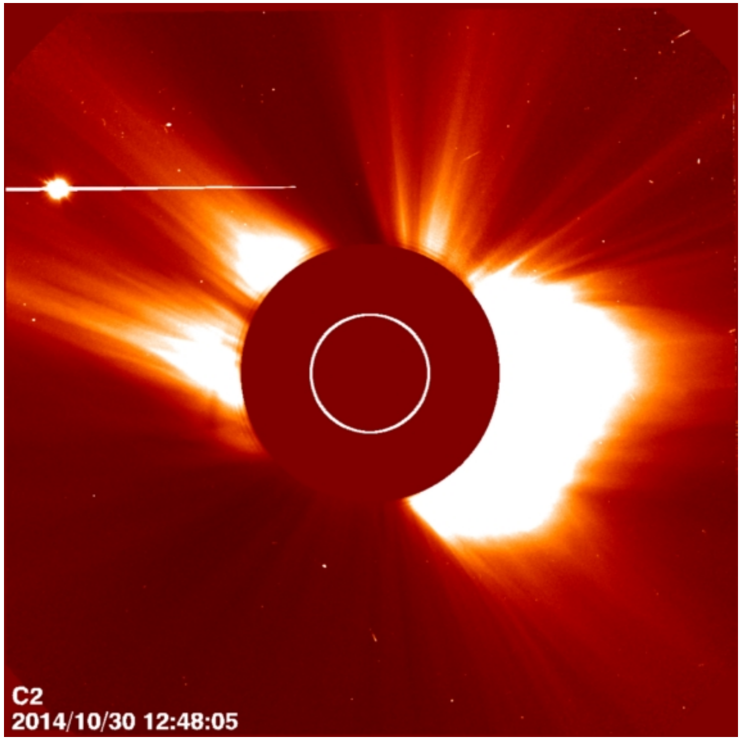
Analysis of a shock formation due to CME-streamer interaction in the inner corona

S. Mancuso, **F. Frassati**, A. Bemporad and D. Barghini

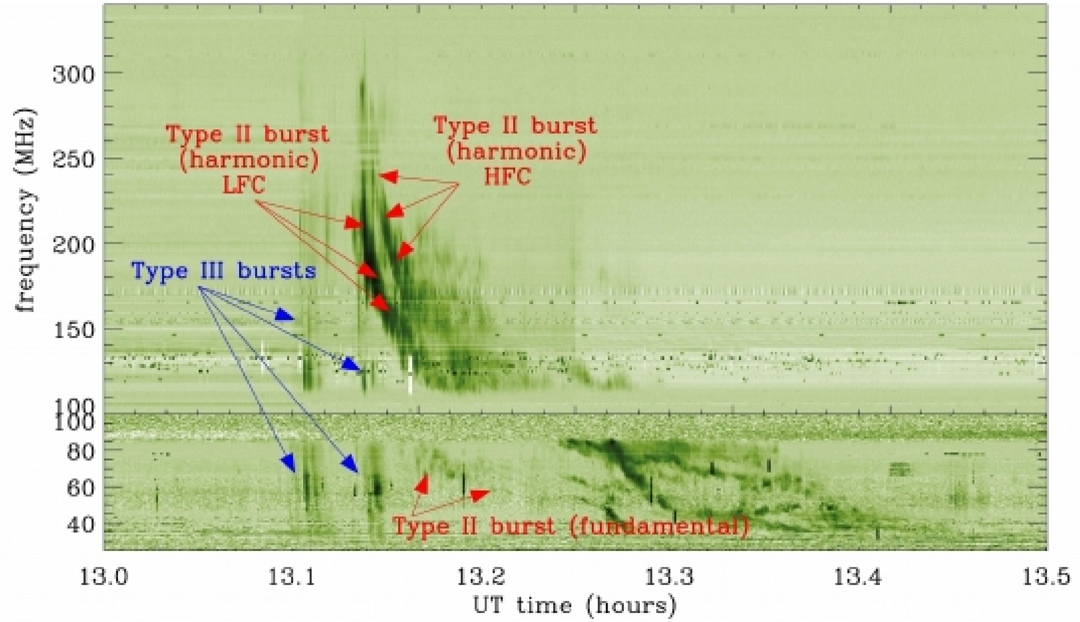
The event

On 2014 October 30 a limb solar eruption occurred in active region NOAA 12201 (S04E70) and involved a C6.9 flare and a CME. The presence of a type II burst starting at 13:08 UT was the evidence of a shock formation.



