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Measuring the coronal and heliospheric magnetic field with visible-light images of CME-driven shock waves

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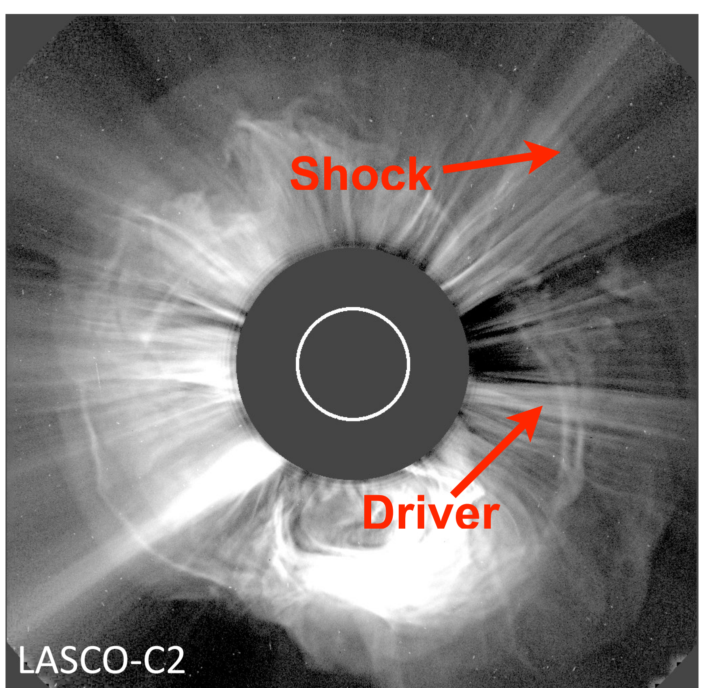
Coronal magnetic-field measurements

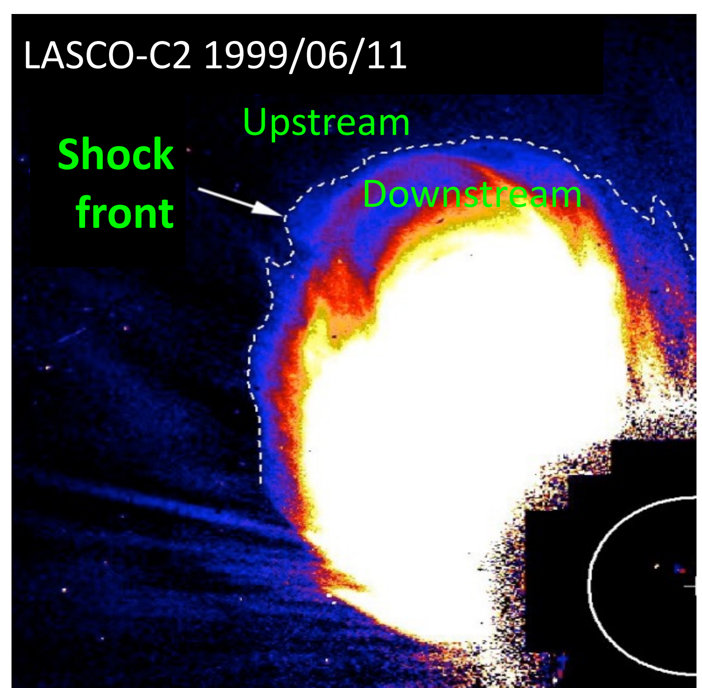
- Knowledge of coronal magnetic field strength and orientation is primarily based on extrapolations of photospheric magnetic fields derived from spectro-polarimetric measurements (Zeeman effect)

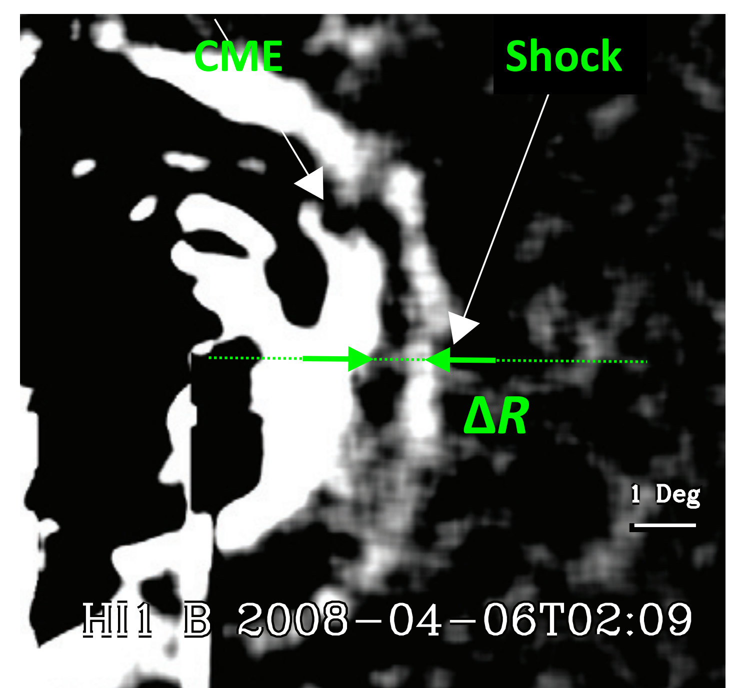
- Different techniques have been developed to estimate magnetic fields in the outer corona
  - radio techniques
    - Faraday rotation
    - circular polarization in radio bursts
  - spectro-polarimetry in IR and UV emission lines (Hanle effect)
  - coronal seismology applied to EUV images of EIT waves
  - analysis of the dynamics of CME-driven shocks in visible-light images
    - *plasma compression ratio*
    - *stand-off distance*

CME-driven shocks

- Fast CMEs can drive shock waves in the corona and heliosphere
  - they can be identified in coronagraphic visible-light images as thin layers of enhanced emission located ahead of the driver (CME front)
- Visible-light images can be used for the determination of:
  - shock front geometry
  - shock velocity
  - plasma compression ratio ($X = \rho_d / \rho_u$)
  - shock stand-off distance (ΔR)

