Measuring coronal magnetic fields with Shocks driven by CMEs

A. Bemporad, R. Susino, and S. Mancuso
INAF-Turin Astrophysical Observatory, Italy

G. Lapenta and F. Bacchini,
CPA, KU Leuven, Belgium

INAF – Italian National Astrophysics Institute

OATo – Turin Astro-physical Observatory

Outline

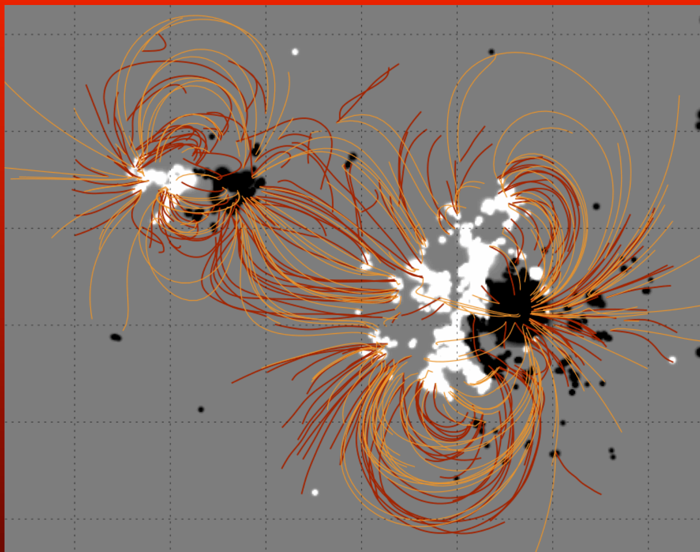
• Introduction: most recent coronal magnetic fields measurements from space and from ground

• Pre- and post-shock field measurements with combined WL and UV observations

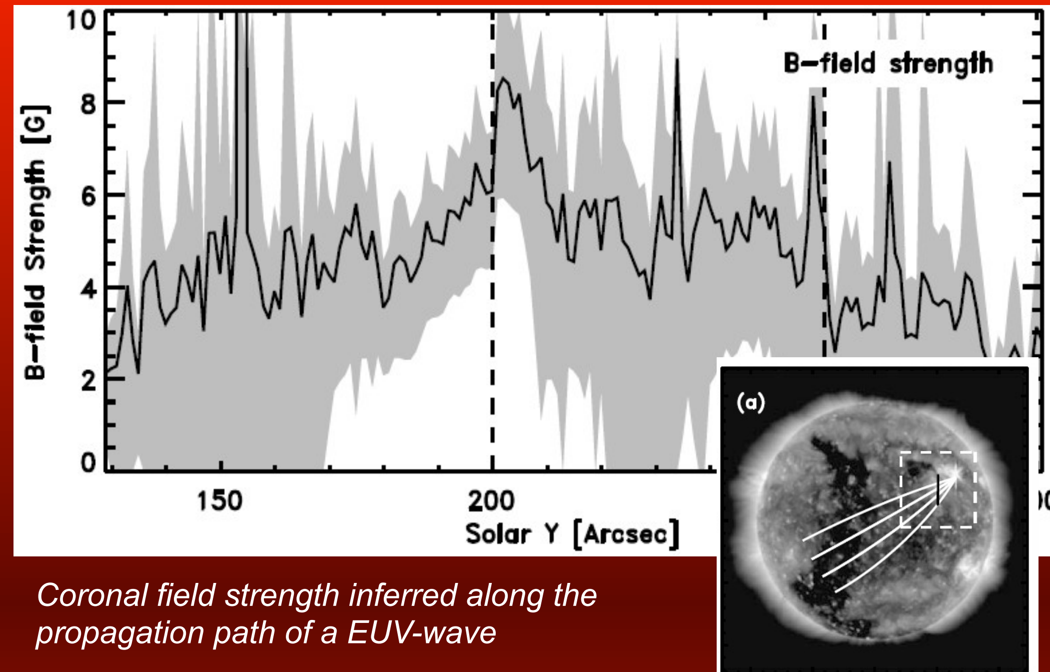
• Pre-shock coronal field measurements with WL observations alone

• Future developments and perspectives

Recent coronal field measurements from space



Comparison between unipolar potential field extrapolations (orange) and 3D reconstructed loops (red) → significant differencess in loop inclination and connectivities



Coronal field strength inferred along the propagation path of a EUV-wave

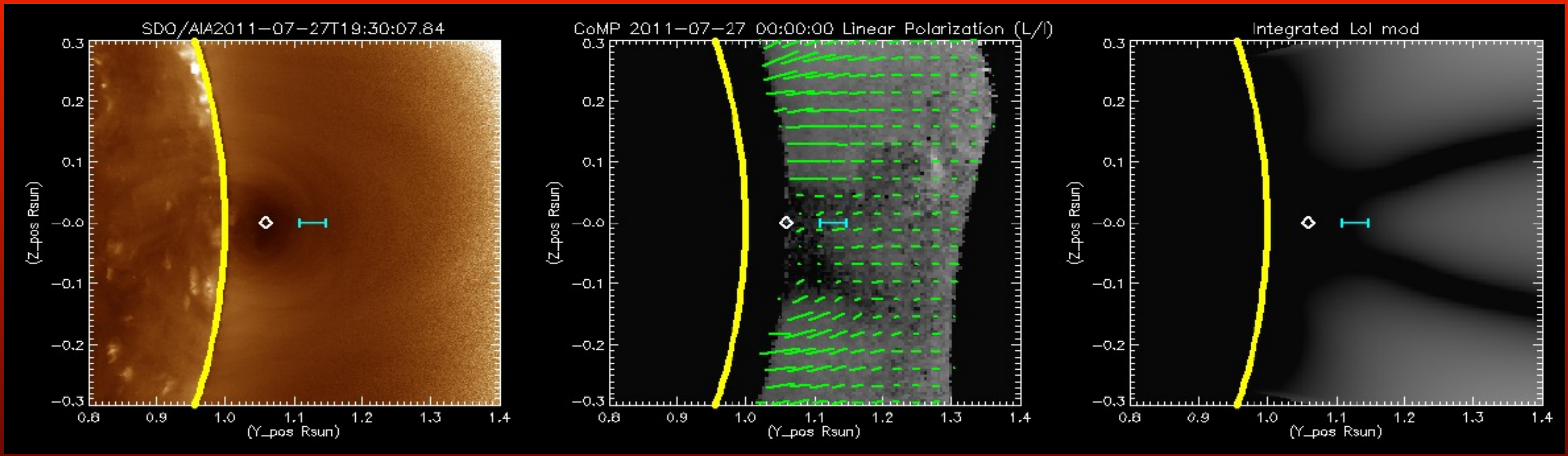
- **Field extrapolations bounded to 3D stereoscopic reconstructions**: forward fitting of 3D loops with multipolar photospheric dipole-fields → disagreement due to non-potentiality and currents, but also to inadequacy of photospheric magnetograms.

(De Rosa et al. 2009; Aschwanden et al. 2012; Chifu et al. 2015)

- **Field strength from propagation of EUV-waves**: by assuming that EUV-wave speed = fast magnetosonic speed and measuring the coronal density and temperature from EUV images/spectra (AIA + EIS data) → need a comparison with extrapolated field to infer height estimates

(Long et al. 2011; West et al. 2011)

Recent coronal field measurements from ground



Example (courtesy of S. Gibson) of a coronal cavity observed by SDO/AIA 171 (left), and the characteristic "V-shaped" Van Vleck signatures in the distribution of the FeXIII 1074nm linear polarization strength as observed (middle) and simulated (right)

Different instruments (e.g.: CoMP, CoMP-S, CorMag) are now providing unique information on coronal fields via:

- **Zeeman effect** on VIS/IR spectral lines (e.g. FeXIII 1074nm) → spectro-polarimetry provides: a) measurements of circular polarization (Stokes V/I) → **B line of sight strength**; b) measurements of linear polarization (Stokes L/I) becoming 0 at Van Vleck angle (~54° between the radial and local field orientation) → **B orientation on the plane of the sky**;
- **Hanle effect** (saturated $A_{ij} < v_B$) on VIS spectral lines (e.g. FeXIV 530nm), spectro-polarimetry provides measurements of linear polarization → **B orientation on the plane of the sky.**

Issues related with LOS integration will be solved via tomographic-inversion once daily obs. will be available (ATSA, COSMO, ASPIICS), assuming stationarity of coronal structures.