Type II radio

e CALLISTO BIR spectrometer (200–400 MHz) + USAF Radio
Solar Telescope Network (RSTN) (25–100 MHz)



Complex type II radio burst starting at about 13:08 UT.
Splitting into sub-bands→

- shock/streamer interactions;
- emission from plasma both upstream and downstream of the shock front.

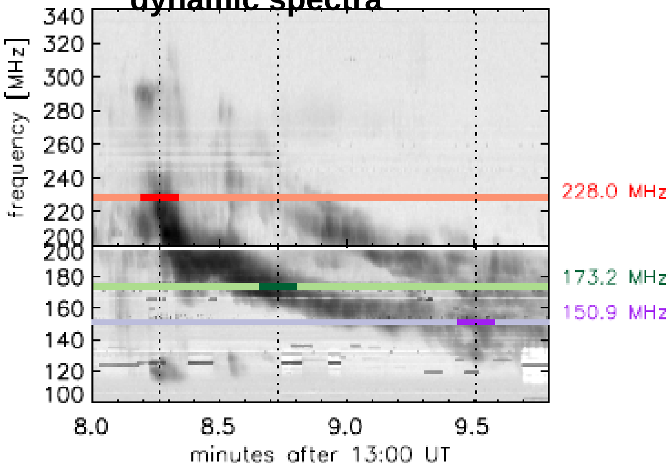
ESA | NASA solar orbiter

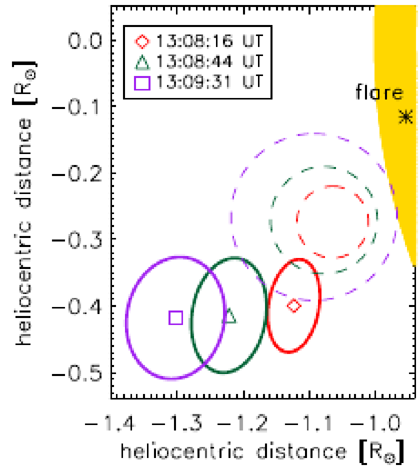
INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

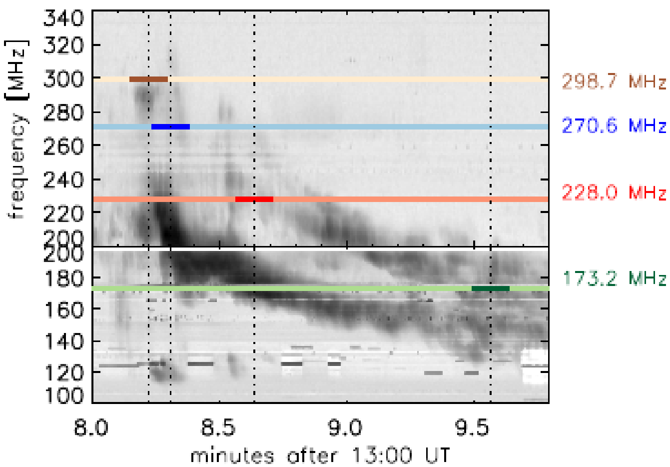
metis

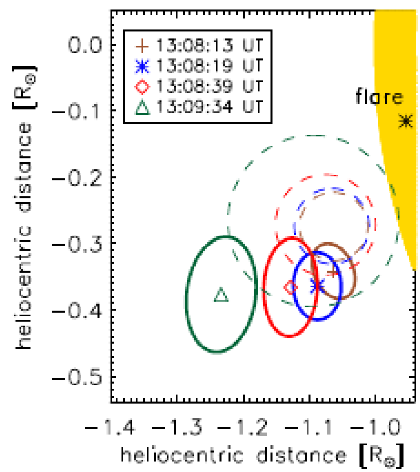
Combined BIR CALLISTO dynamic spectra

Radio sources observed by NRH









- NRH sources estimated by fitting 2D elliptical Gaussian functions.
- BIR CALLISTO spectra show splitting of the harmonic component into a lower (L) and upper (U) frequency component due to the expanding shock.