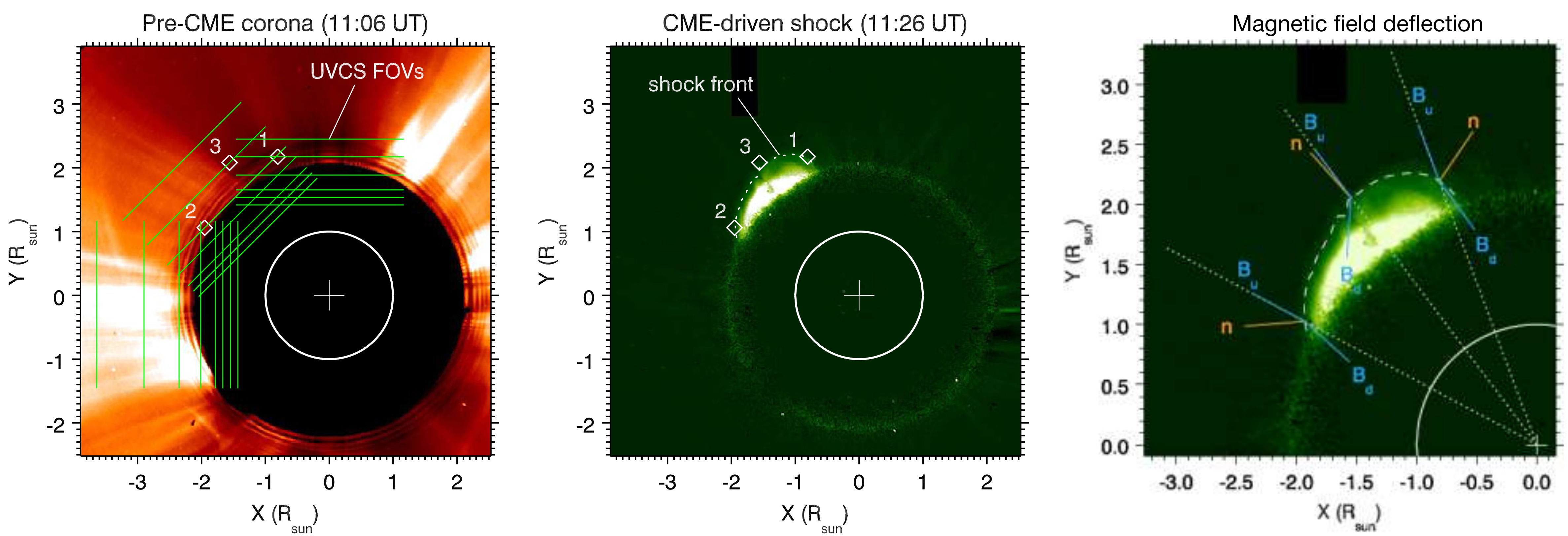




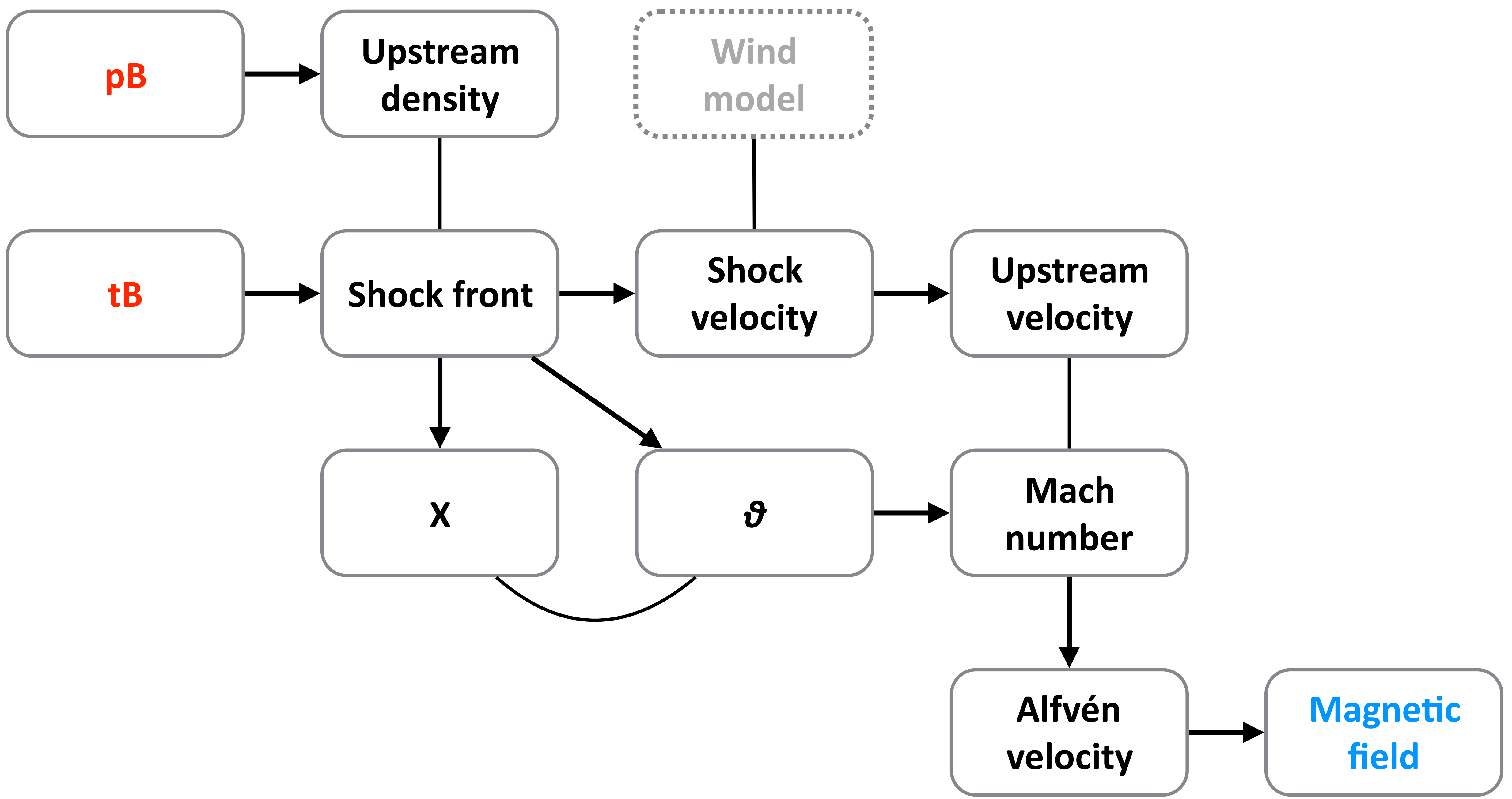


Previous works

- Unique information can be derived from the analysis of simultaneous visible-light and UV data (Bemporad & Mancuso 2010; Bemporad, Susino, & Lapenta 2014; Bacchini et al. 2015):
- LASCO plus UVCS observations
  - plasma compression ratio along the shock front
  - full set of upstream plasma parameters (T, n, v_{sw})
- Rankine-Hugoniot equations for oblique shocks
  - downstream parameters including *B* vector on the plane of the sky
    - plasma heating
    - magnetic field compression
    - *v* and *B* vector deflection

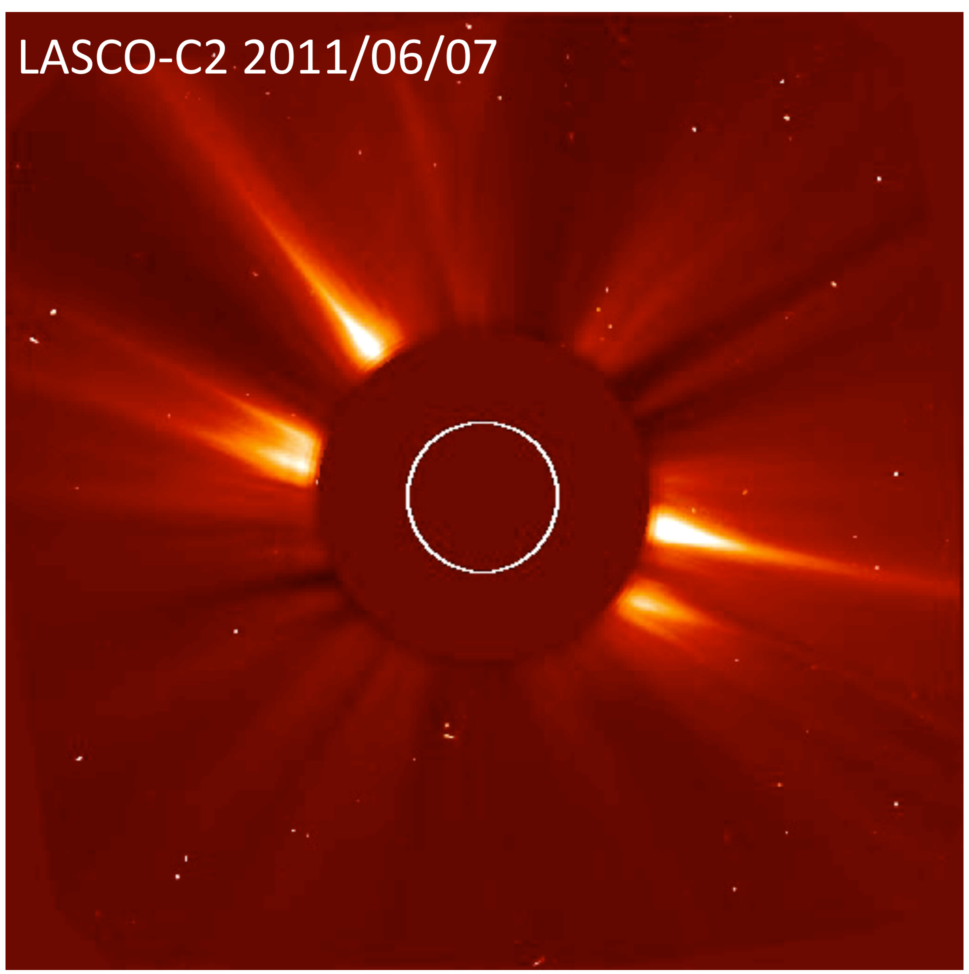


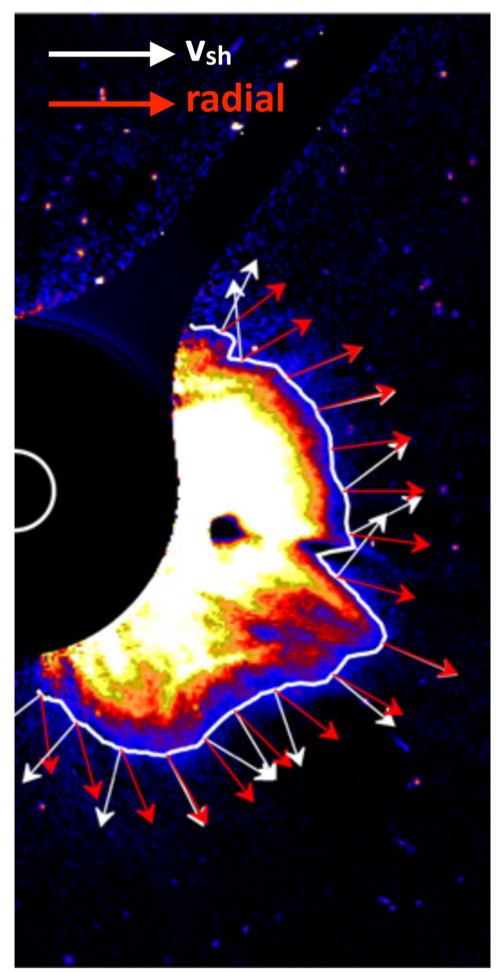
Magnetic field from shock dynamics



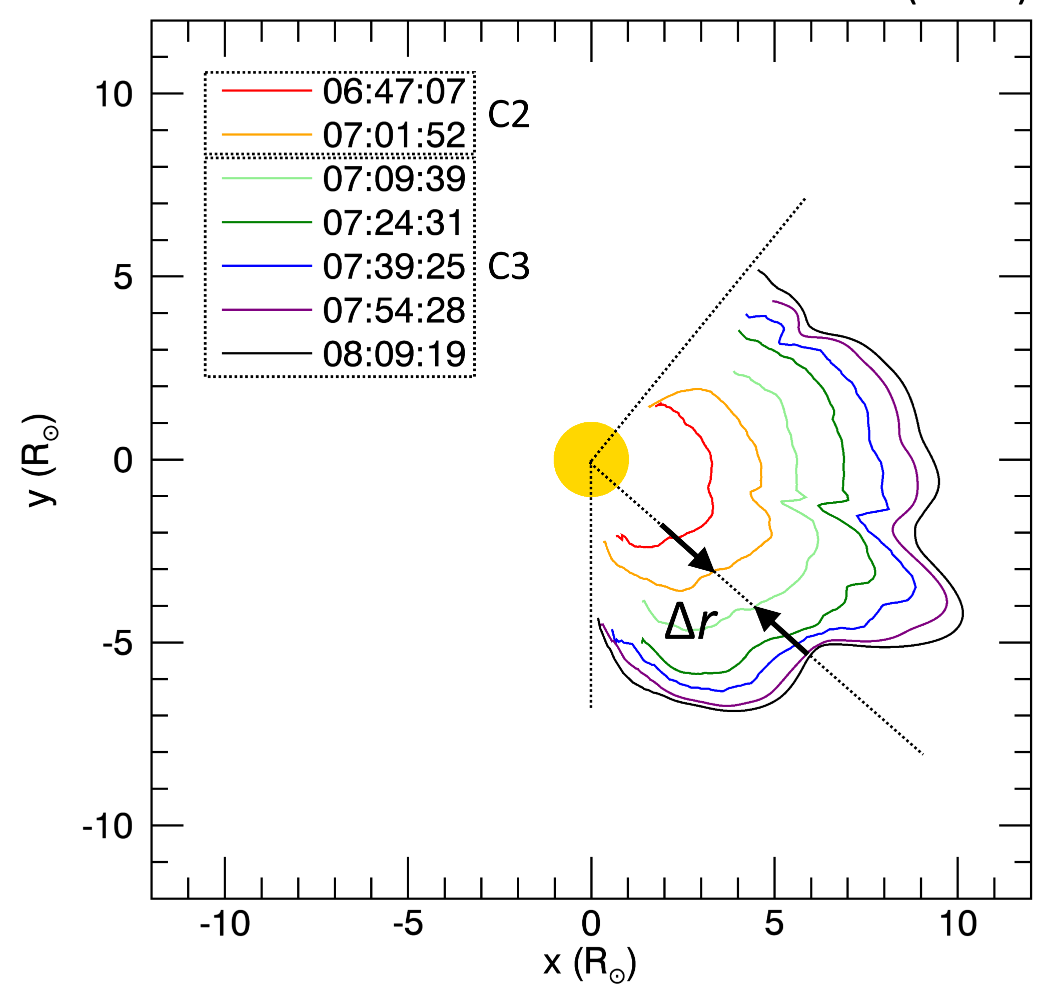
Test case

- Analysis of a CME associated with an M2.5 flare, an EUV wave, type-II and III radio bursts, and gamma-ray emission
- Shock front is identified in LASCO-C2 and C3 images up to ~ 10 $R_\odot$
  - measurement of angle ϑ between radial direction and shock normal
  - derivation of shock velocity v_{sh} (from the ratio $\Delta r/\Delta t$)





