CME TRACKING and SPACE WEATHER FORECASTING with PUNCH

Dave Webb (co-leader PUNCH WG2A)

Contributers:

- **Huw Morgan** ***(Aberystwyth University, UK),*** **Kaine Bunting** ***(British Antarctic Survey, UK)***, **Nguyen Chien** ***(Univ. of Edinburgh, UK)***
- **Christian Moestl, Tanja Amerstorfer, Justin LeLouedec, Maike Bauer** ***(Austrian Space Weather Office)***
- **Arnault Thernisien** ***(NRL)***
- **Volker Bothmer** ***(University Göttingen's Inst. for Astrophysics and Geophysics)***
- **Bernard Jackson** ***(UCSD)***
- **Dusan Odstrcil** ***(NASA)***

- **Some techniques being developed to track CMEs from near the solar surface through the inner heliosphere, and for use for forecasting space weather (SWx) effects.**

- **For tracking CMEs and forecasting SWx using imagers, a CME must be detected in the images, and certain characteristics derived from them.**

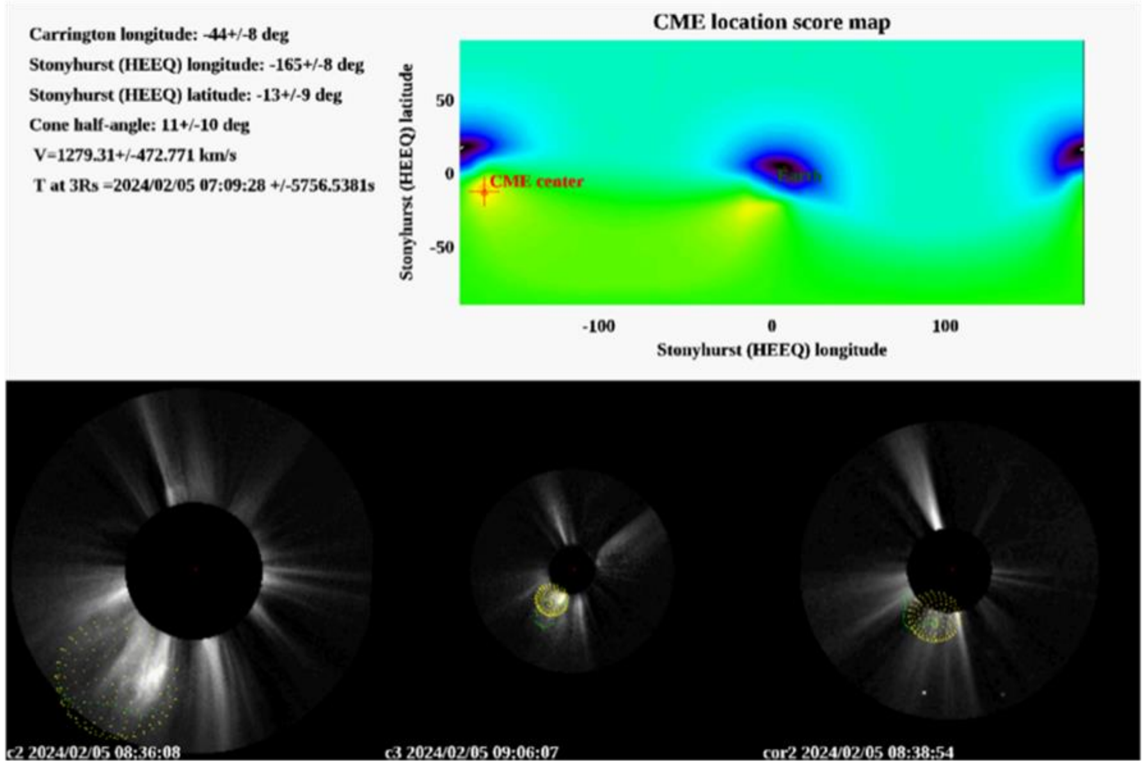
- **These characteristics are then input into a solar wind model to provide a forecast of the CME's time of arrival at Earth, or elsewhere.**

- **Characteristics needed: (1) CME timing at the inner boundary, (2) its speed, (3) its location (longitude/latitude) and (4) its size (angular extent).**

- **Next: 6 techniques being developed that can be used with PUNCH data.**

ACME-3D Detection and Tracking Program (Huw Morgan)