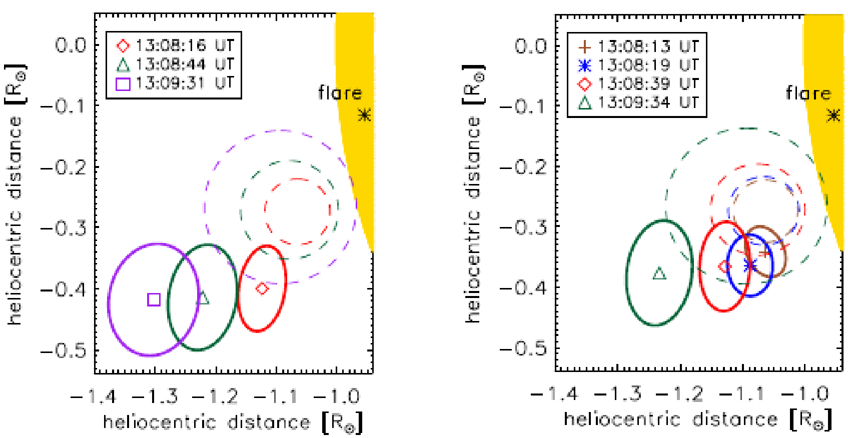
L and U frequency sources were also localized at five NRH frequencies
298.7 MHz;
270.6 MHz;
228.0 MHz;
173.2 MHz;
150.9 MHz.

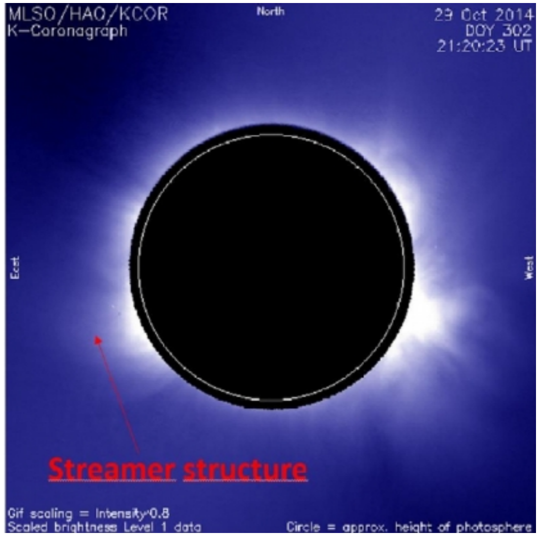
OHB CGS ThalesAlenia Space

IFN ASF ifsi OAC OACt OAPA OATs Osservatorio Astronomico Torino UNIVERSITÀ DEGLI STUDI FIRENZE MPS LAM

Primary Band Splitting

Time (after 13:00 UT)	U	L	
08:13-08:19	298.7 / 270.6	228.0	clearly not co-spatial
09:31 – 09:34	173.2	150.9	clearly not co-spatial

