A consideration of the multi-viewpoint and single-viewpoint exploitation of heliospheric imaging in light of over a decade of operation of the STEREO/HI instruments

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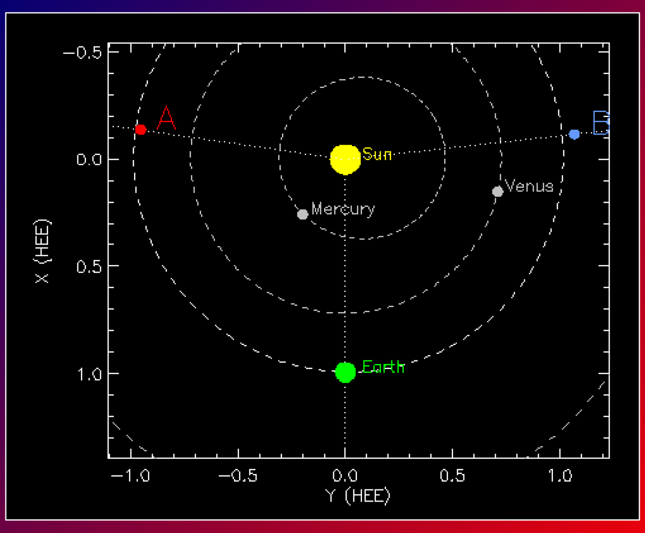
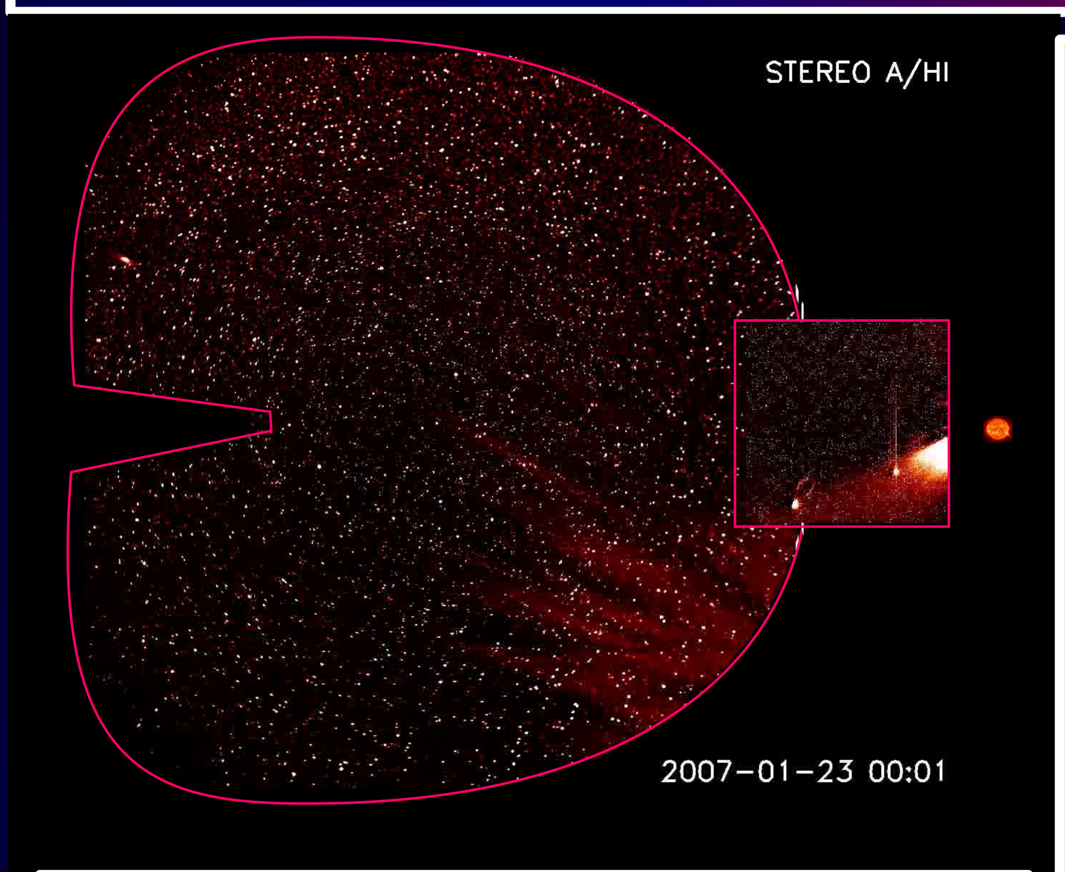
After more than a decade of successful operation of the Heliospheric Imagers (HI) on-board NASA's twin-spacecraft STEREO mission, we are in a unique position to assess the large volume of research that exploits the data therefrom. We review selected publications that characterise the 3D kinematic properties of coronal mass ejections (CMEs), as they propagate to 1 AU and beyond; such information is vital for the provision of accurate CME arrival predictions for space weather usage. We consider the benefits of heliospheric imaging from two vantage points over such imaging from a single view point. Given the expectation of future operational heliospheric imaging from only a single off-Sun-Earth line vantage point, such an assessment is timely.