Coronal field measurements with Shocks

A new technique to **measure coronal fields crossed by CMEs** proposed by Gopalswamy & Yashiro (2011) by applying the Furris & Russell's (1994) relation between the **standoff distance** ΔR of an interplanetary shock and the radius of curvature R_c of the driver:

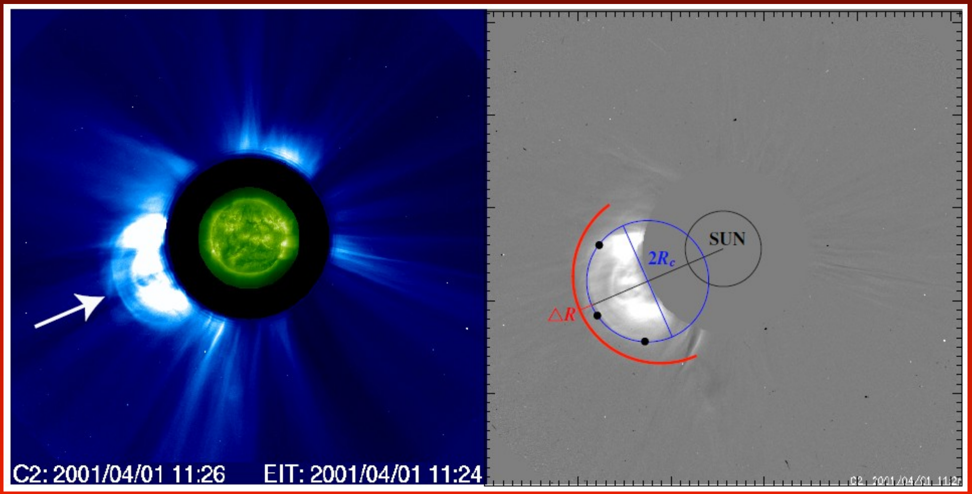
$$M_{\Delta R}^2 = \frac{\Delta R / R_C(\gamma+1)+1.6}{\Delta R / R_C(\gamma+1)-0.8(\gamma-1)}$$

(Kim et al. 2012)

$\Delta R = R_{shock} - R_{fluxrope}$, M = shock Mach number, γ adiab. index.
Technique: measure R_{shock} *and* $R_{fluxrope}$ from WL images → estimate of $M = v_{in}/v_A = (v_{shock} - v_{solarwind})/v_A$ → measure v_{shock} and assume $v_{solarwind}$ → estimate of $v_A = B/(\mu\rho)^{0.5}$ → measure ρ (from pB images or type-II radio burst) → **estimate of B**.

→ applied to shocks observed in WL coronagraphic images (Kim et al. 2012), **EUV disk imagers** (Gopalswamy et al. 2012) and **WL Heliospheric imagers** (Poomvises et al. 2012).

Limits: field can be measured only at the nose where quasi-parallel shock can be assumed



(Kim et al. 2012)

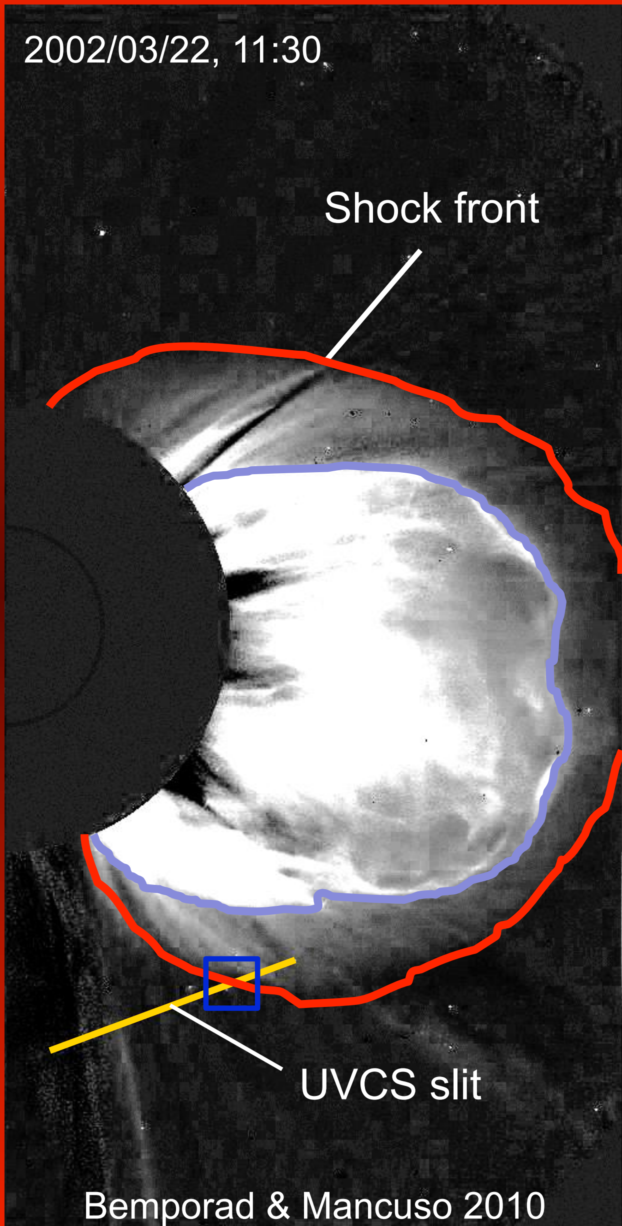
Alternatively coronal field can be measured directly from the **density compression ratio *X*** at the shock front:

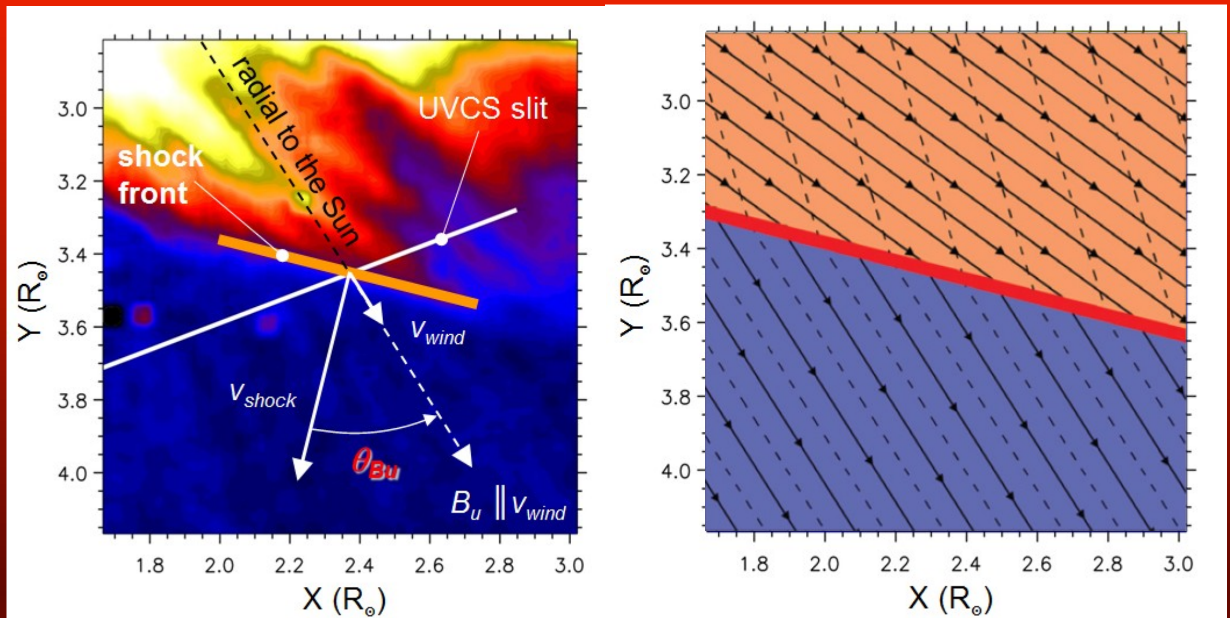
$$M_{\rho}^2 = \frac{2X+\gamma+1}{\gamma+1-X(\gamma-1)}$$

Results: B and v_A measured in a wide range, B consistent with previous measurements.

Problem: shock **compression ratios X from WL likely underestimated** by a factor of ~ 2 because of LOS assumptions.

