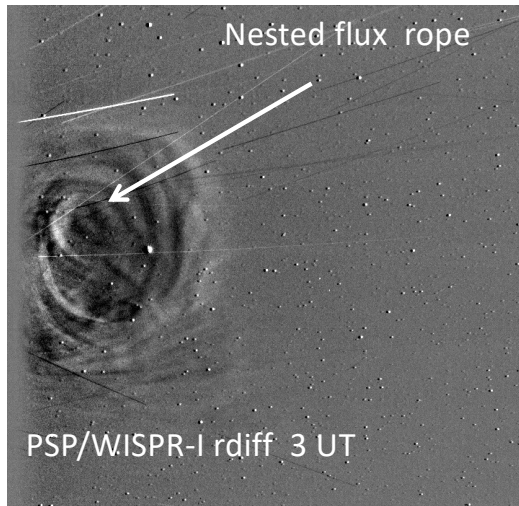
- CME source is flux rope constrained in corona from formation on Jan 23 to ejection on Jan 25
- Trajectory from Tracking & Fitting (verified with by Triangulation with HI-1A) give longitude inconsistent with alternative AR source – HCI longitude is 40° west of AR location on Jan 25 (*Liewer et al A&A 2021*)



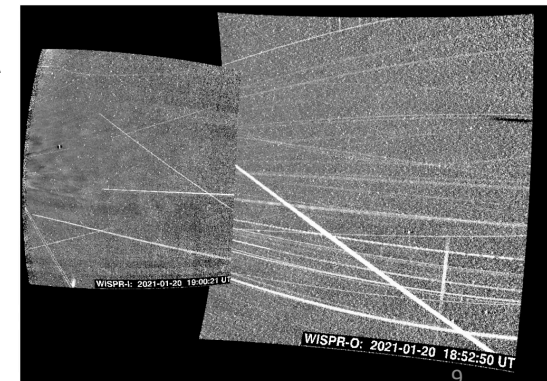
Watch here!



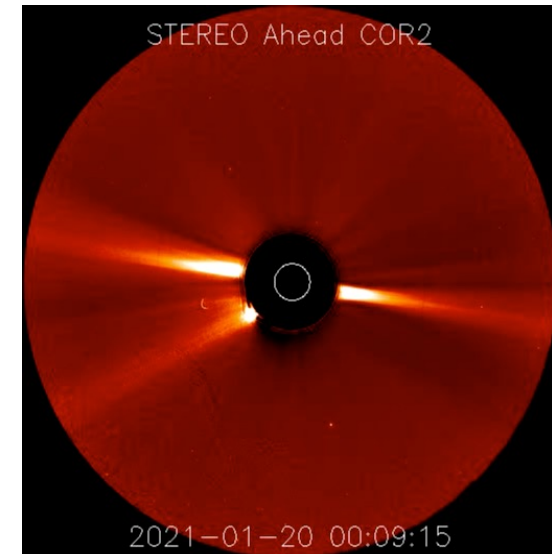
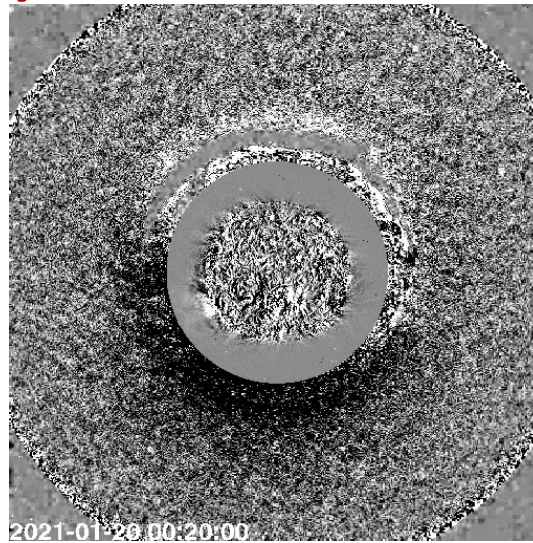
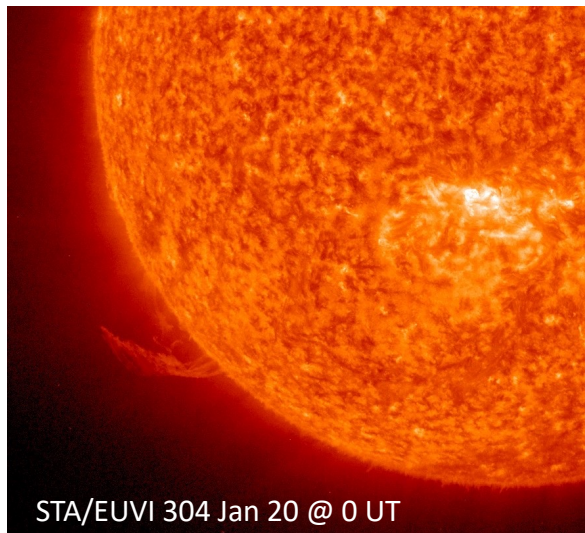
Orbit 7: 2021 January 20 Filament Eruption and CME seen by STEREO A PSP & STA Separated by 185°-- WISPR sees CME from opposite side