The NASA STEREO Mission

- Twin spacecraft launched Oct 2006 into near 1 AU solar orbits such that STEREO-A runs ahead of Earth and STEREO-B lags behind Earth, with the Earth-Sun-spacecraft angles increasing by ~22.5° per year. Thus, enabling imaging of Earth-directed CMEs from off the Sun-Earth line.
- Having passed through superior conjunction, STEREO-A & B are now 98° & 96° from the Sun-Earth line (Mar 5, 2019).
- STEREO-A is operating nominally. Contact with STEREO-B was lost in Oct 2014, prior to conjunction; attempts to re-establish contact were partly successful but a long-term recovery programme has now been abandoned.





The STEREO Heliospheric Imagers

- Wide-angle imagers with occultation and baffle systems achieving light rejection of ~ 10^{-13} solar brightness.
- 20° (HI-1) and 70° (HI-2) fields of view centred on ecliptic plane, centres offset from Sun by 14° and 54° (see image, left).
- *See Eyles et al., 2009, Solar Phys. 254; Harrison et al., 2008, Solar Phys. 247.*

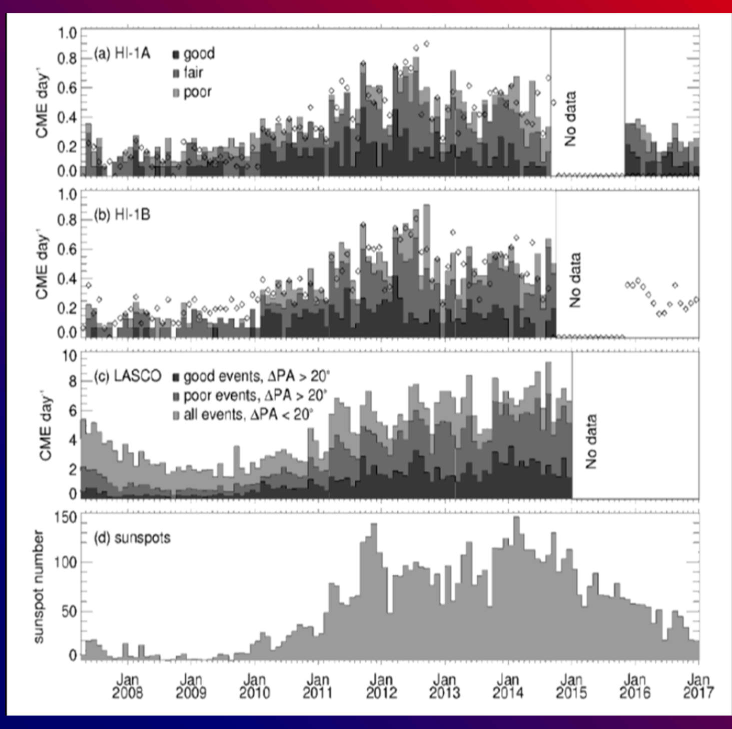
Exploitation of the HI instruments is illustrated by the topical coverage of the 300-plus HI publications to date (publication list at www.stereo.rl.ac.uk), ranging from studies of CME onset, propagation, evolution and impact, to co-rotating/stream interaction regions, from CME-CME and CME-CIR interactions to stellar variability (including novae), cometary, interplanetary dust and exoplanet studies. The HI instruments have also been used to study asteroids and planets, the F-corona and cosmic rays. Selected studies, below, illustrate space-weather related aspects of research exploiting the HI instruments, focusing on the 3D aspects.