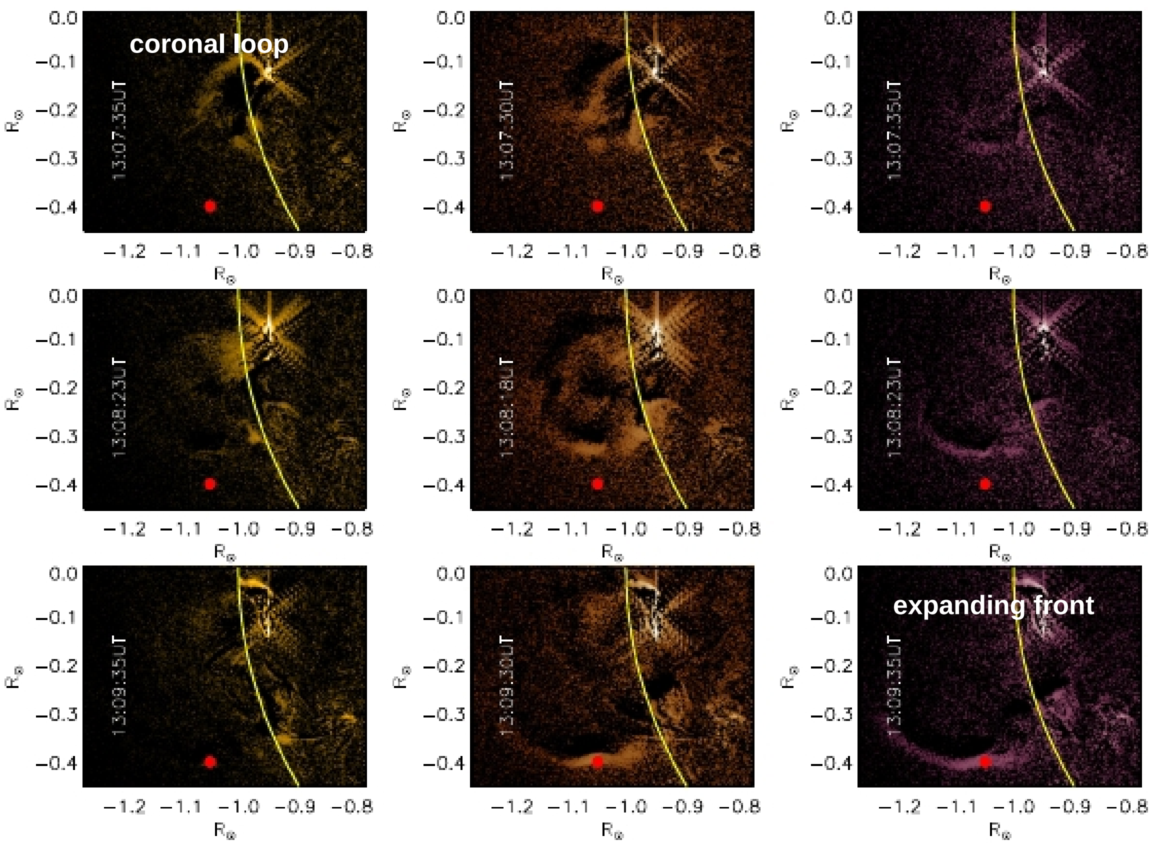


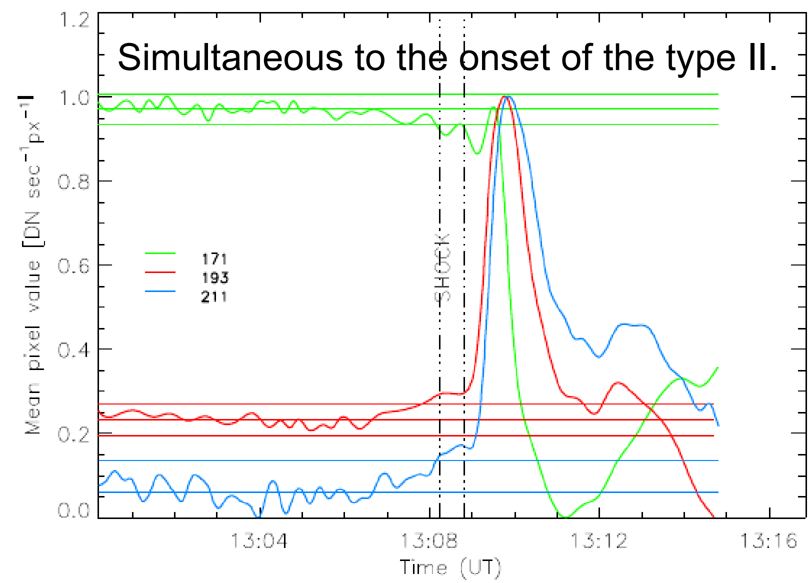


Band-splitting origin is supposed to be due to emission from two different parts of the same shock front expanding through plasma structures with different electron density and magnetic field distributions.