Susino et al. (2015)



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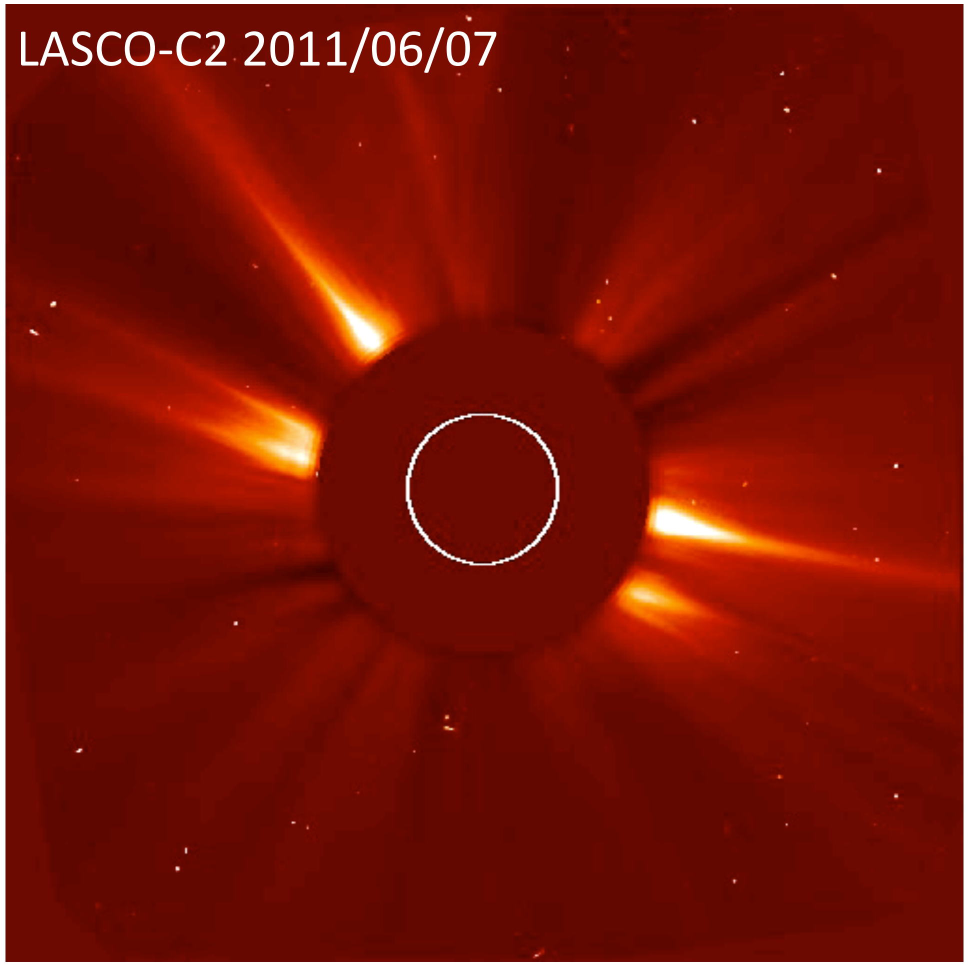

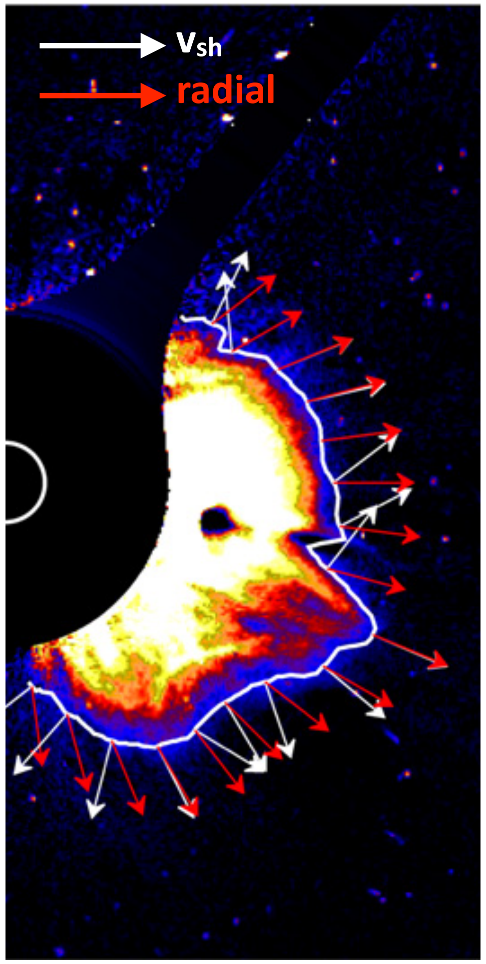

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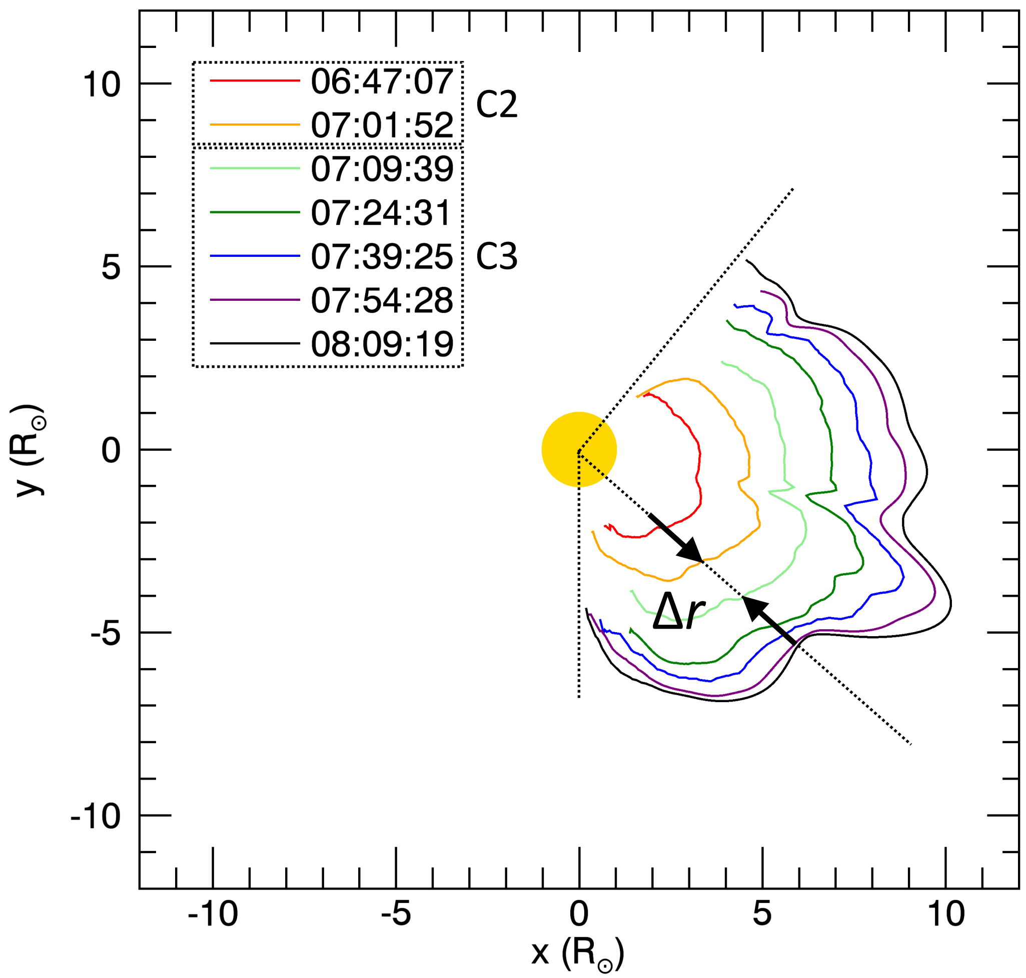
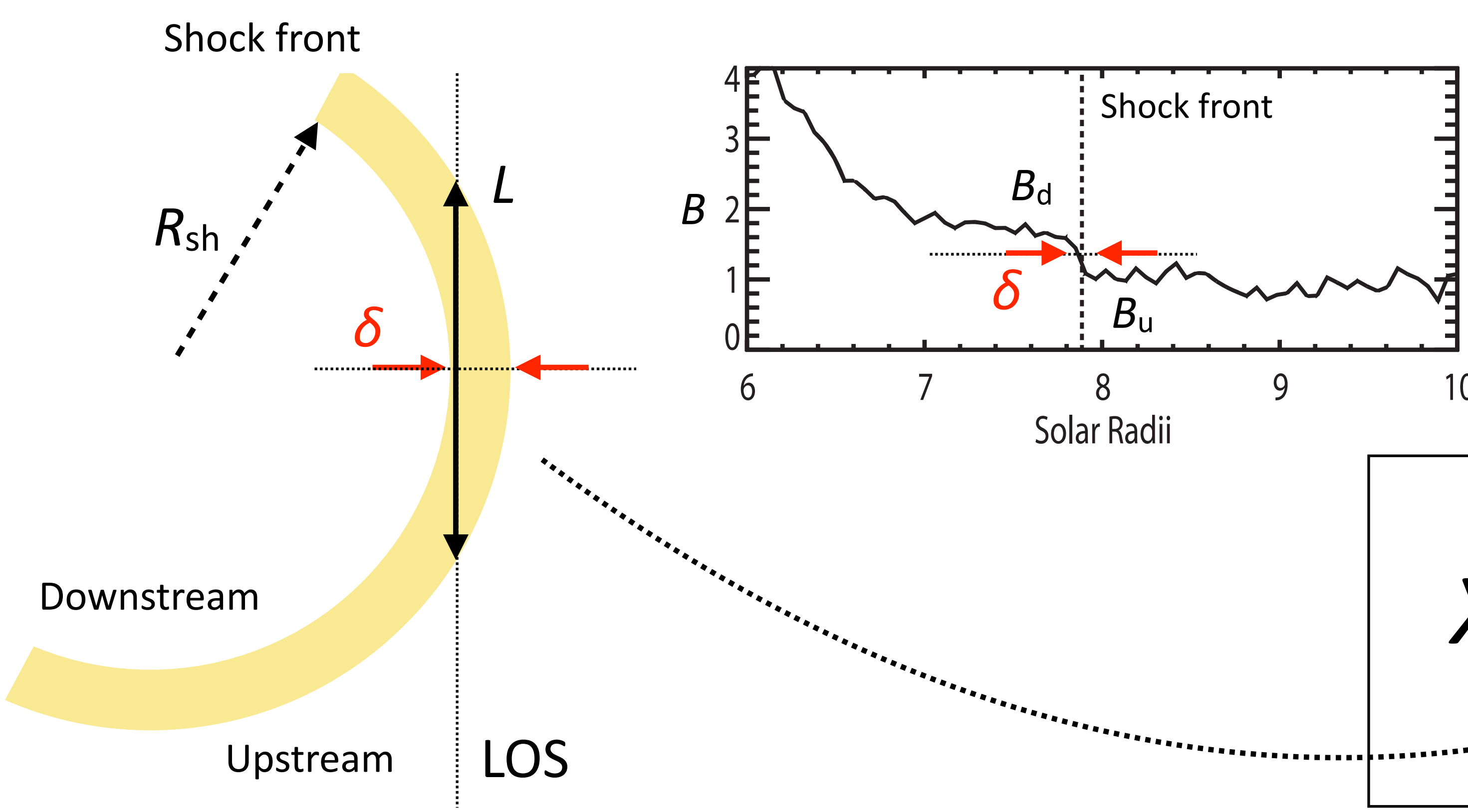