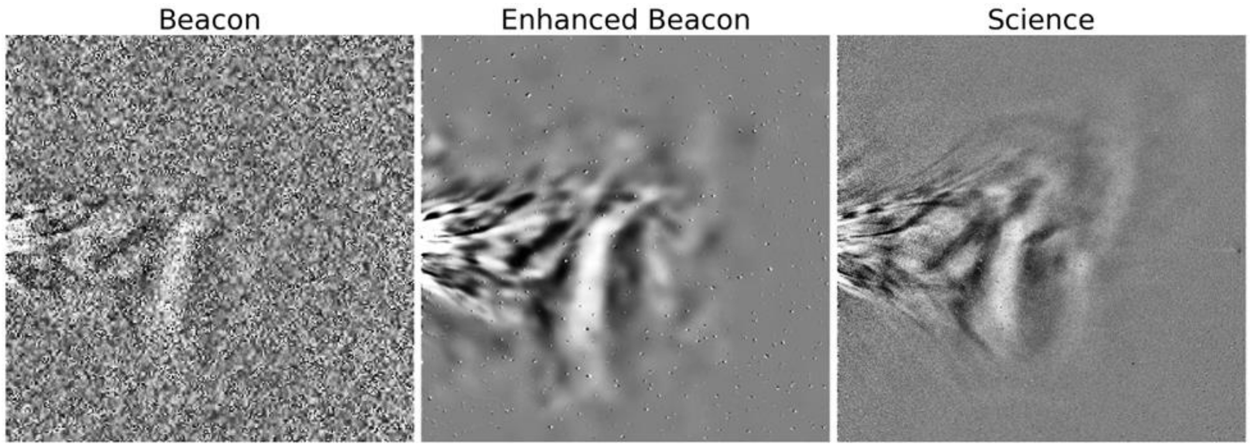
- **ACME-3D is automated CME detection and characterization software package developed for use at UK Meteorological Office Space Weather Operations Center (MOSWOC). ACME-3D is a modular software package designed to accommodate new datasets such as PUNCH.**
- **PUNCH will improve the capability of operational SWx forecasting through its high-quality imaging and routine frequent data capture. Its polarized brightness (pB) images will allow collecting relevant CME characteristics useful for forecasting applications:**
  E.g., CME masses and independent methods for estimating CME projection along the LoS that can complement and enhance the geometrical approach of ACME-3D.

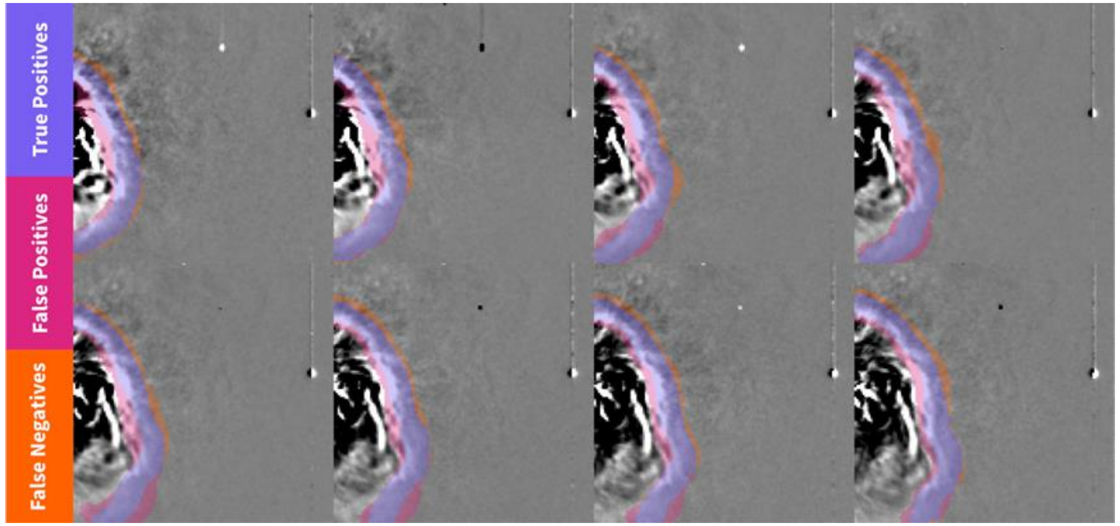


- **ACME-3D output showing a CME detected on 5 February 2024 in LASCO and COR-2A NRT data.**
- ***Top:* 'heat map' where yellow/red colors indicate where CME is likely located. Red cross shows most likely location, with est. uncertainties and Earth in center.**
- ***Bottom:* Available NRT images close to 09:00UT, with green points showing detected CME front edge, and yellow points the boundaries of the cone model.**
- ***Top left text:* Est. properties of CME based on cone model with uncertainties.**

Using PUNCH Data for Real Time CME Arrival Predictions (Christian Moestl et al.)