Results from combined WL and UV data





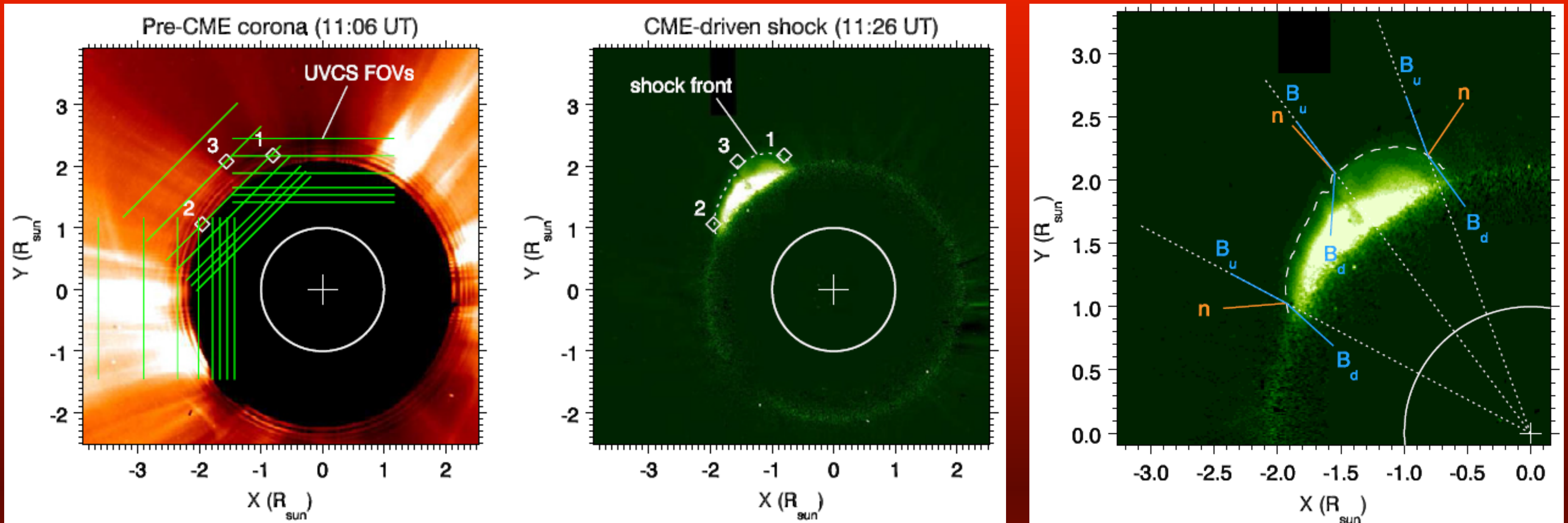
Bemporad & Mancuso (2010)

MHD Rankine-Hugoniot eq. can be rewritten so that:

$$\begin{bmatrix} T_u, n_u, v_u, \\ \vartheta_{Bu}, \vartheta_{vu}, r \end{bmatrix} \rightarrow \text{Rankine-Hugoniot eq.} \rightarrow \begin{bmatrix} B_u, T_d, B_d, \\ v_d, \vartheta_{Bd}, \vartheta_{vd} \end{bmatrix}$$

Detection of shock in UV and WL → MHD-Rankine Hugoniot eq. for oblique shock → *X* (~2), heating factor (~8), ***B* strength up- & down-stream** (0.019G to 0.037 G), **magnetic and velocity fields rotation** across the shock (~23° and 15°).

Results from combined WL and UV data

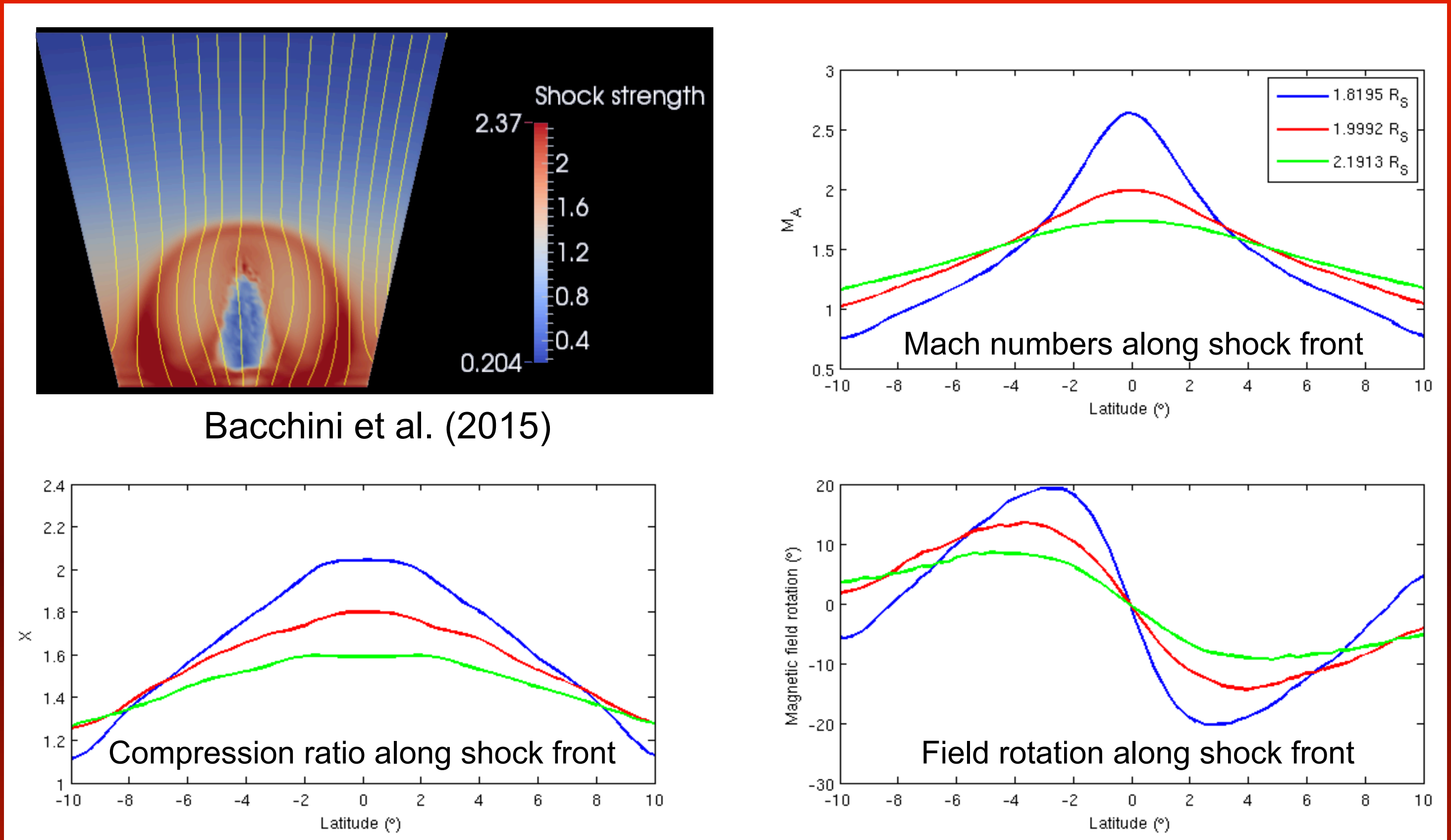


Bemporad, Susino & Lapenta 2014

Unique information on shocked plasma derived from analysis of **both UV and WL data**:

• LASCO + UVCS pre-CME data → **upstream parameters** (T, n, v_{out}), but the magnetic field.
• upstream parameters + shock **compression ratio *X*** from WL → **R-H equations for oblique shock** → **downstream parameters** including **full *B* vector** on the plane of the sky.
• **Shock transit** → **compression** (factor ~ 1.7–2.7), **heating** (factor ~ 1.5 – 3.0 at the flanks, ~ 8 – 12 at the nose), ***B* compression** (factor ~ 1.2 – 1.9) & **deflection** (~ 14° – 22° at the flanks, > 40° at the nose). **Heating derived with RH-Eq. more likely represents proton heating**, while temperature increases by adiabatic compression (factor ~2 at the nose, ~1.2–1.5 at the flanks) likely more representative of electron heating → **shock transit** → **T_e – T_p decoupling**.