→ The NRH observations would thus represent type II emission at the intersection of the expanding shock surface with the streamers' axes.

EUV Intensities analysis





Temporal variations of observed intensities related on the evolution of electron density and ionization state (depending on temperature) of the plasma → useful to infer the presence of the shock from the observed images

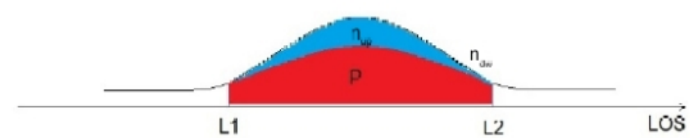
Estimated temperature of the emitting plasma : T ~ 1.5 – 4 MK

Density Compression ratio

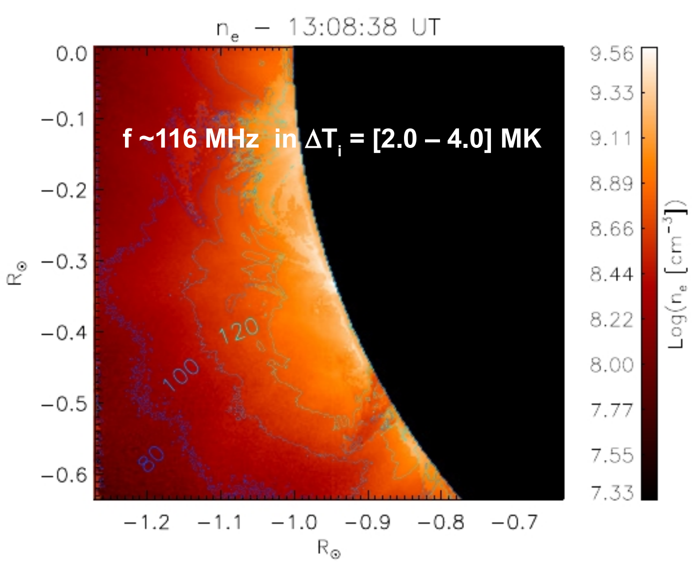
RADIO - Time interval = [13:08.5 - 13:08.7] UT, the upper splitted harmonic band is further splitted into two sub-components that most probably originate from simultaneous radio emission occurring in the upstream (ahead) and downstream (behind) region of a shock. The compression ratio X is given by:

$$X = \frac{n_{e,D}}{n_{e,U}} = \left(\frac{f_U}{f_L}\right)^2 \approx 1.2 - 1.4 \qquad [f_{pe} \sim 120 \text{ MHz}]$$

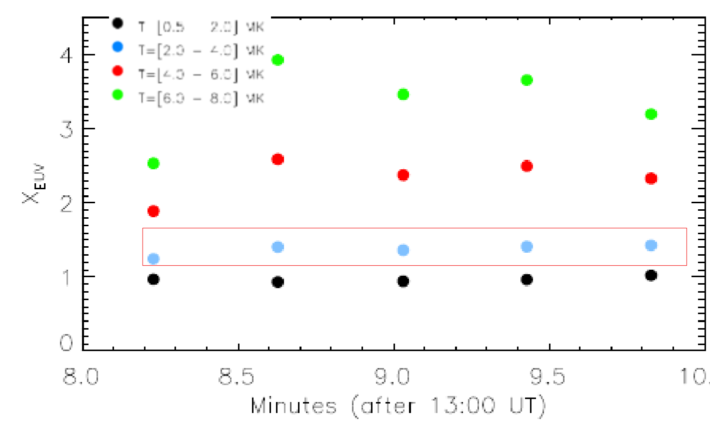
EUV – Estimation of X across the EUV compression front → necessary to take into account the effects of integration along the LOS. Assuming that an EUV front with thickness L transits on the plane of the sky (POS) induces, on average, an unknown density compression by a factor X →



$$X = \sqrt{\frac{(EM_D - EM_U) + P_U}{P_U}} \approx 1.23 - 1.42 \qquad P_U = L \cdot < n_{e,U}^2 >_{LOS}$$



Where P_U represents the contribution to the pre-event EM from the coronal plasma region located between L1 and L2.