- **With drag-based ELlipse Evolution model based on Heliospheric Imager observations (ELEvoHI), PUNCH obs. can be incorporated to model the IP evolution of CMEs and predict their arrival time, speed and likelihood of arrival at Earth.**
- **ELEvoHI developed and tested to serve as fast and easy way to apply CME propagation model that only needs the time-elongation measurements of the CME front as observed with HI images as input.**





STEREO-HI beacon Image (left) is enhanced (center). The generative model extracts front and important features of CME. *Right:* STEREO-A HI1 images showing the evolution of the CME. Colors show auto detection model results.

- **Also Graz group have catalog of in-situ observations of ICMEs containing magnetic obstacles (https://helioforecast.space/icmecat). Contains ICMEs detected with the active spacecraft Wind, STEREO-A, Parker Solar Probe, Solar Orbiter, BepiColombo. Using this catalog results from ELEvoHI for CME arrival times at different spacecraft are validated.**
- **Might adapt our 3DCORE flux rope model to model PUNCH observations to derive est. of 3-D magnetic structure of CMEs.**

CME Propagation from PUNCH NFI to WFI; Forward Modeling (Arnault Thernisien)

- **Graduated Cylindrical Shell (GCS - Thernisien, 2011) is 3-D geometric model of a flux rope CME. Its purpose is to fit CME direction, extent, and speed as observed by coronagraphs and HIs.**
- **Are updating the existing forward modeling tool to allow fitting the GCS model with both PUNCH NFI (coronagraph) and WFI (HIs) and combined mosaic that merges PUNCH instruments in one frame.**
- **Update will add settings for the PUNCH instruments, based on their World Coordinate System (WCS) FITS header pointing data, optical projection, and distortion.**
- **Tool will allow using data not only for PUNCH and the older LASCO and SECCHI telescopes, but also, be able to simultaneously fit data from the WISPR and SoloHi HIs, and new NOAA CCOR coronagraphs.**