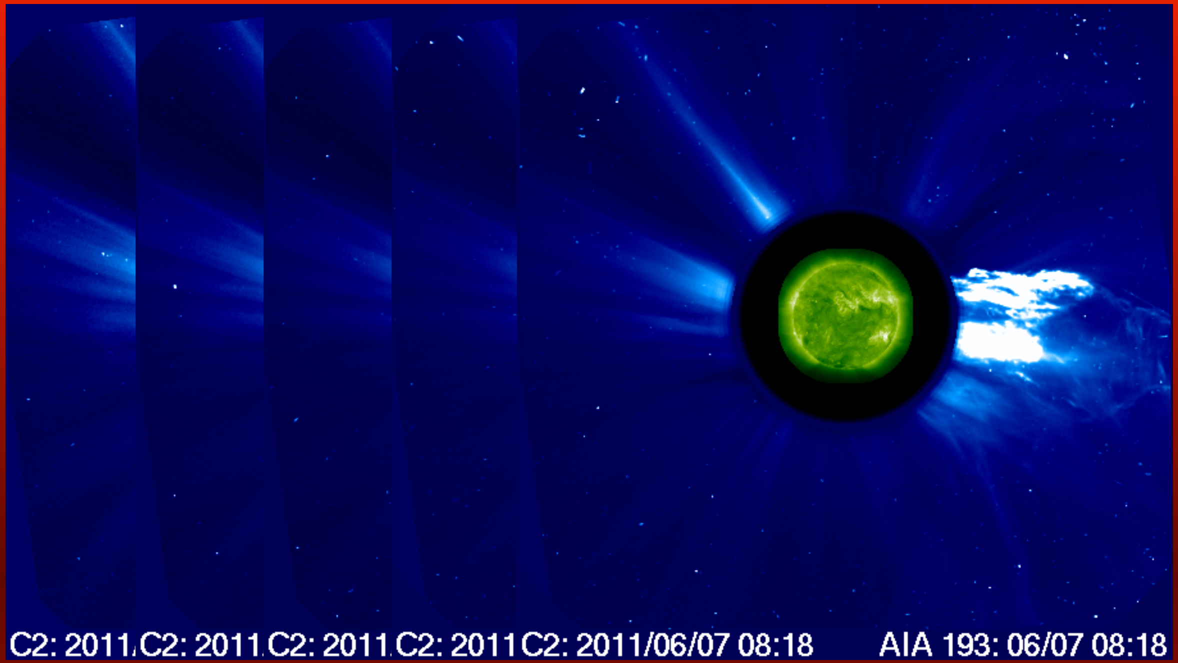
Test of results with MHD simulations

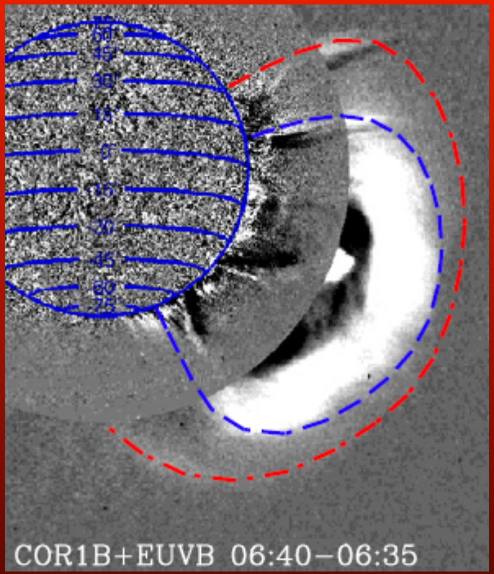


2D single-fluid MHD simulations of a coronal shock were performed (by the Group at CPA–KU Leuven) with FLIPMHD3D (based on Brackbill, 1990).

Results: very **good agreement** between **observations and numerical simulations** for the spatial distribution and time evolution of 1) compression ratios X, 2) Mach numbers M_A, and 3) magnetic field deflections across the shock surface.

The June 7th 2011 eruption





CME bubble and compression front (Cheng et al. 2012).

Spectacular eruption (associated with M2.5 flare, type-II and –III radio bursts, γ-ray emission, Ackermann et al. 2014). Many different works published relative to this eruption focusing on:

- dynamics and plasma properties of **returning plasma blobs** (Carlyle et al. 2014; Dolei, Bemporad & Spadaro 2014; Innes et al. 2012; Williams et al. 2013)
- associated **EUV waves** (Cheng et al. 2012) and **type-II burst** (Dorovskyy et al. 2015)
- energy release from **falling material impact** on the sun (Gilbert et al. 2013; Reale et al. 2013)
- **reconnection driven** by the CME (van Driel-Gesztelyi et al. 2014)

Our analysis focused on the WL data relative to the associated shock wave.

2D maps of coronal fields from WL observation of CME-driven shocks

- Analysis of WL (*pB*) coronal pre-CME image → 2D map of ambient pre-CME coronal densities **n_e**.
- Identification of shock surface location (pixel by pixel) in WL images →
  - a) shock kinematic → 2D map (altitude vs. latitude) of shock velocity **v_{shock}** ;
  - b) orientation of shock surface with respect to the radial direction → shock inclination angle **ϑ_{shock}** at different latitudes.
- Hypothesis on the pre-shock coronal outflow speed v_{wind} → 2D map of shock upstream velocity **v_{up}**.
- Analysis of WL (*tB*) intensity variation across the shock surface → shock compression ratios **X_{shock}** at different altitudes and latitudes
- Hypothesis on the expression of Mach number for the general case of oblique shock (next slide) → 2D map of shock Mach number **M_A**.
- Combination of M_A and v_{up} 2D maps → 2D map of the upstream Alfvén velocity **v_A**
- Combination of v_A and n_e maps → **2D map of pre-shock coronal field strength *B* (without application of MHD-RH equations)**

Compression ratios and Mach numbers from WL

- **Pre-shock densities** derived with latest pre-CME LASCO pB image.
- **Compression ratios *X*** derived all along the shock front by:

1. measuring the WL intensity ratio between the front and the corona,
2. taking into account LOS integration effects (shock depth *L* along the LOS from its projected thickness: L=0.9 $R_\odot$ for C2, 1.1 < L < 1.3 $R_\odot$ for C3),
3. deriving the density in the shocked region reproducing the WL increase.

Results: *X* maximizes at shock nose, *X* decreasing with shock altitude.

- **Mach numbers M_A** derived all along the shock front by:

1. measuring from WL images the inclination θ of shock surface with respect to the radial,
2. applying the empirical formula (tested in Bemporad et al. 2014 and Bacchini et al. 2015) for M_A in the case of oblique shock (β << 1, γ = 5/3)

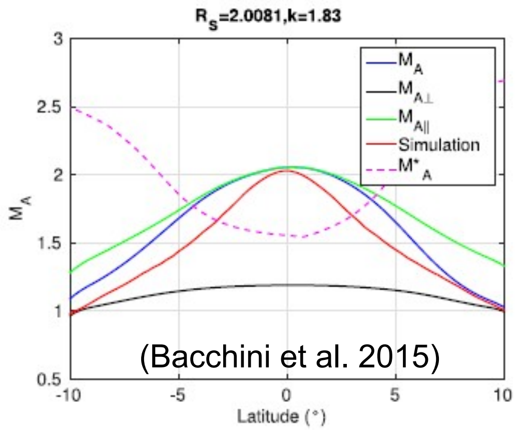
$$M_{A\perp} = \sqrt{\frac{X(X+5)}{2(4-X)}}$$

(Bemporad & Mancuso 2012)

$$M_{A\parallel} = \sqrt{X}$$

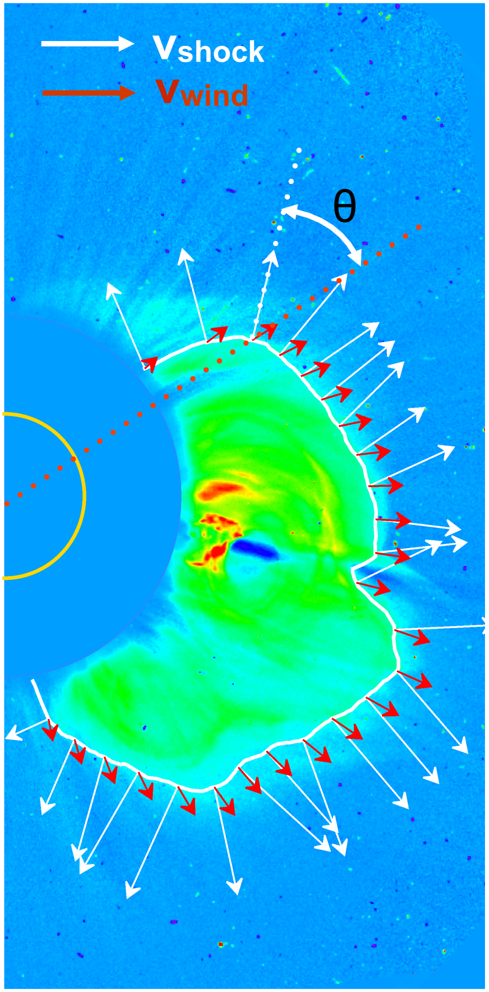
$$M_{A\angle} = \sqrt{(M_{A\perp}\sin\theta)^2 + (M_{A\parallel}\cos\theta)^2}$$

Results: M_A maximizes at shock nose, decreasing with shock altitude.