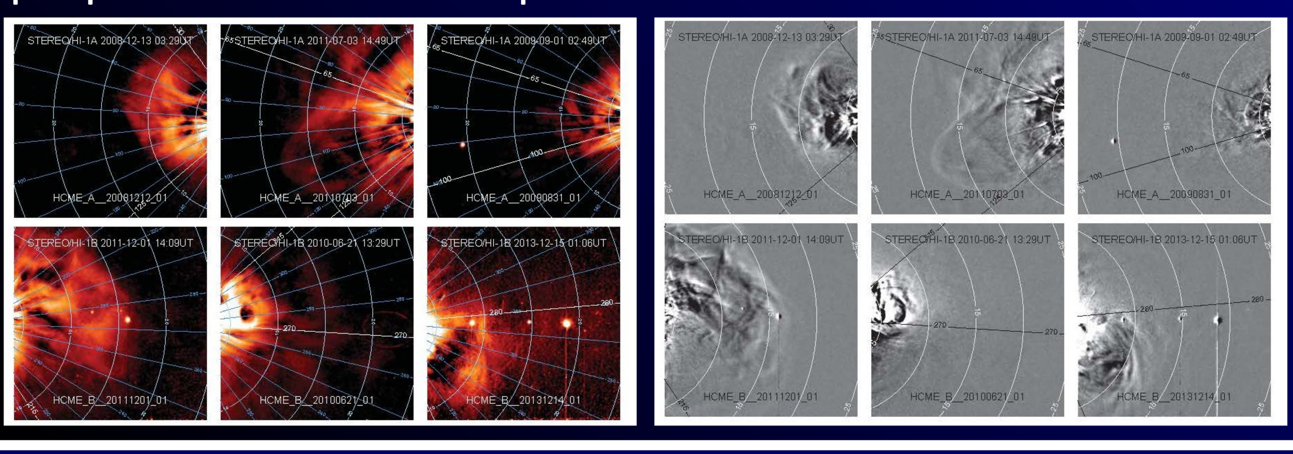
EU FP7 HELCATS (2014 – 2017)

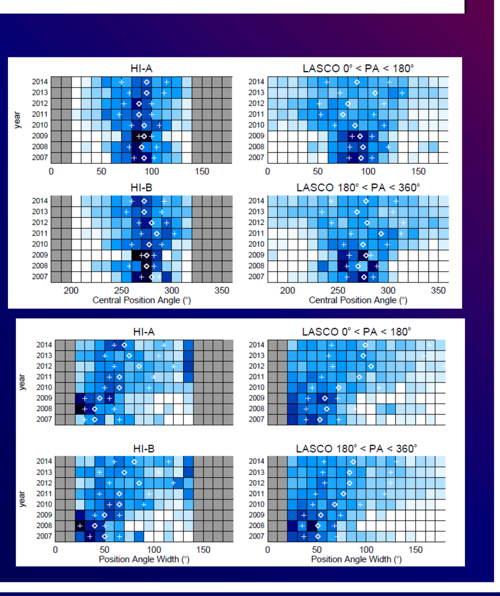
HELCATS (Heliospheric Cataloguing, Analysis & Techniques Service) is a recently completed RAL-led FP7 project centred on analysis of STEREO/HI observations [*www.helcats-fp7.eu*]. At the core of the project was the comprehensive cataloguing of solar transients in the heliosphere including the assessment and validation of models.

The HI catalogues Harrison et al. (2018), Barnes et al. (2019)

The HICAT and HIGeoCAT catalogues from the HELCATS project are the official STEREO HI event lists, using manual identification and exploitation of the Self Similar Expansion Fitting model (SSEF, *Davies et al., 2012, ApJ 750*), applied to data from one STEREO spacecraft in each case, to provide kinematic information, including longitudinal direction, latitude, projected onsets and arrivals. First detailed analyses of these catalogues are given by *Harrison et al. (2018, Sol. Phys. 293)* & *Barnes et al. (2019, Sol. Phys. Submitted)*, including statistical analyses of CME properties in the heliosphere.