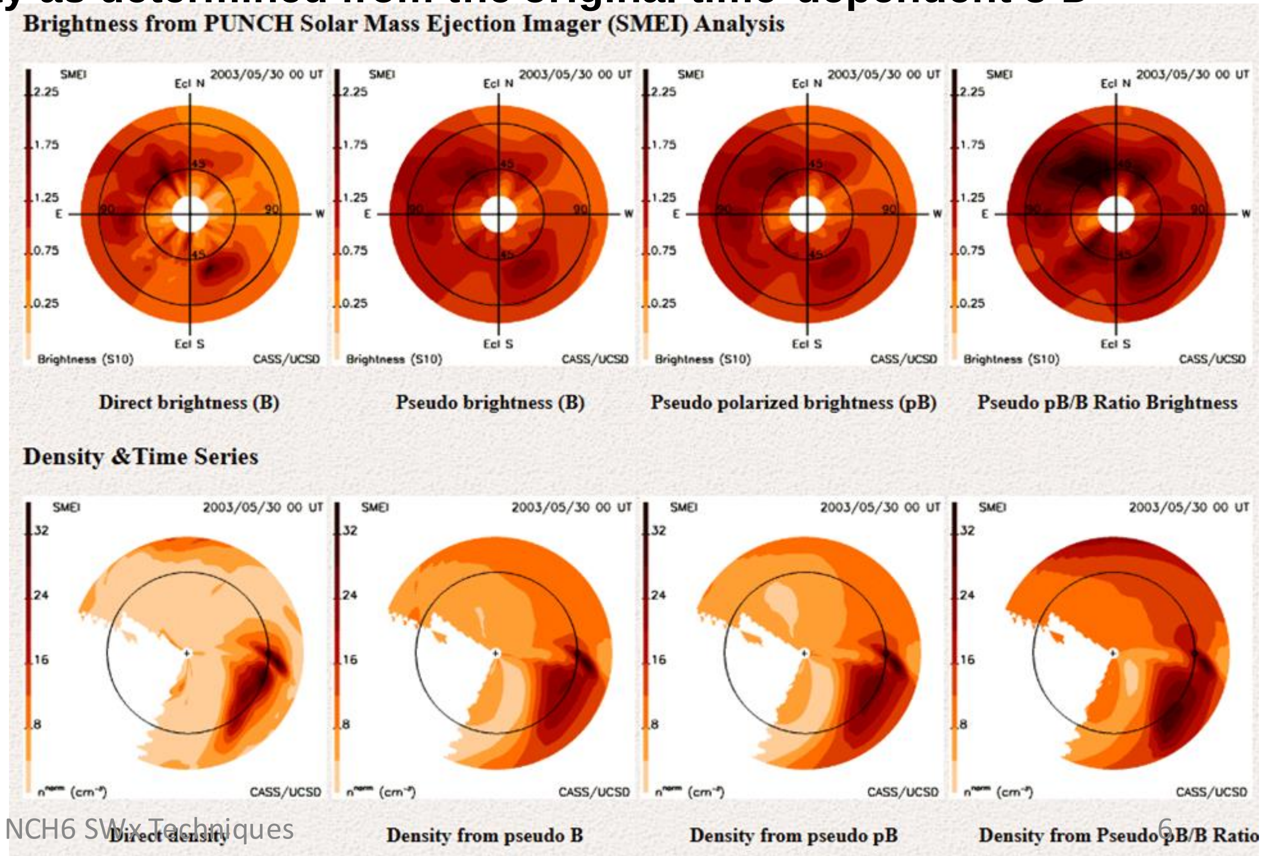
3-D Reconstructions of CME and Shock Structures (Volker Bothmer)

- **The Solar, Heliospheric and SWx Research Group at University Göttingen's Inst. for Astrophysics and Geophysics in Germany will use the data from PUNCH to reconstruct global 3-D structure of CMEs and associated IP shock waves and track their evolution in corona and inner heliosphere.**
- **Goal: Understand kinematics of CME propagation and facilitate more precise SWx forecasts by using derived CME parameters as input to the group's existing CME dynamic drag propagation models.**
- **Preparation for the upcoming Vigil SWx mission.**
- **Of special interest are interaction of CMEs with ambient SW and stream interaction of multiple CMEs with different propagation speeds.**
- **Data also used to investigate global nature of co-rotating interaction regions (CIRs) formed ahead of fast solar wind streams from coronal holes.**

PUNCH Tomographic Reconstructions (Bernard Jackson)

- **UCSD's iterative time-dependent 3-D reconstruction program characterizes topology throughout inner heliosphere based on IP scintillation (IPS) and Thomson scattering brightness observations. Tested using Solar Mass Ejection Imager (SMEI) brightness to learn how well the 3-D reconstructions perform to reproduce a known CME and background solar wind.**
- **From density volumes generated over time we have now produced digital brightness (B) and polarization Brightness (pB) measurements along lines of sight (LoS) that can be used again in the 3-D reconstruction analyses.**
- **Here we show direct brightness and direct density as determined from the original time-dependent 3-D reconstructions in this case from SMEI.**

- **Once heliospheric density is determined an R^{-2} density fall-off normalized to 1 AU is removed.**
- **The model from this 3-D reconstruction provides the Pseudo brightness (B) and Density derived from this reconstruction.**
- **These density volumes over time can provide Pseudo polarized brightness (pB). LOSs also used to reconstruct volumetric Density from pseudo pB over time (SMEI had no polarization data).**
- **Ratio pseudo pB/B for each LoS also provides the 3-D reconstruction analysis of Density. Used to reconstruct large-scale heliospheric features in 3-D over time.**



- **The “ground truth” used to demonstrate accuracies of these densities → How well do Thomson scattering results fit densities observed in-situ by heliospheric spacecraft monitors for same time as the 3-D reconstructed densities? Usually correlation is very good.**
- **These are low-resolution results that use derived densities averaged over 5º centers. Recent SMEI analyses performed in high-resolution images based on LoSs at 1º image centers.**
- **Key question for tomography is how best to determine flow speeds of CMEs in heliosphere. A correlation-tracking method will be in the SOC pipeline to measure the ambient solar wind. But this method will be less reliable for measuring fast CMEs. Another method being developed for PUNCH is based on the so-called “Magnetic Balltracking” method, originally developed by Attie & Innes (2015).**