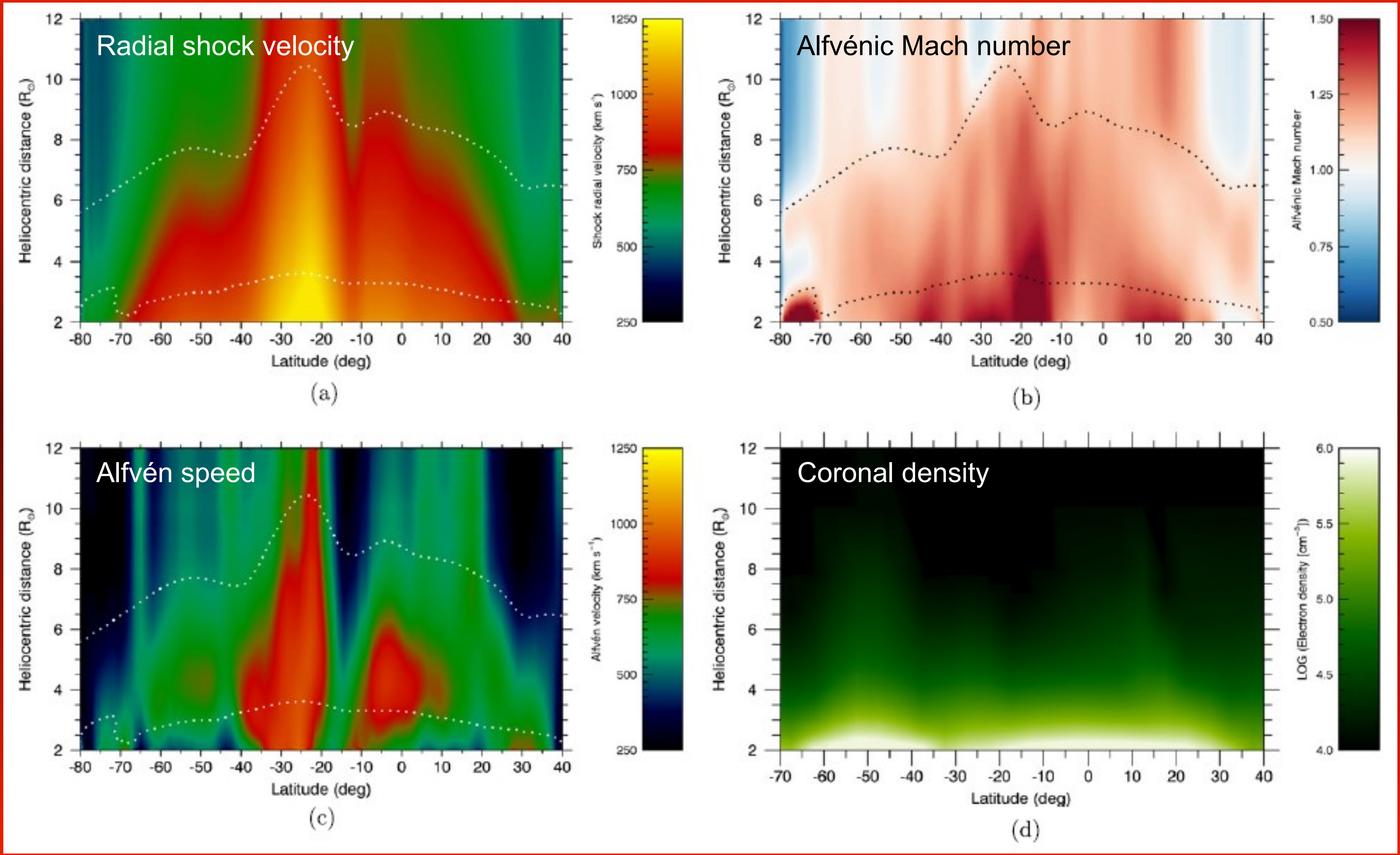


(Bacchini et al. 2015)

LASCO C2 07:01:52

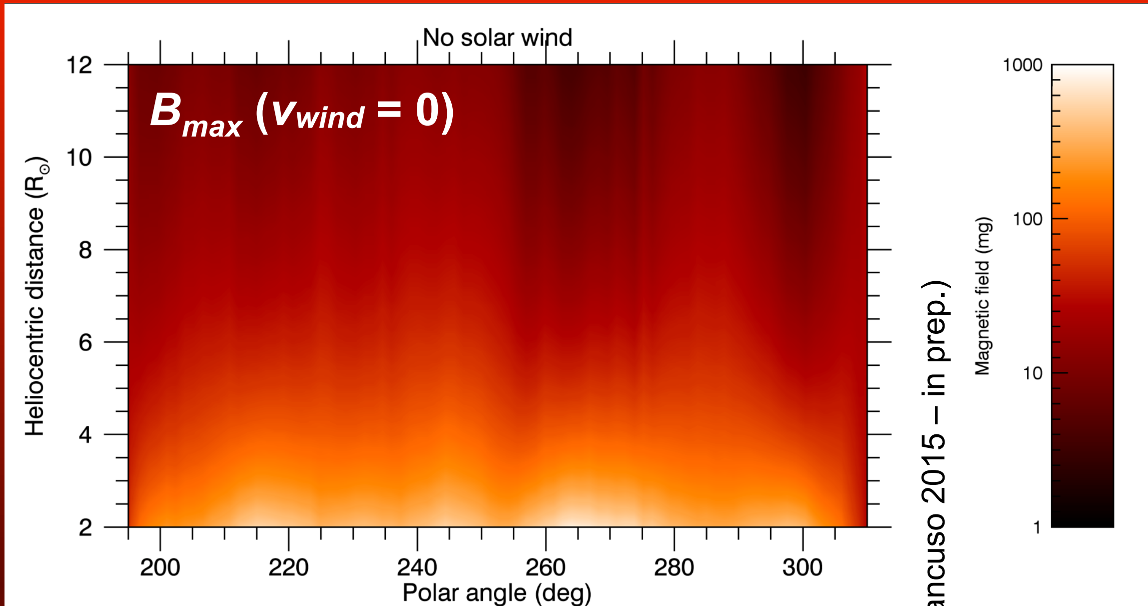


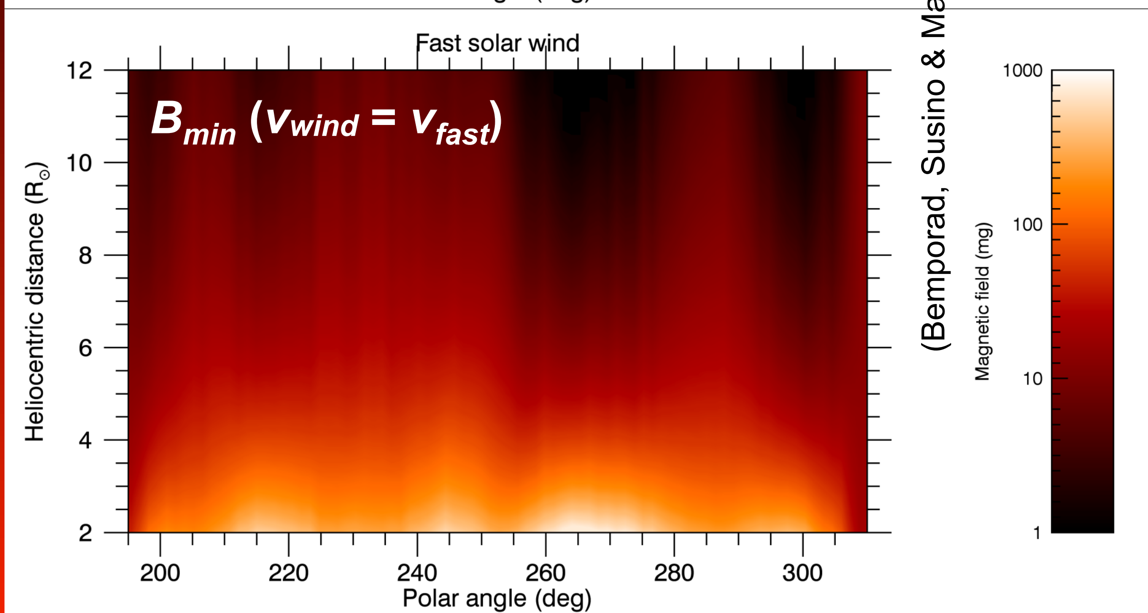
Results: 2D maps of v_{shock}, M_A, v_A, n_e



Susino, Bemporad & Mancuso (2015)