- Trajectory determination shows CME roughly midway between PSP and STA
- Both WISPR and COR2 show flux rope structure - WISPR shows more internal structure suggesting nested flux ropes (*Veronig et al 2018*)
- Is the “eye” the original flux rope seen bey STA/EUVI?
- Note: After leaves COR2A FOV, dramatic changes in shape of CME seen by WISPR (*Braga et al, in preparation*)



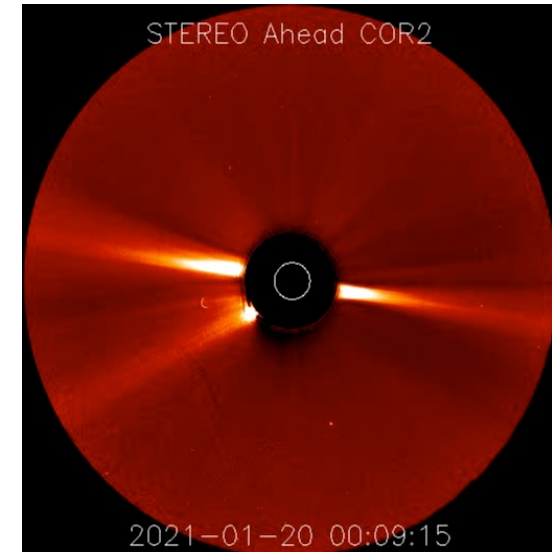
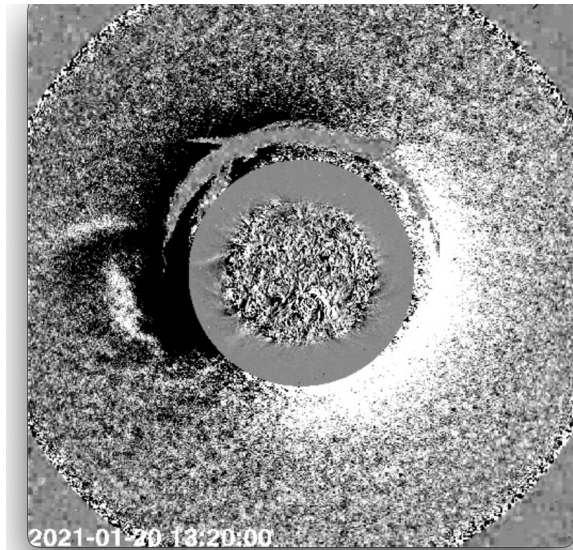
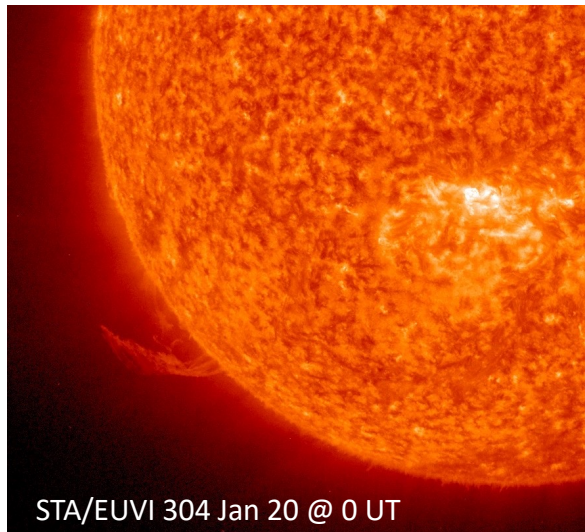
Orbit 7 2021 January 20 CME Evolution Seen by STEREO A



Composite by P. Hess

- Late 1/20 to early 1/21: EUVI 304 observes rise of prominence ~60 S just behind east limb
- 1/21 6-12 UT EUVI-COR1 movie shows cavity expanding asymmetrically to the north
 - Presumably, CME is guided to the HCS by the overlying magnetic fields (*Byrne, 2010; Liewer et al, 2015*)
- Jan 21 12UT Tip of cavity visible in COR2 slightly north of equator

Orbit 7 2021 January 20 CME Evolution Seen by STEREO A



- Late 1/20 to early 1/21: EUVI 304 observes rise of prominence ~60 S just behind east limb
- 1/21 6-12 UT EUVI-COR1 movie shows cavity expanding asymmetrically to the north
 - Presumably, CME is guided to the HCS by the overlying magnetic fields (*Byrne, 2010; Liewer et al, 2015*)
- Jan 21 12UT Tip of cavity visible in COR2 slightly north of equator



Joint PSP/WISPR and STA/SECCHI Observations of CMEs Summary & Conclusions



- Joint observations of 2010 Apr 2 CME: STEREO HI-1A data used to verify trajectory determination using WISPR data alone
 - New Tracking & Fitting Technique for determining the trajectories of solar eject needed because of effect of PSP's rapid motion on image analysis (*Liewer et al Sol Phys 2020*)
- Streamer Blowout CME 25-27Jan2020 (*Liewer et al A&A 2021*)
 - Used simultaneous STA/HI-1 & PSP observation to triangulate to determine CME location
 - Results Consistent with trajectory solution from Tracking & Fitting of WISPR data
 - From STA/EUVI 171, concluded that CME source is probably flux rope constrained in corona from formation on Jan 23 to ejection on Jan 25
- CME from Orbit 7 January 25-27, 2021
 - Evolution of from high latitude prominence to low latitude CME seen by SECCHI - EUVI, COR1&2
 - Cavity seen to expand asymmetrically as CME is guided to HCS by overlying magnetic field
 - WISPR images suggest a nested flux rope structure of CME