Compression ratio and Mach number

- Compression ratio *X* is inferred all along the shock front curves by:
  - taking into account LOS integration effects by estimating the shock depth *L* along the LOS from its projected thickness
  - deriving the density jump in the shock region of length *L* giving the best reproduction of the visible-light brightness variation across the shock
- Mach number *M* is derived by applying an empirical formula that is valid in the case of oblique shock (for $\beta < 1$ plasma conditions)



$$X \approx \frac{B_d - B_u}{f \cdot B_u} + 1$$

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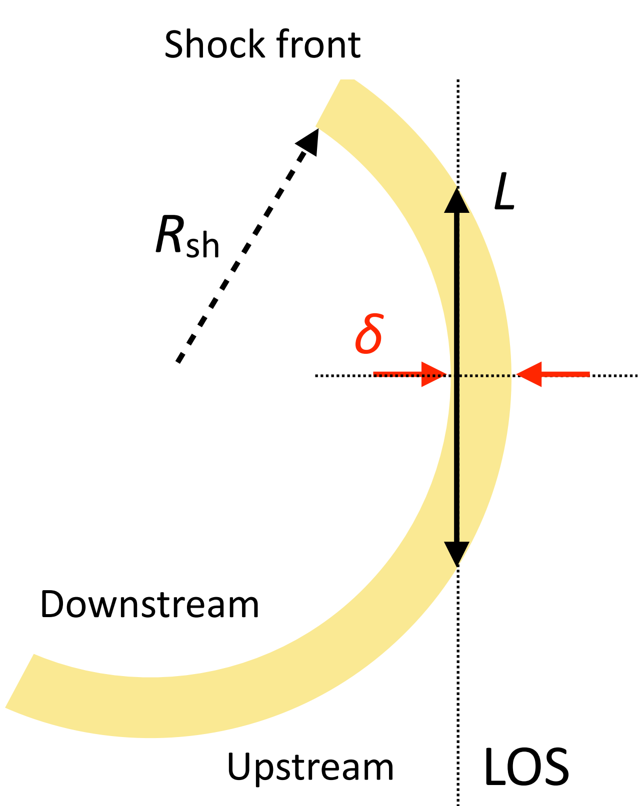