Results: 2D map of coronal Magnetic Fields

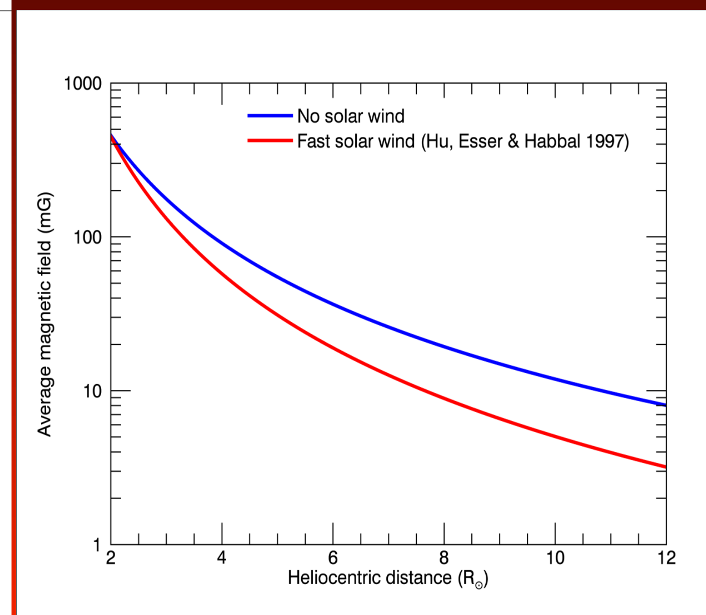




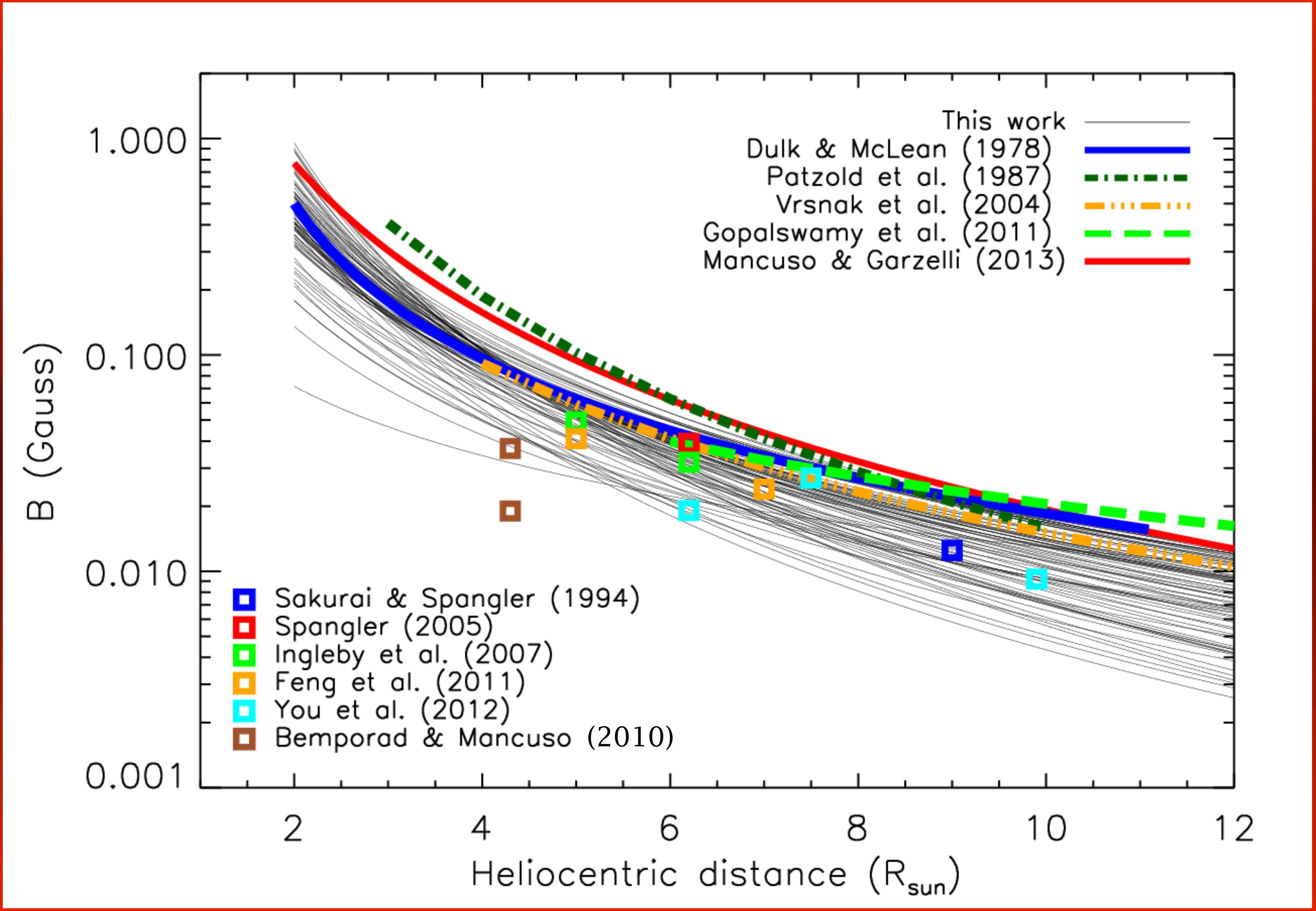
(Bemporad, Susino & Mancuso 2015 – in prep.)

Upstream coronal magnetic field: derived from the Alfvén speed, assuming either **no solar wind** (*B* upper limit) or **fast solar wind** (*B* lower limit) using the model of Hu, Esser & Habbal (1997).

$$B_u = v_A \sqrt{\mu_0 m_p n_e}$$

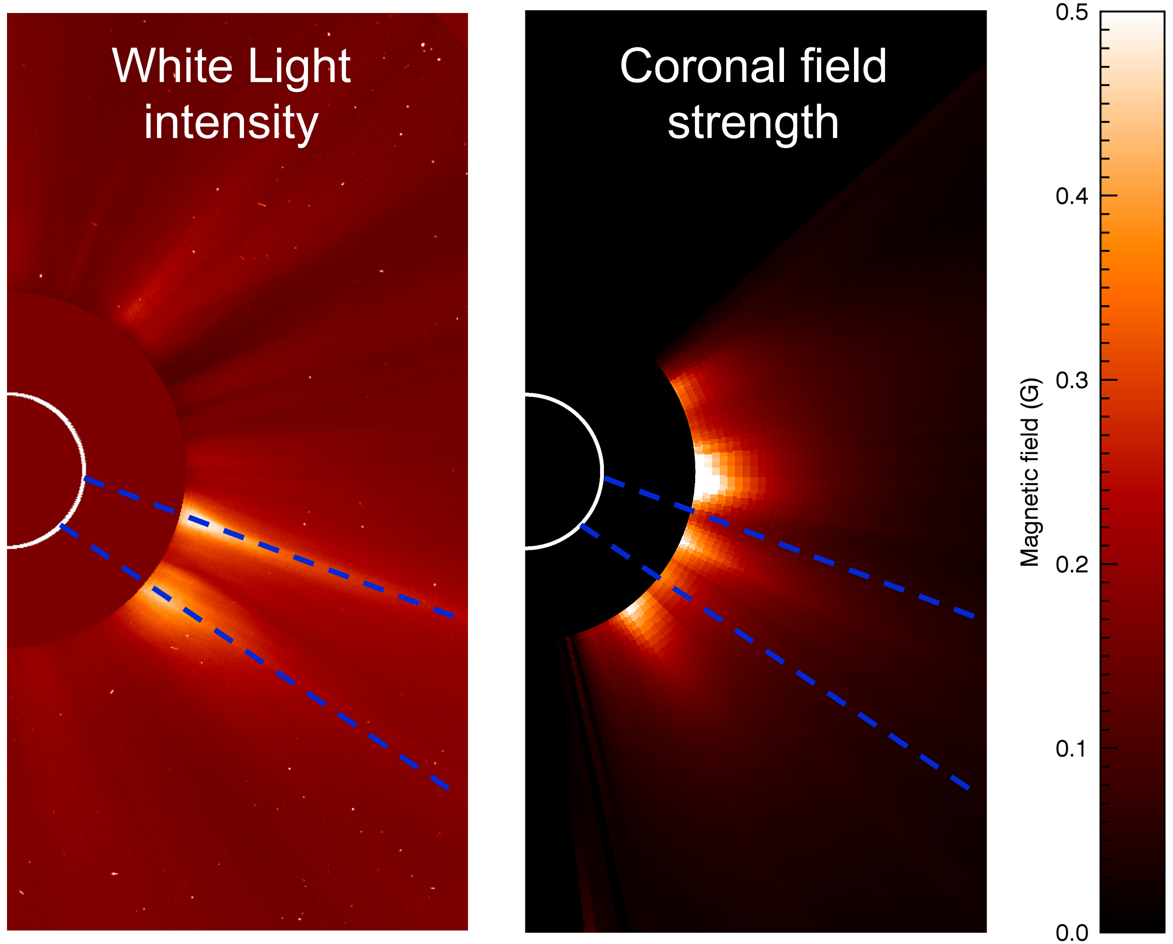


Coronal Magnetic Fields



Susino, Bemporad & Mancuso (2015)