- $T_U = T_{peak,dEM}(t_0) \approx 1.85$ MK

- The transit time of the shock wave < 1 minute << time required for ionization equilibrium for spectral lines in the considered AIA band-passes → $T_D = T_{peak,dEM}(t_1) \approx 1.92$ MK.

T_D →assuming the presence of a shock (with $\beta = \frac{2n_e k_B T_e}{B^2/2\mu_0} \rightarrow 0$).
NO information about the magnetic field direction with respect to the shock front → $0<\theta_{sh}<\pi/2$, but in the case of type II emission in the lower corona quasi-perpendicularity supposed to be reached, →

$$\frac{T_D}{T_U} = \frac{1}{X}\left[1 + \left(1 - \frac{1}{X} - \frac{X^2-1}{2M_A^2}\right)\gamma M^2\right]$$

→ $T_D \approx 2.76$ MK > 2.2 MK (adiabatic compression , $\gamma=5/3$ – monoatomic gas)

$c_s = \sqrt{\gamma k_B T_U / m_H} \approx 160 \text{ km s}^{-1}$ Sound speed

$v_{sh} \approx 950$ km s^{-1} , shock speed

$M_A = v_{sh} / v_A = 1.27$ Alfvén Mach number

$v_A \approx 750$ km s^{-1} Alfvén speed

X = 1.3 (mean value of density compression ratio)

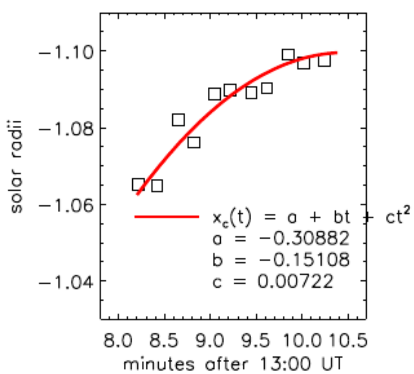
$M = v_{sh} / c_s$

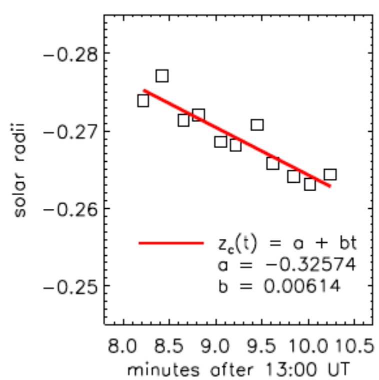
Evolution of the CME front...

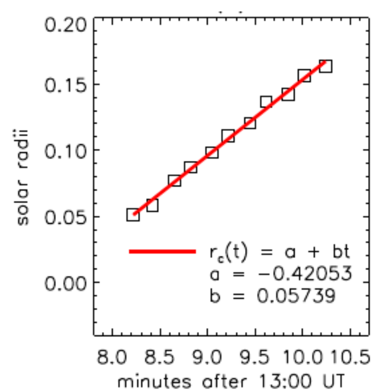
General case : for a fast-moving CME the overlying shock surface should be oblate.