- **UCSD tomography requirements for using PUNCH data for CME tracking and forecasting:**

(1) At least two weeks of image data, and preferably one month of preparation/processing time.
(2) Images should have a long baseline removed, so that both corotating and fast transient structures can be reconstructed.
(3) Data must be cleaned of auroral background. During geomagnetic storms, e.g., aurora can add significant image noise.
(4) PUNCH Level 3 data are based on making high resolution images and interpolating these between images. UCSD tomography does not require high resolution, but must input images at the exact midpoint times.
(5) Tomography depends on knowing solar wind and CME flow speeds → Ideal if speeds can be derived from the PUNCH images themselves.

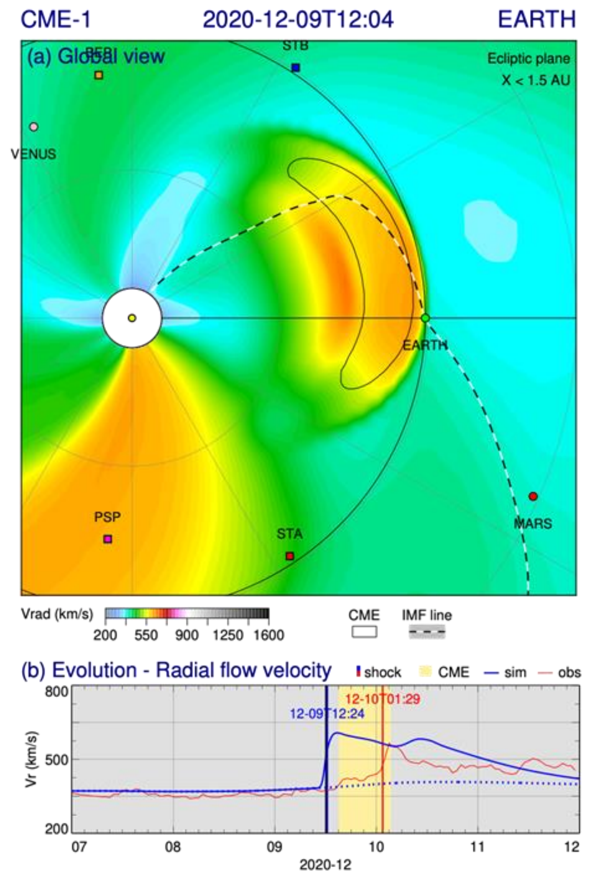
ENLIL MHD Model: Heliospheric Space Weather Predictions (Dusan Odstrcil)

- **While many heliospheric models can predict the propagation of CMEs, the 3-D numerical heliospheric model ENLIL has been used extensively in SWx operations. It is used at the NASA/CCMC, and also used operationally at NOAA, NASA, the UK Met Office, and in Korea and Australia.**
- **ENLIL uses an ideal 3-D MHD model to describe fully ionized plasma with volumetric heating. Model also uses 2 additional equations to trace IMF polarity and CME material.**
- **All CMEs observed by coronagraphs can be routinely simulated, but their predicted time of arrival (ToA) at Earth is often inaccurate. We investigated improving ToA predictions of the CME-driven shocks or disturbances at Earth by incorporating HI images.**