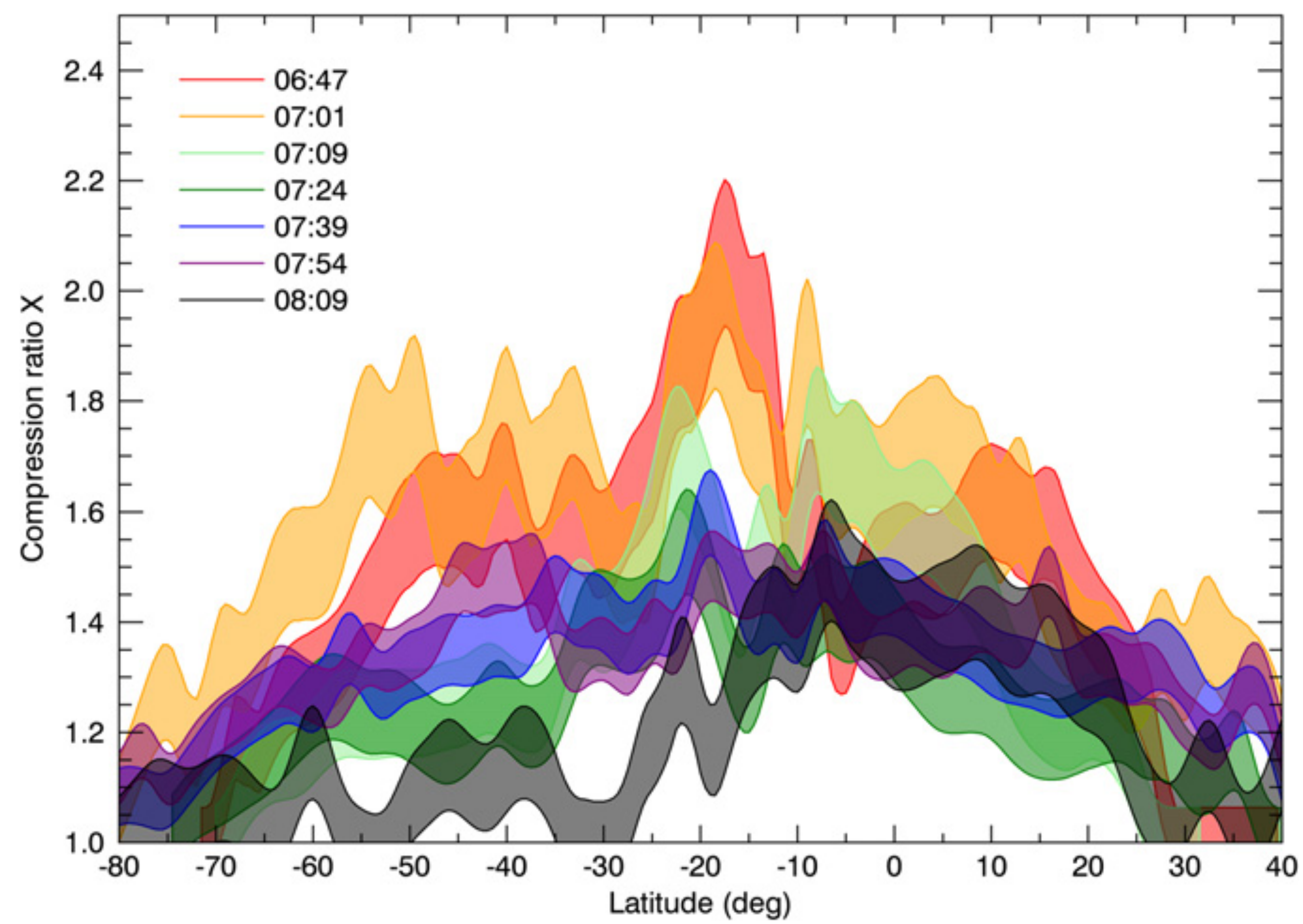

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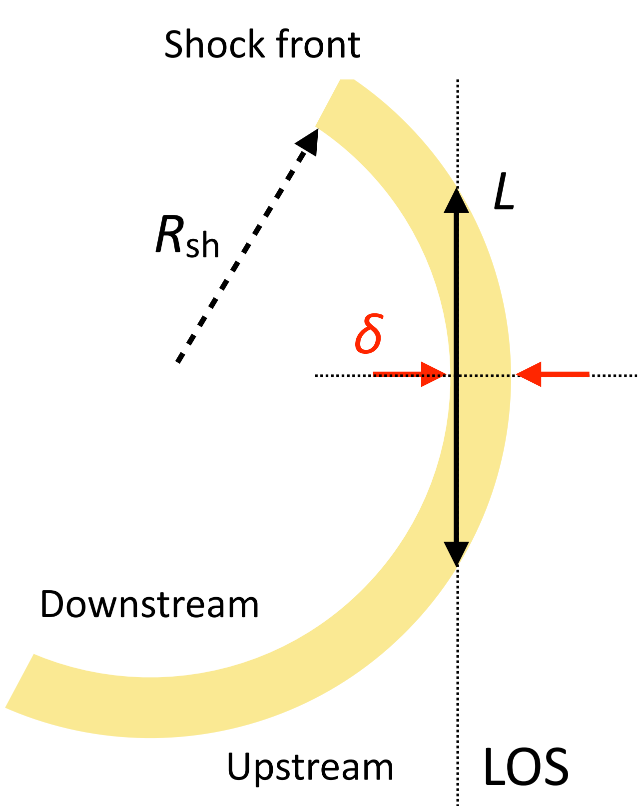
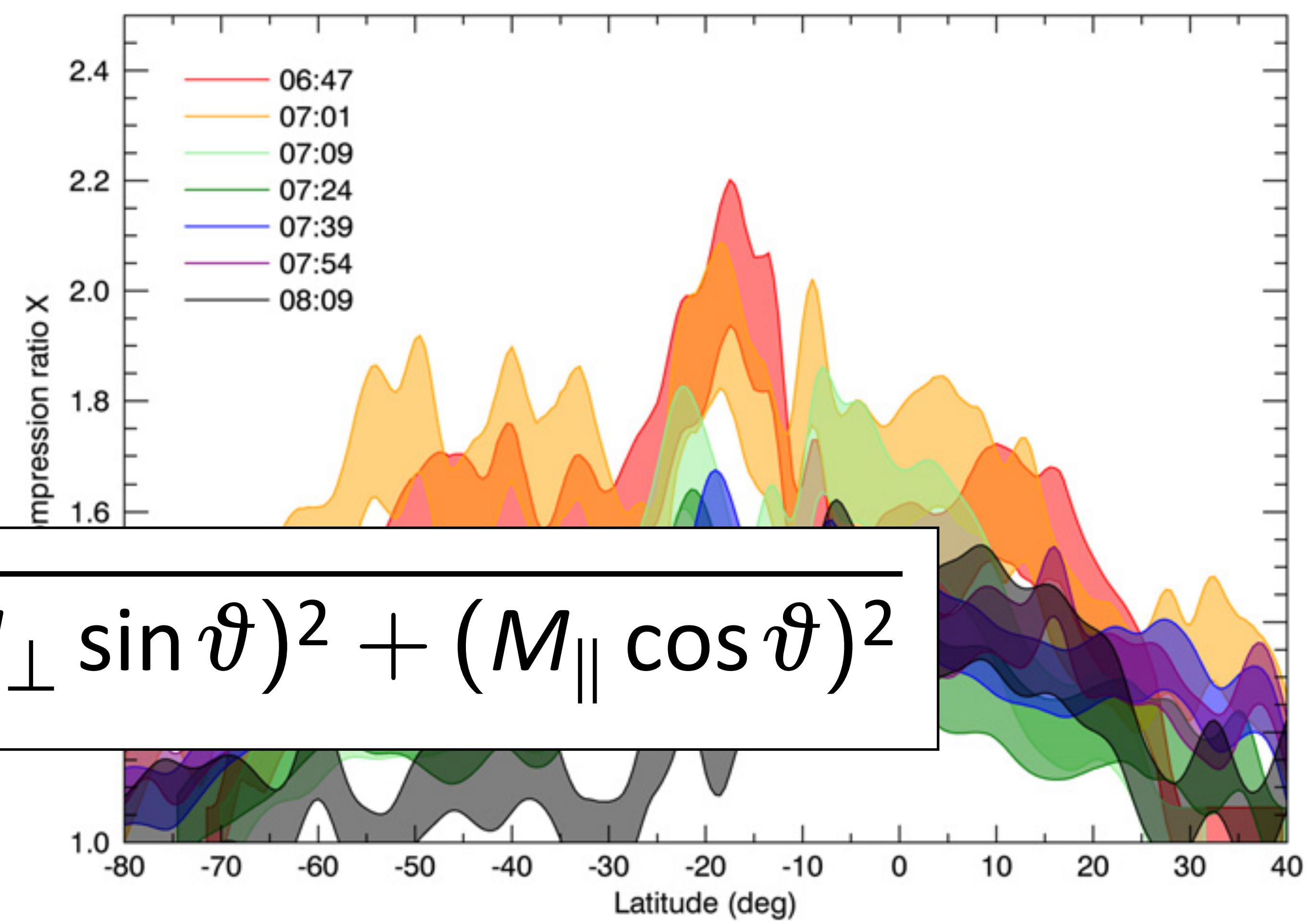
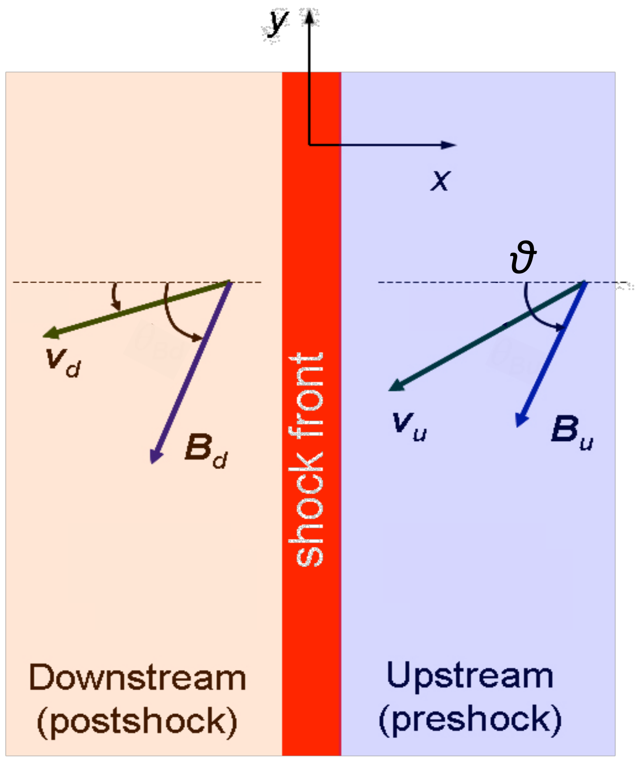


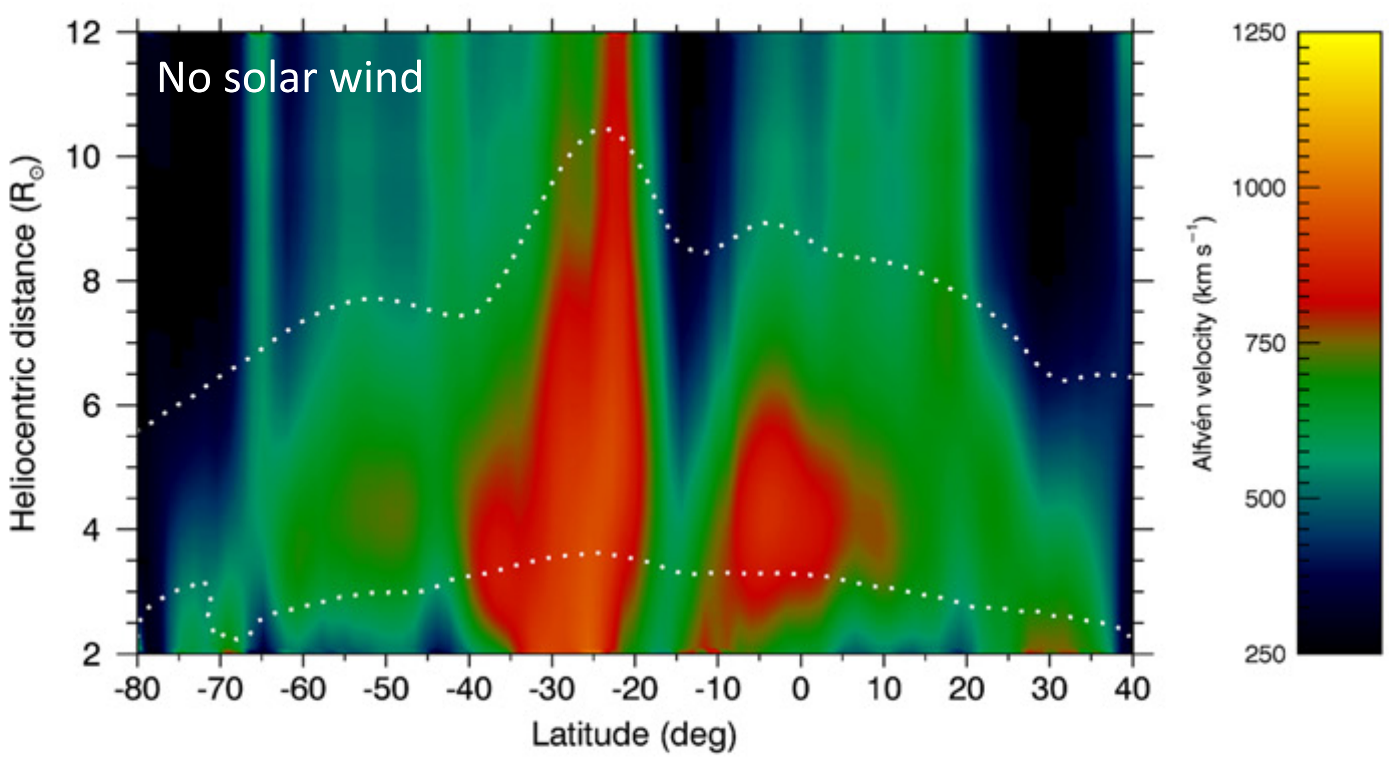
$$M = \sqrt{(M_{\perp} \sin\vartheta)^2 + (M_{\parallel} \cos\vartheta)^2}$$