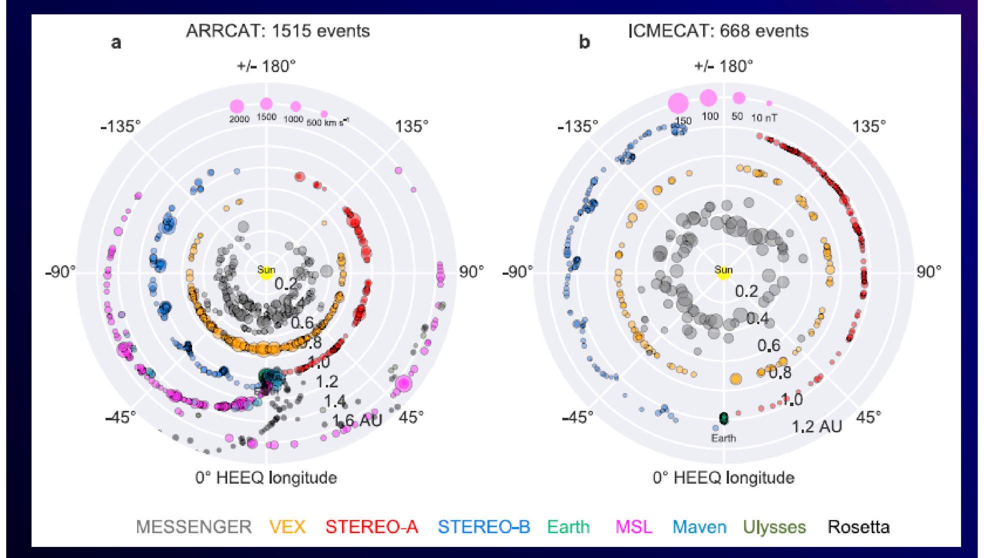


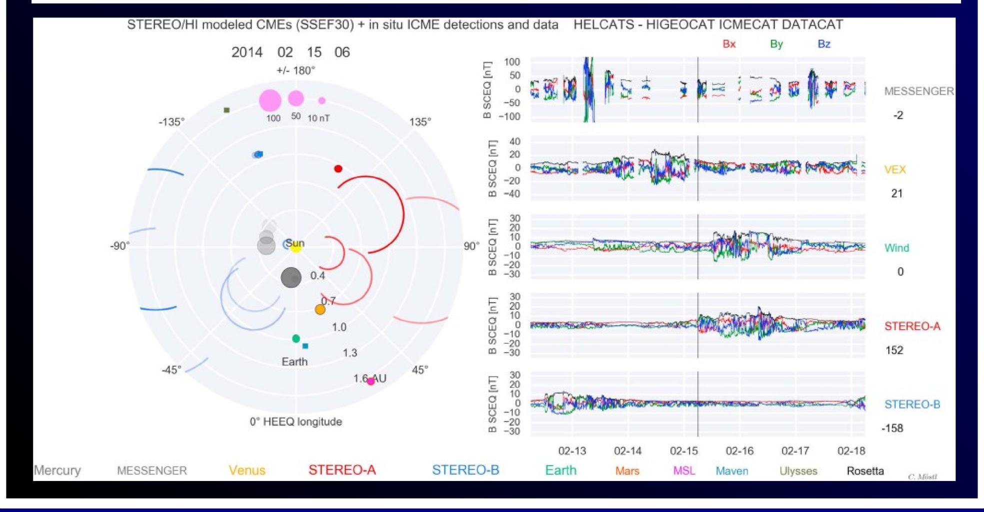




Linking HI events with in-situ arrivals Möstl et al. (2017) Space Weather, 15

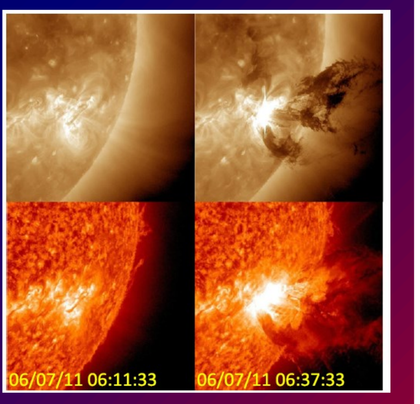
The kinematic properties of CMEs, derived from HI imagery and included in the HI catalogues, are compared to event arrivals at many solar system locations, including Earth, Mars, Venus and remote spacecraft such as STEREO-A and B, Rosetta, MESSENGER and Ulysses. The comparisons are used to assess the efficacy of the modelling approach for predicting CME arrivals using the single-spacecraft SSEF model. Predicted arrival times are, on average, within 2.6 ± 16.6 h of the in-situ arrival time.