Coronal Magnetic Fields

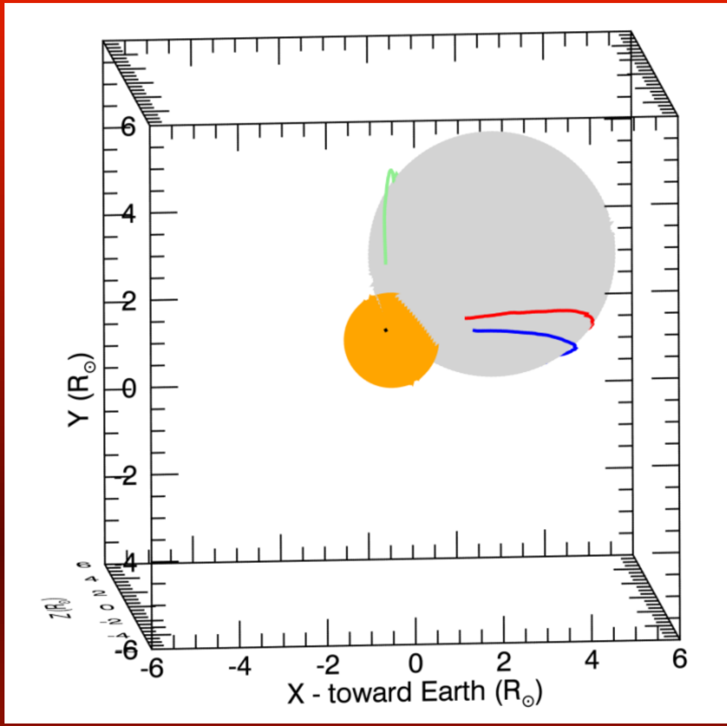


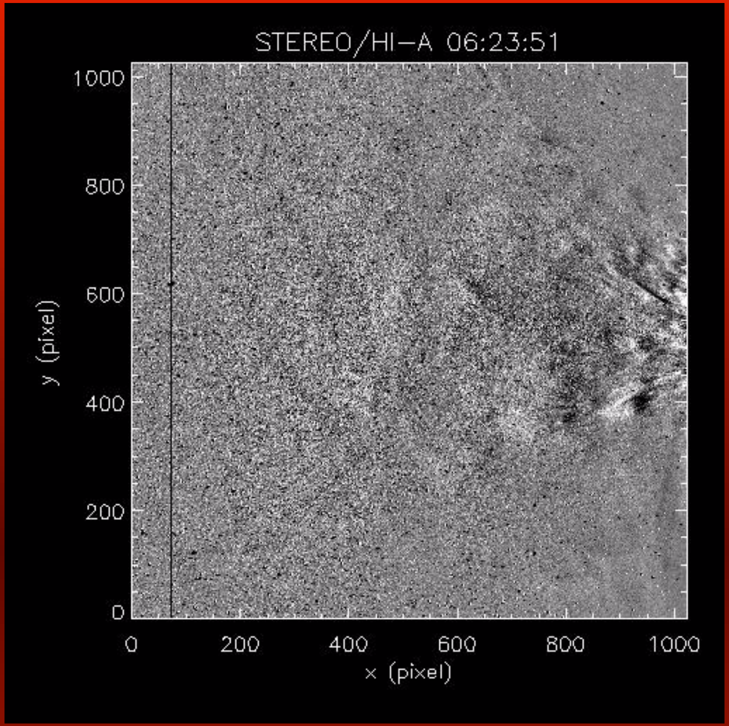
Susino, Bemporad & Mancuso (2015)

Results: brighter features in WL (streamers) associated with lower magnetic field strength and vice-versa → in agreement with the location of neutral CSs.

This is the **first ever 2D coronal magnetic field map derived with such large altitude and latitude coverage**.(~110° in latitude, 12 R_{sun} in altitude)

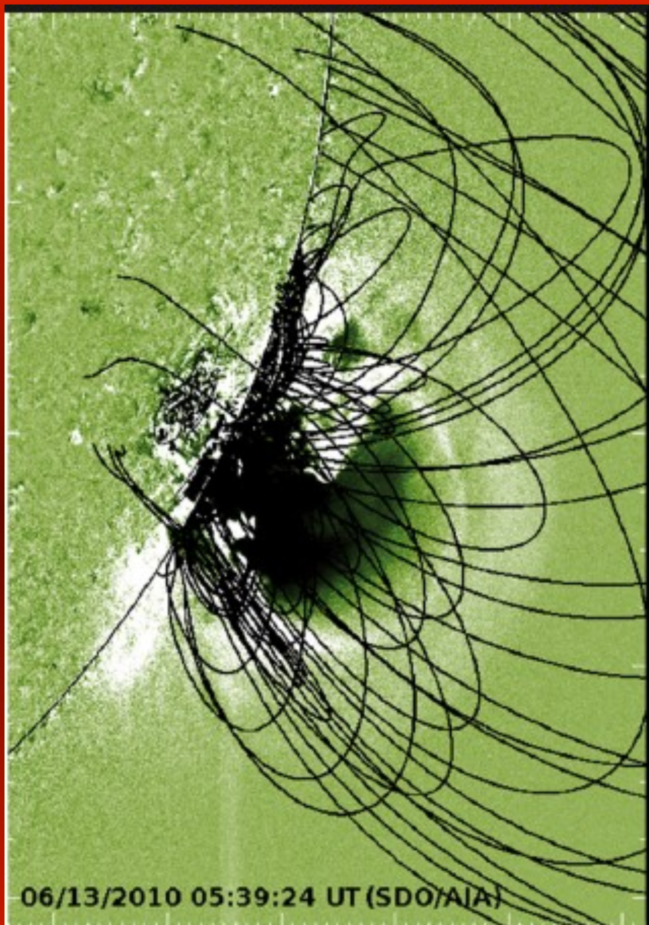
Future developments (1/2)





- Identification of **shock front** in COR-A and –B data → **2D maps of mag. fields** in the intermediate corona (~ 2-10 R_{sun}) at **different longitudes** → comparison with field extrap. and 3D MHD models (**WG5 – Bs challenge**);
- identification of possible **SEP sources** in the corona → **3D reconstruction** of the **shock surface** with LASCO, COR1-A and COR1-B **+** comparison with SEP fluxes measured by SOHO and STEREO + SEP propagation model (**WG6 – SEP source**);
- identification of **interplanetary shock** in HI data → determination of 2D maps of magnetic fields in the outer corona (**WG5 – Bs challenge**)

Future developments (2/2)

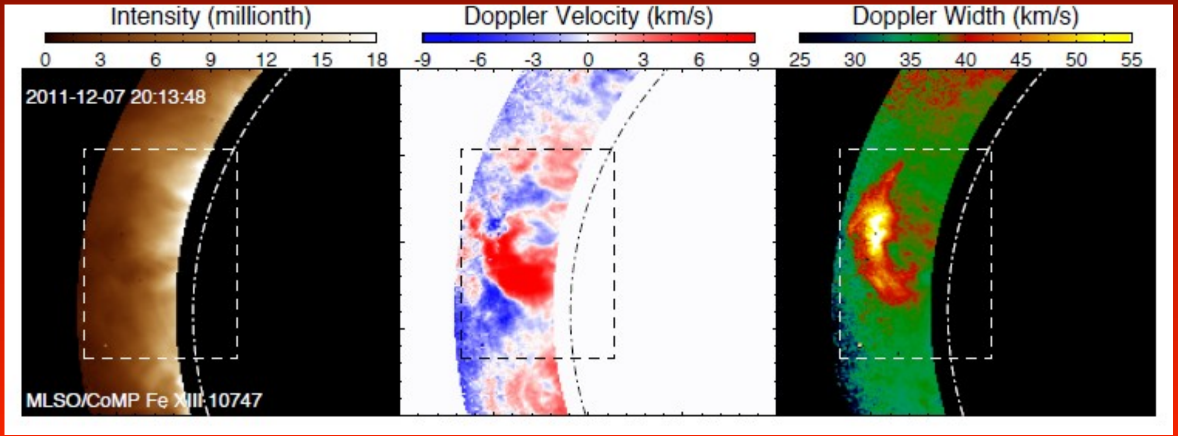


Kozaref et al. (2011)