Alfvén velocity

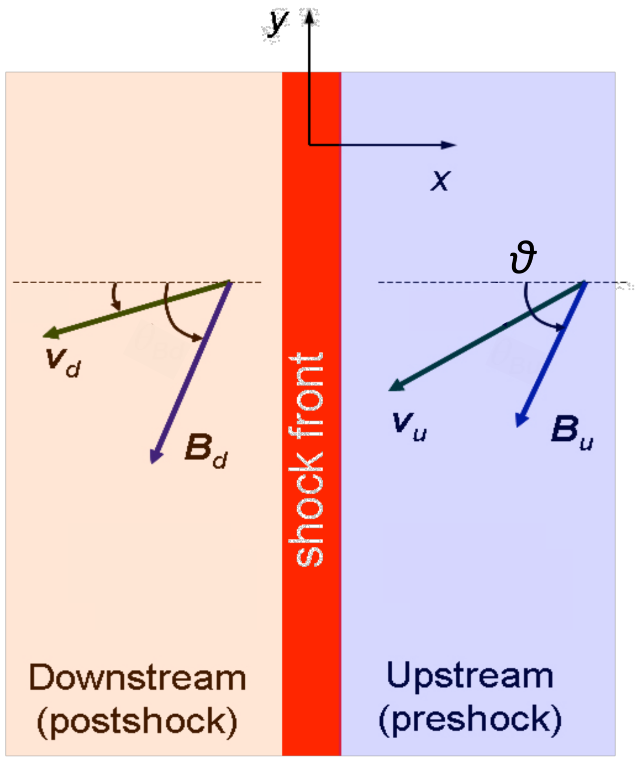


$$v_A = \frac{\|\mathbf{v_{sh}} - \mathbf{v_{sw}}\|}{M}$$



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

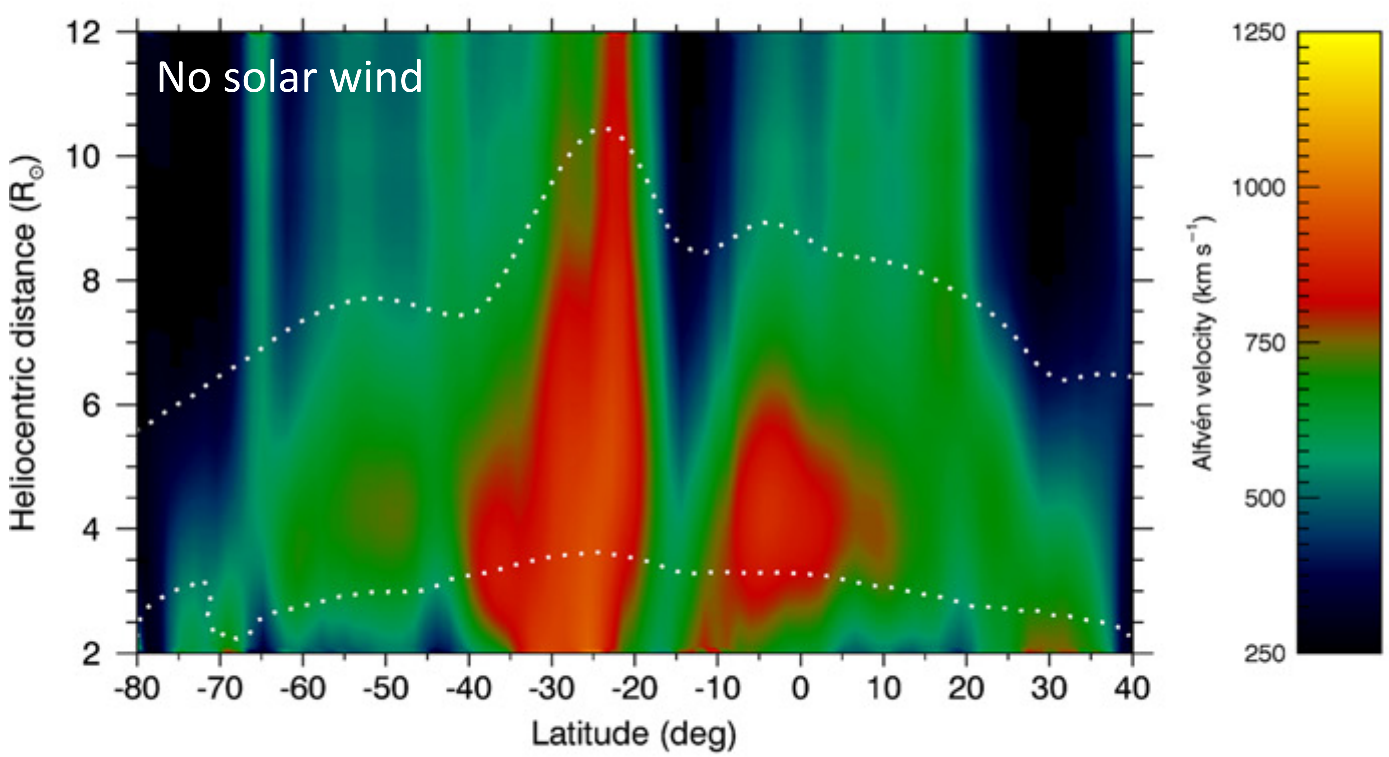
Alfvén velocity



$$v_A = \frac{||\mathbf{v}_{\mathrm{sh}} - \mathbf{v}_{\mathrm{sw}}||}{M}$$

$$v_A^{(x)} = v_{\mathrm{sh}} - v_{\mathrm{sw}} \cos\vartheta$$

$$v_A^{(y)} = -v_{\mathrm{sw}} \sin\vartheta$$



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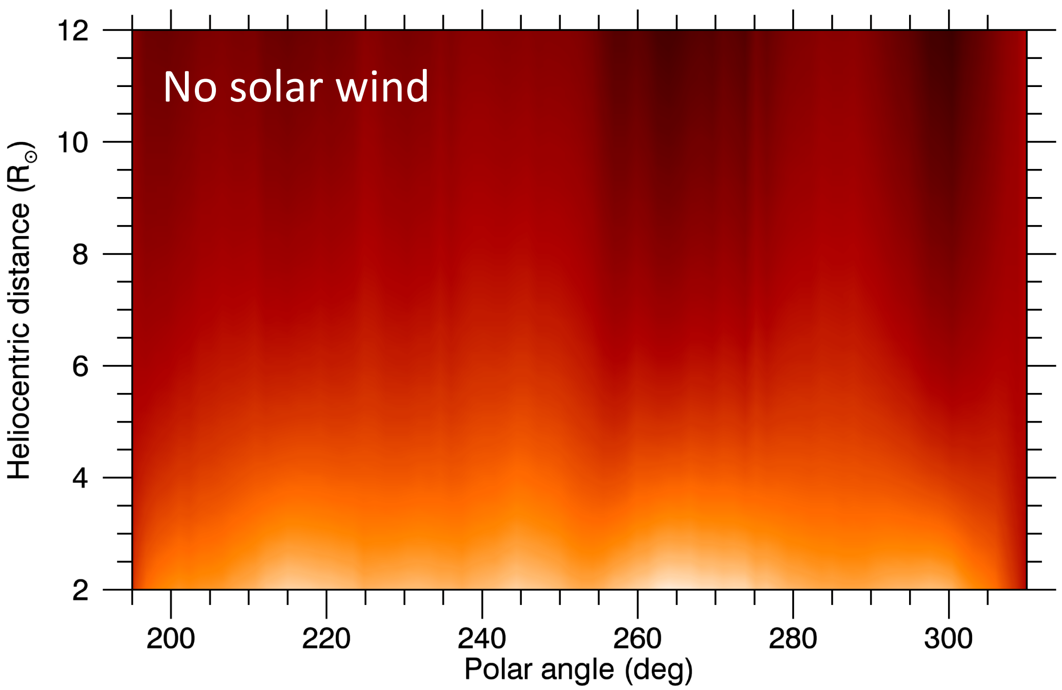
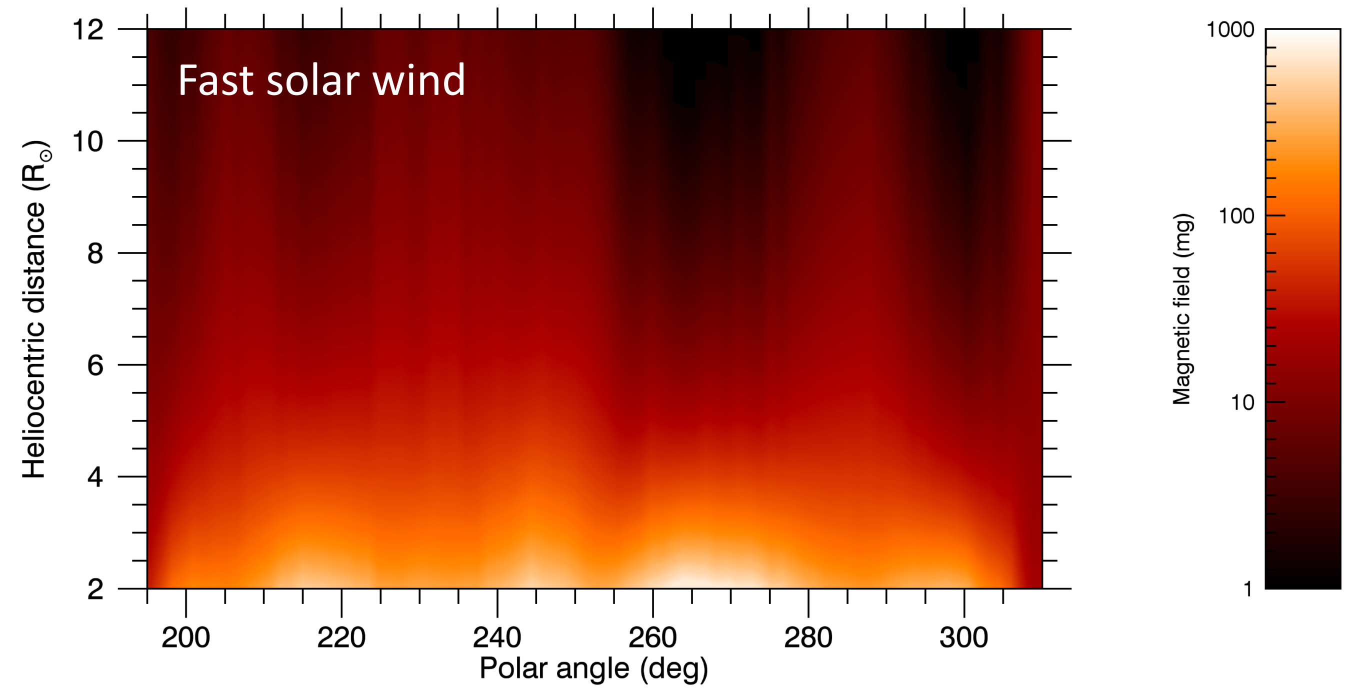
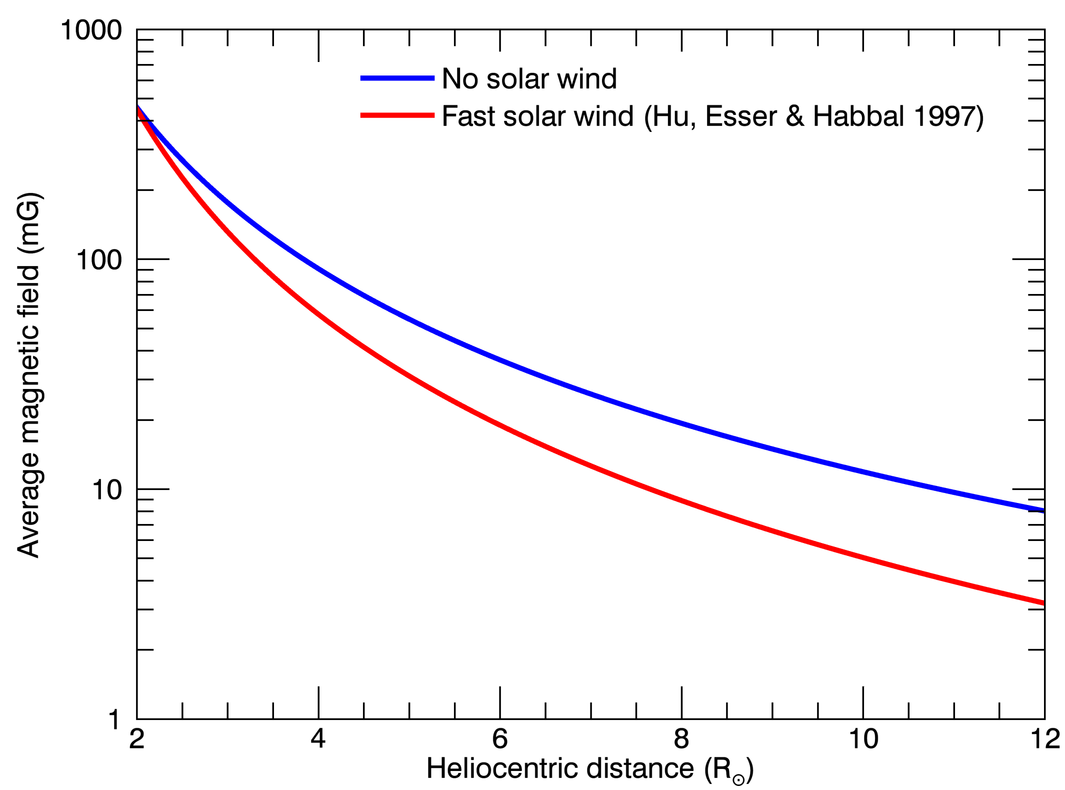
Coronal magnetic field / 1