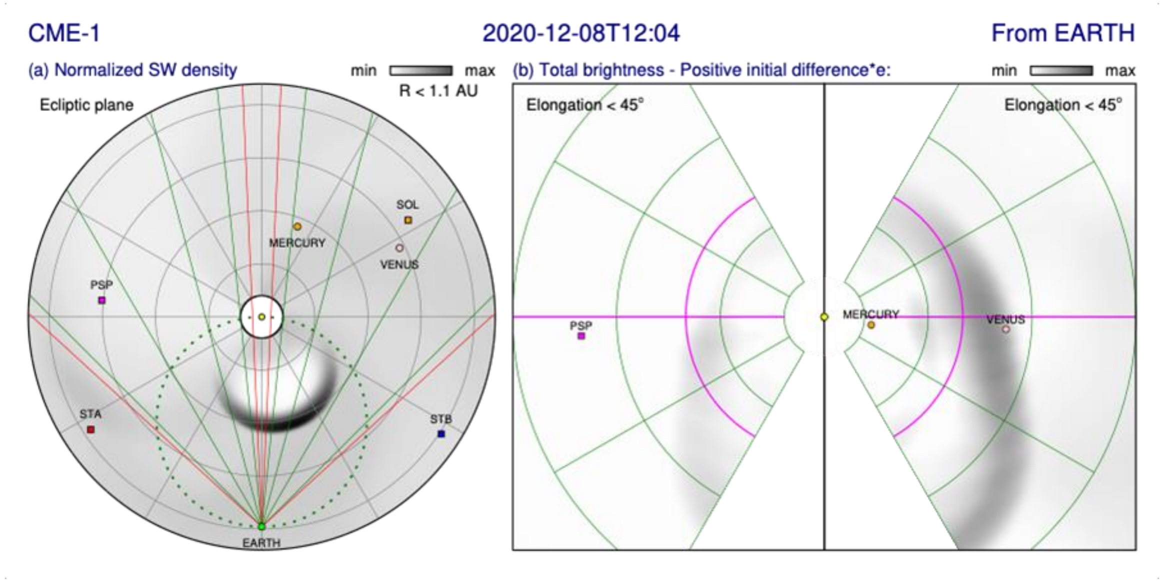
- ***Example event*: Operationally predicted with widely varying TOAs at Earth, primarily from uncertainties in fitting (e.g., a cone model) the geometric and kinematic parameters of the distorted CME shape with multiple fronts.**

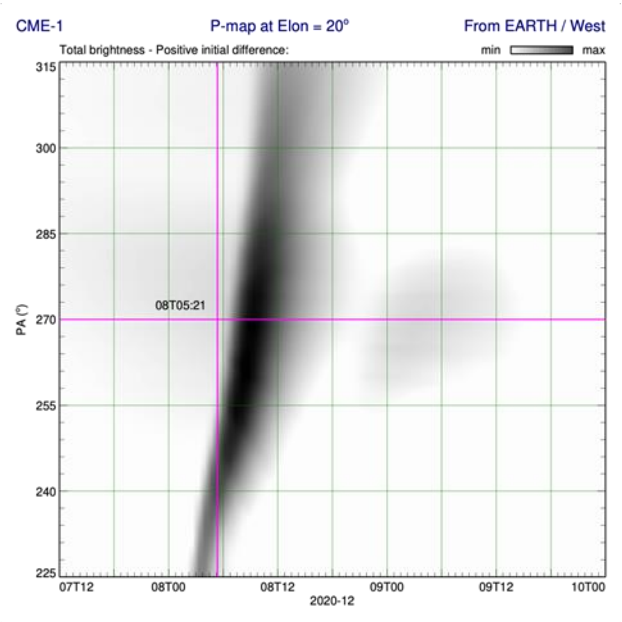
- ***Right:* Predictions of the CME event computed with one CME front. The SW velocity in the ecliptic is shown together with CME extent (black).**

- ***Bottom:* Evolution of predicted radial SW velocity (solid blue with background dotted blue) together with measured values (shown by red).**



- ***Below left:*** **Simulated density and corresponding synthetic WL image for one CME case. WL images calculated from Earth view. Density plots shown in the ecliptic together with the Thomson curve. The WL signatures are clearly visible despite disturbances being farther from the Thomson curve.**





- ***Right: S*****o-called P-maps for same CME case. P-maps show total WL brightness at a fixed elongation as function of PA and time. Unlike J-maps, P-maps show differences in the width and latitudinal position of CMEs. Total WL brightness is shown as a positive difference from the initial state as it passes elongation at 20º and the arrival time is detected at the helio-equator.**
- **Incorporating heliospheric WL imagery into SWx forecasting can improve prediction accuracy by: (1) avoiding inaccurate model initialization, and (2) suggesting the best prediction(s) from ensemble models. However, current WL imaging has limitations, including insensitivity to some CME parameters an variability in CME fronts. PUNCH mission will provide better quality heliospheric images, including the pB, and will enhance our understanding of CMEs and improve SWx forecasting.**