Select good candidate events for the determination of **lower coronal field strenght, compression & deflection** (**WG5 – Bs challenge**) across the shock from the early evolution in EUV images; this will need:

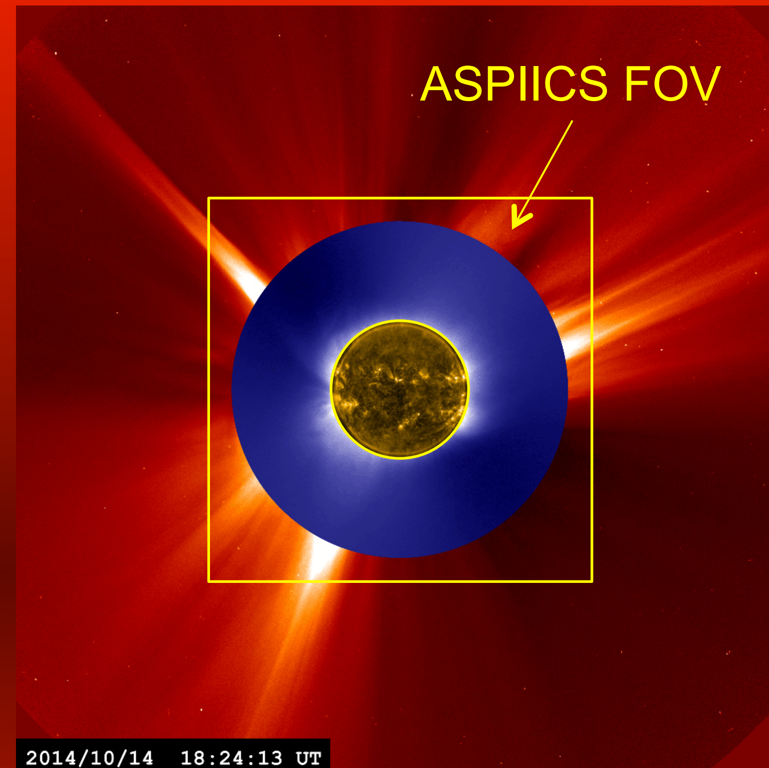
- inclusion of a coronal field extrapolation/model for the pre-shock field orientation,
- inclusion of pre-shock coronal field orientation as observed with spectro-polarimetry (CoMP data),
- comparison between magnetic field strengths measured with shock and spectropolarimetry and extrapolated field,
- discuss how results are related on the assumed pre-shock field inclination.

Tian et al. (2012) →



Future perspectives (1/2): PROBA-3/ASPIICS

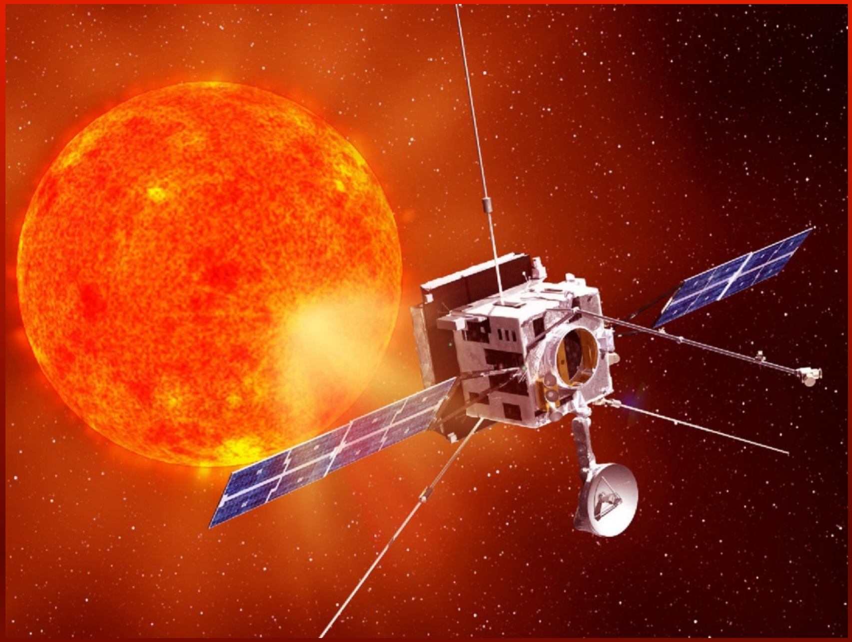
ASPIICS FoV: 1.08 – 3.0 R_{sun} (4.2 R_{sun} in the corners)

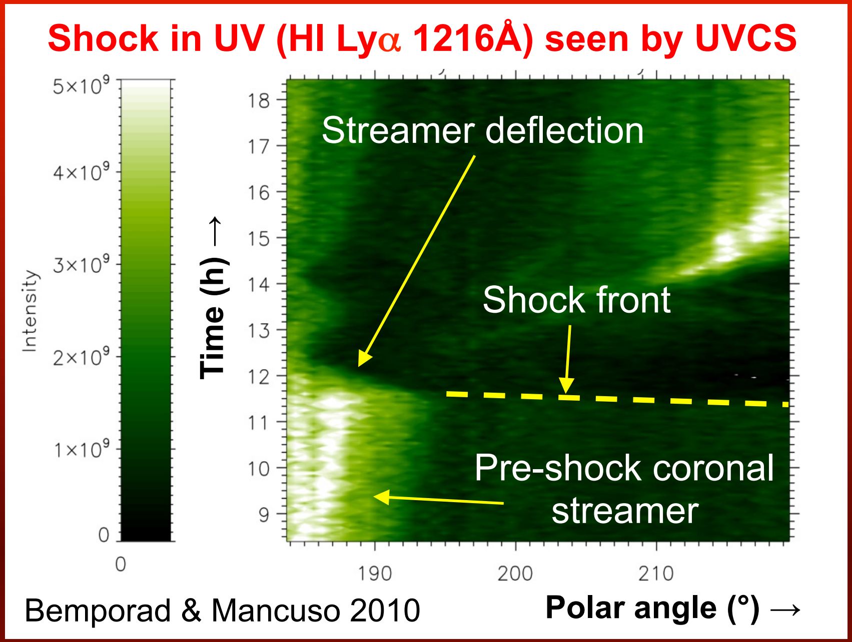


Proba-3 is ESA's – and the world's – first precision **formation flying mission**. A pair of satellites will fly together maintaining a fixed configuration as a 'large rigid structure' in space to prove formation flying technologies. The paired satellites will form together **a 150-m long solar coronagraph (ASPIICS)**.

The ASPIICS Coronagraph will have **5 channels**: 1 white light, 4 polarised light, 1 narrow-band filter (He I D3 line at 5876 Å) → discussion on possible inclusion of narrow-band filters for FeXIV 5303 Å «green» line is in progress → coronal **field measurements** with Hanle effect

Future perspectives (2/2): Solar Orbiter/METIS





Solar Orbiter/METIS will provide the first ever obsevations of solar corona in **WL** and **UV** (**HI Lyman-α 1216** Å). Coronal **HI Lyman-α is** almost entirely due to radiative excitation by chromo-spheric radiation, followed by spontaneous emission (**resonant scattering** - Gabriel 1971).

Shocks transit → shock heating of protons + adiabatic heating of electrons → neutral H atoms (initially unaffected) surrounded by hotter and faster plasma → increase in collisional ionization rate by e^- and charge exchange rate with p^+ → **sudden HI Lyman-α intensity decrease** due to 1) **higher T** and 2) **higher v_{out}** (Doppler dimming) → post-shock plasma barely visible in **HI Ly-α.**

⇒ Described techniques will allow to infer the **shock heating** and **coronal fields**, given the **pre-shock densities from WL** (pB) and **pre-shock temperatures from I(lyα)/pB ratio**.

Summary & Conclusions

• **UV and WL data combination** → unique information on CME-driven shocks: *full pre- and post-shock plasma parameters* (*T*, *n*, *v*) and *magnetic field vec*tor ***B*** on POS along the shock front → modification in the ambient field met by the CME

• **WL coronagraphic images** can provide many information as well → shock compression ratio, velocity, Mach number in the region crossed by the shock → identification of super- sub-critical regions

• This allowed us to derive the **2D distribution of magnetic field strength** up to 12 R_{sun} (not only radial profiles at shock nose, but also latitudinal distribution).

• **Future developments:** extend these studies at the lower corona (combining EUV images, field extrapolations, field reconstructions with CoMP) and at the extended corona (with images acquired by the heliospheric imagers)

• **Future perspectives:** combine these techniques with future magnetic field spectro-polarimetric observations that will be provided by PROBA-3/ASPIICS; apply these techniques to future Solar Orbiter/METIS observations of shocks.