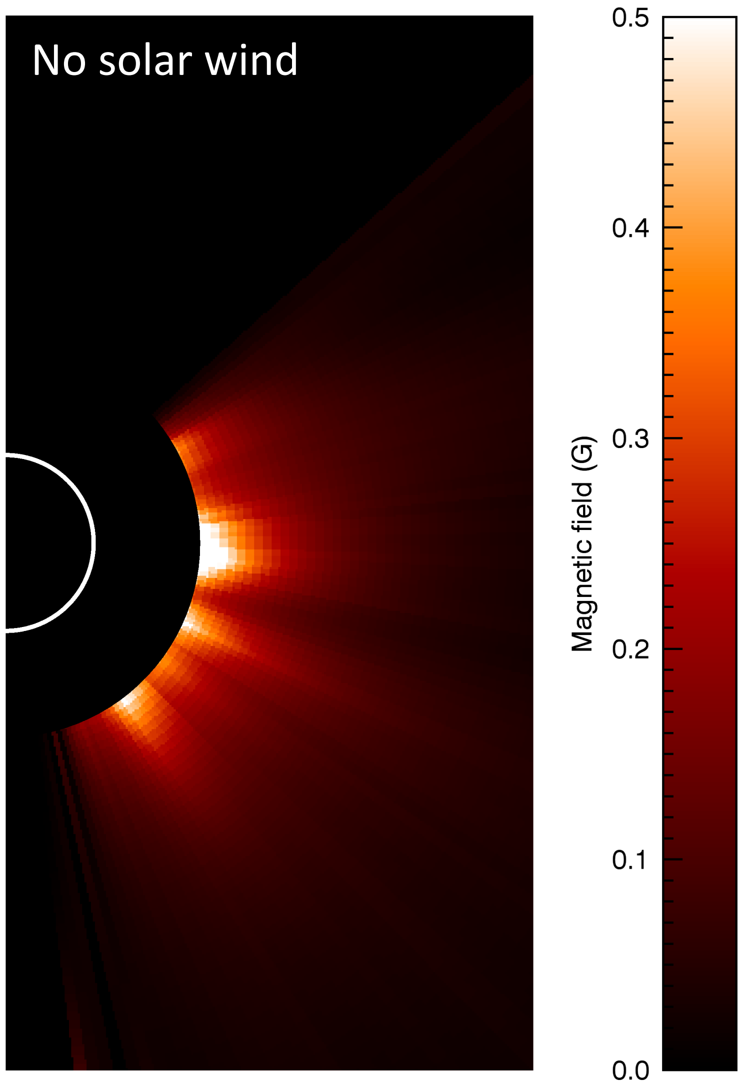


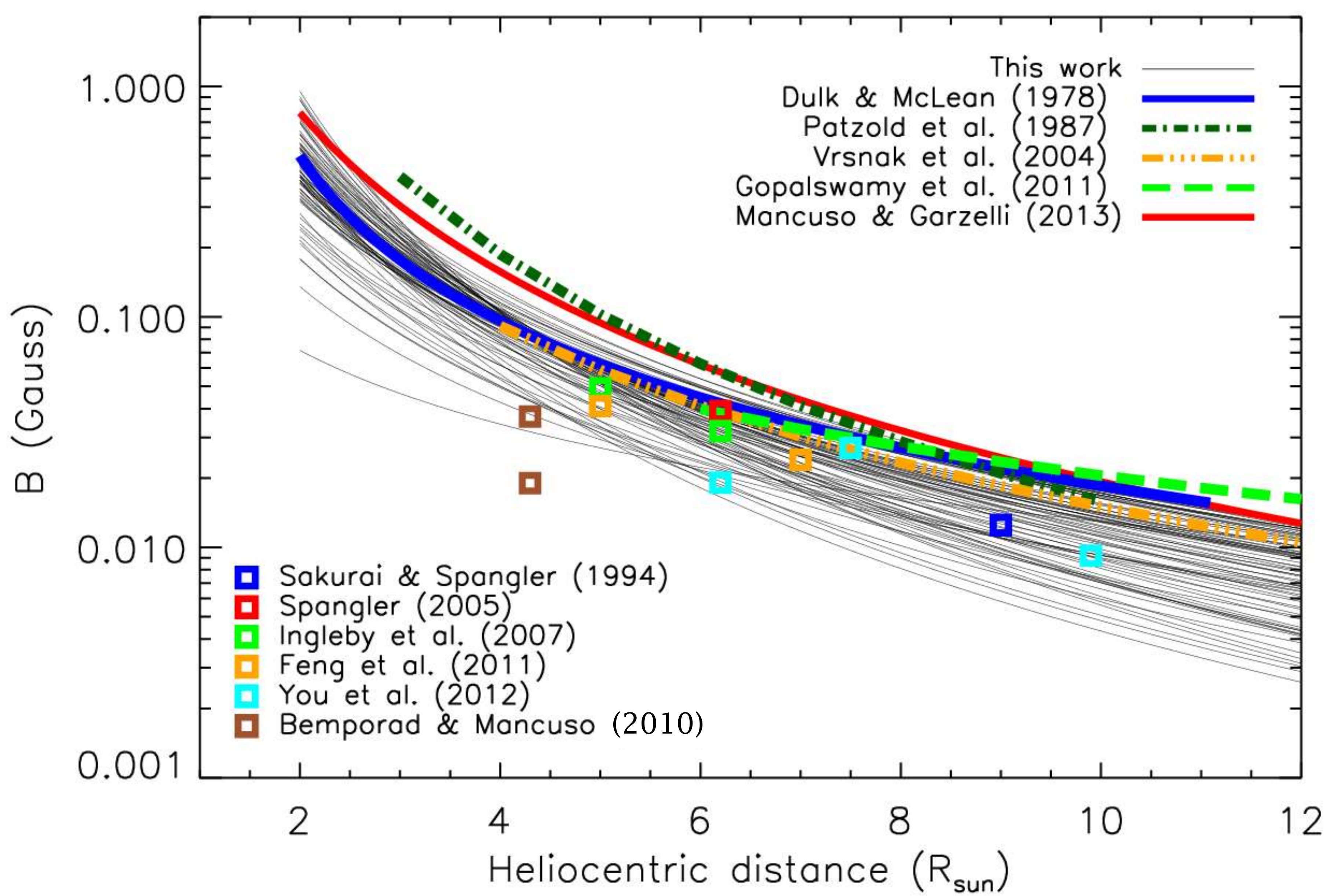




$$B \propto v_A \cdot \sqrt{n}$$

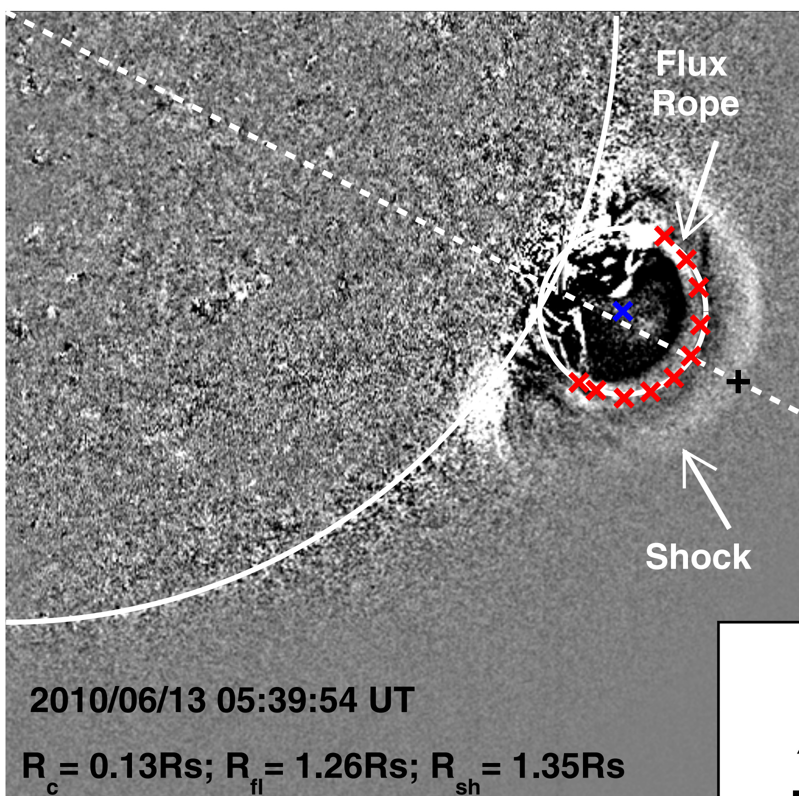
Coronal magnetic field / 2





Stand-off distance method

- Hydrodynamic relationship between the standoff distance Δ*R* of a shock, the radius of curvature (R_c) of the driver, and the Mach number
- Assumptions on wind velocity and plasma density are needed to derive *B*
- Limited to radial profiles of magnetic field, but up to 1 AU following the interplanetary shock