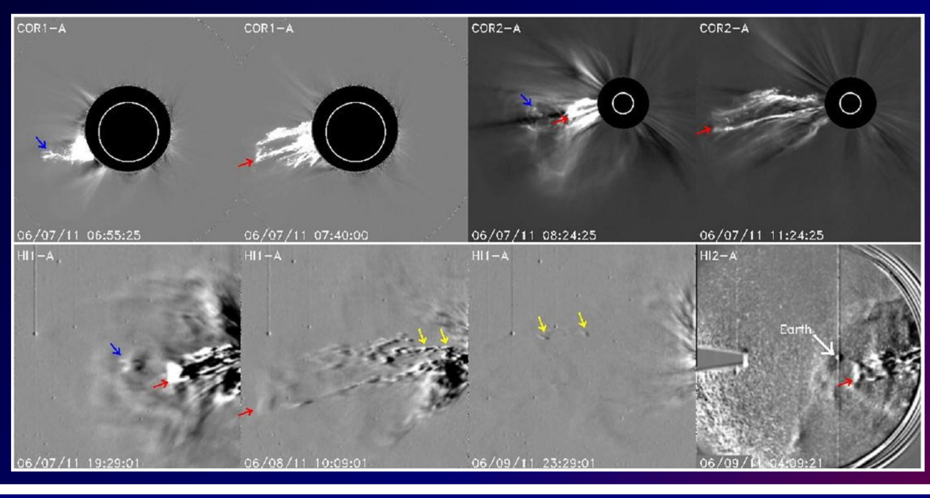


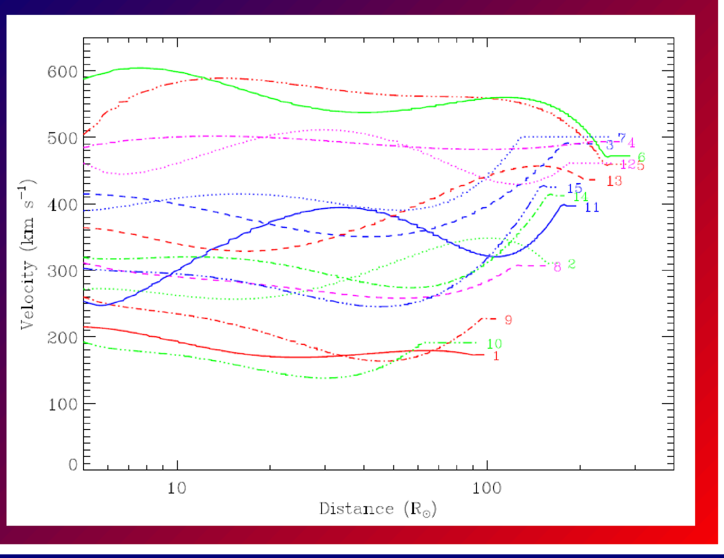


3D prominence reconstruction using triangulation Wood et al. (2016) Astrophys. J. 816

Analysis of one of only two clear prominence eruptions that can be tracked by STEREO all the way to 1 AU, using HI. A time-dependent 3D reconstruction of the prominence structure was made using point-by-point triangulation. Unlike its host CME, the prominence material decelerates little out to 1 AU, due to it moving upwards inside the CME, showing that a prominence is not necessarily tied to a CME's magnetic structure. Velocity-altitude profiles of a number of identified substructures is shown.







Discussion

The HI instruments have been a demonstrator for off Sun-Earth line space weather applications. *Harrison et al.* (2017, Space Weather 15) provide an assessment of the value of HI observations to space weather forecasting through a review of published papers, with a more complete analysis than we are able to show here. Methods have been used to study CME development exploiting single and twin-spacecraft HI observations employing a range of models, in particular to derive CME longitudinal directions, with some success, and with clear pointers to beneficial applications for space weather endeavours.

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