Gopalswamy et al. (2012)

$$\frac{\Delta R}{R_c} = K\frac{(\gamma - 1)M^2 + 2}{(\gamma + 1)(M^2 - 1)}$$

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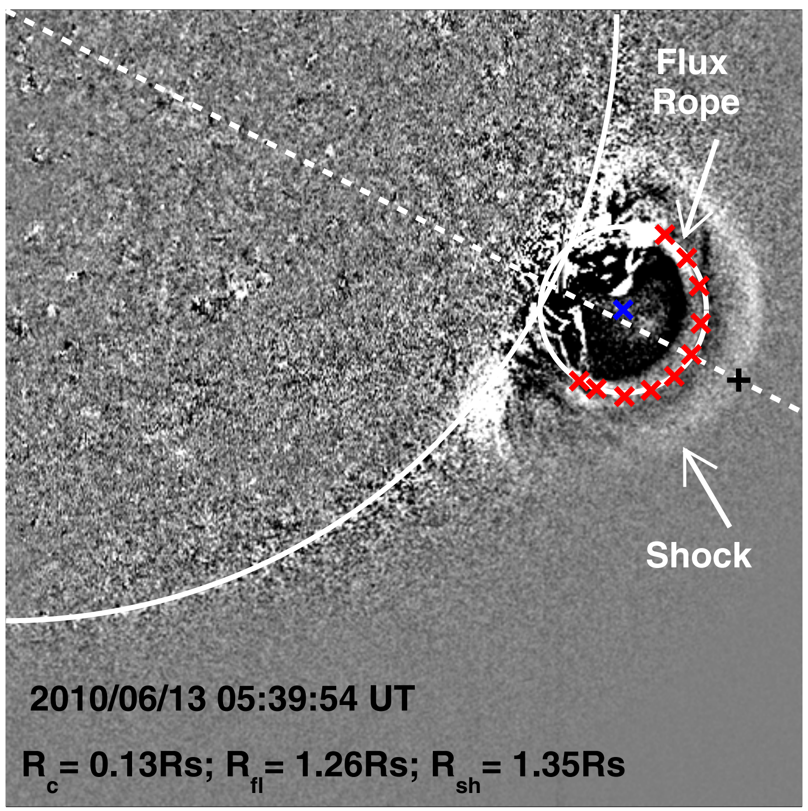

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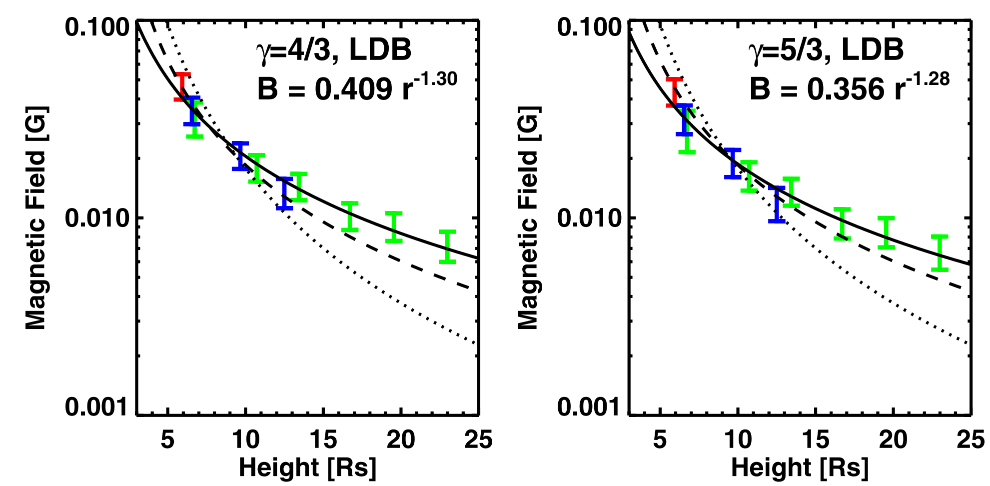
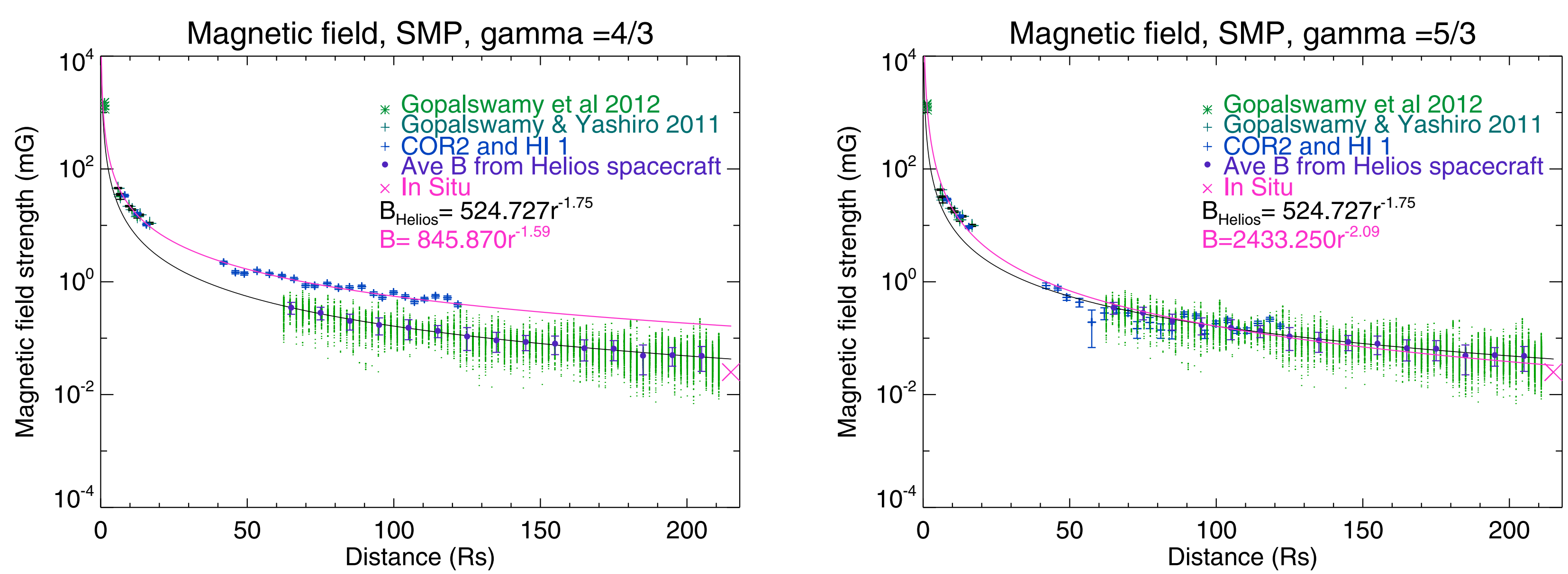
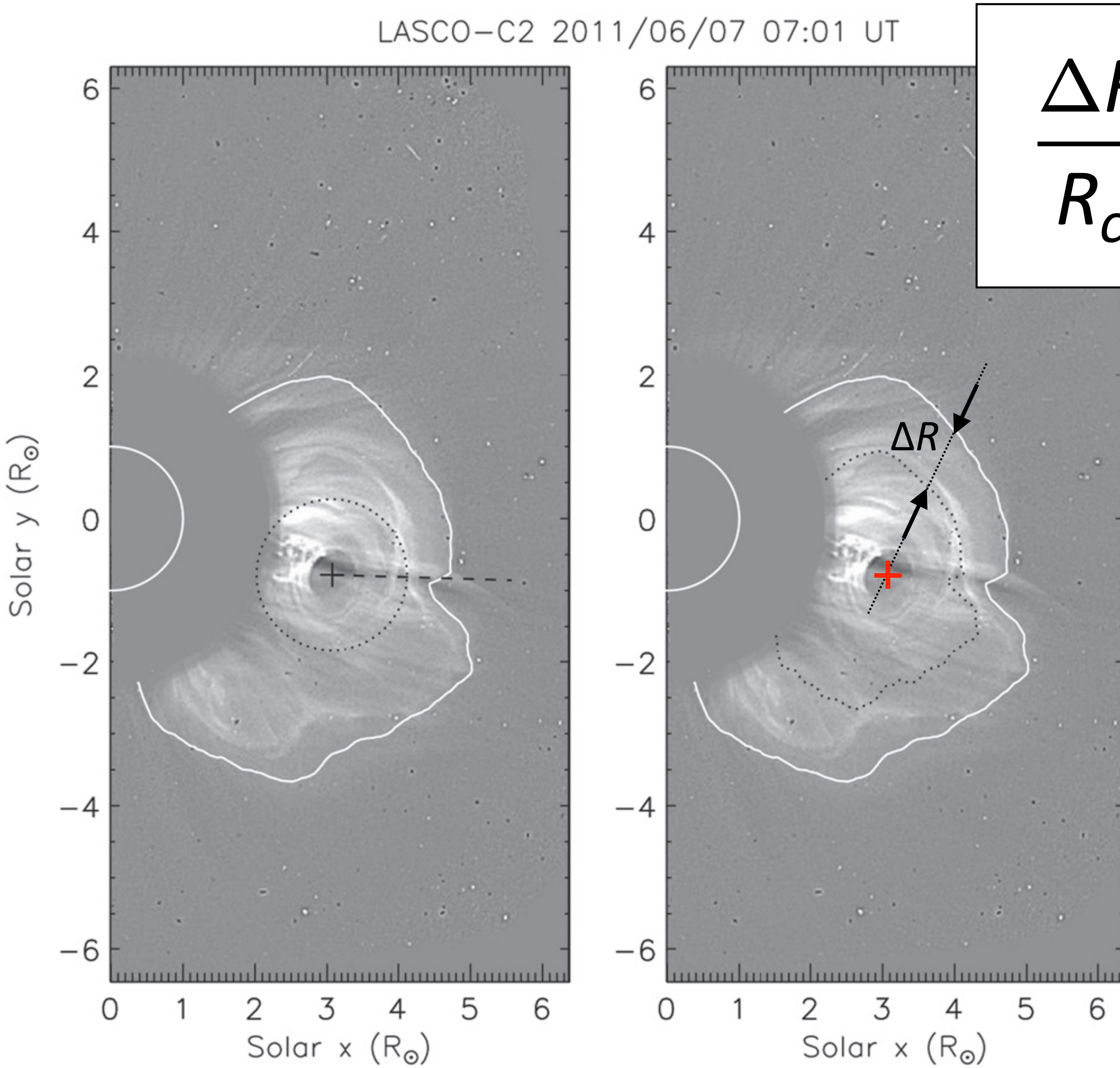




Poomvises et al. (2012)

Comparison with stand-off distance

- R_c is derived from the estimated values of M along the front



$$\frac{\Delta R}{R_c} = K\frac{(\gamma - 1)M^2 + 2}{(\gamma + 1)(M^2 - 1)}$$

- There is noticeable agreement between the derived R_c curve and the flux-rope features visible in the core of the CME

Conclusions

- Visible-light coronagraphic images can provide many information on CME-driven shocks and the ambient solar corona they cross
  - 2D maps of the average magnetic field strength can be derived (*under certain assumptions*) from the analysis of the shock dynamics

- Metis will provide high-resolution, high-cadence images of the solar corona in the polarized visible light and H I Lyman-α line
  - compression ratio and Mach number will be derived from visible-light images
  - outflow wind velocity will be derived from combination of *pB* and UV Lyman-α images using Doppler dimming analysis
  - the full set of pre-/post-shock plasma parameters could be also determined, provided a method to estimate the electron temperature from combination of Metis visible-light and UV images