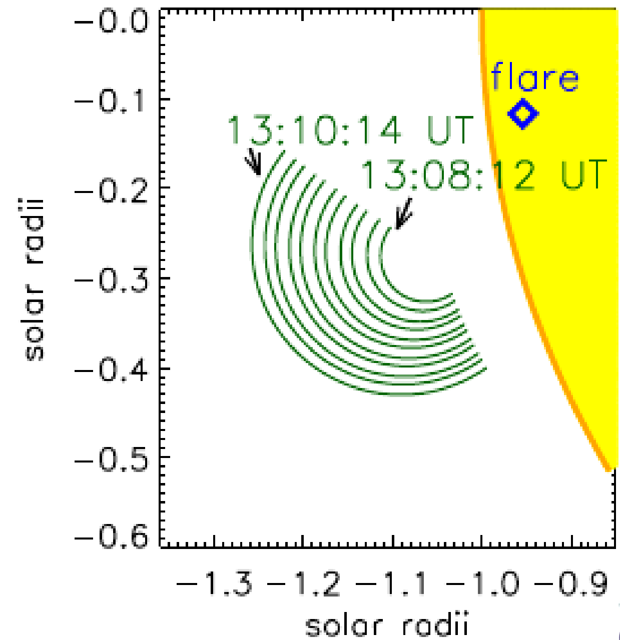
The observed EUV front: Produced by an expanding quasi-circular loop (hp 1)
Represent the projection of a bubble-like structure on POS (hp 2)

Adopting (2) → the model of the evolution of the expanding front obtained by fitting to the data the temporal evolution of the coordinates in the POS (x − z) of the center of the circle [x_c (t), z_c (t)] and of its radius r_{cme}(t) with low-order polynomials.







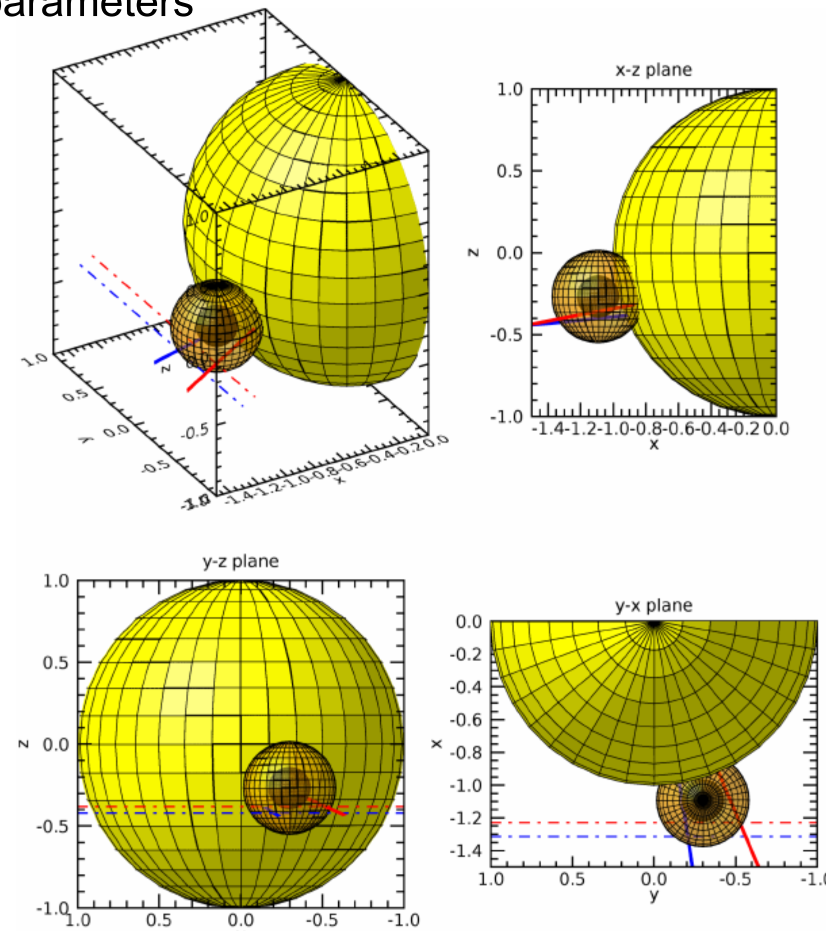


… and 3D reconstruction

- $r_{sh}=a_0 + a_1\, r_{cme}$ (radius of curvature of the shock surface, a_0, a_1 free parameters).
- Angle of propagation of the CME bubble → free parameter.
- The streamers are straight and radial in the y − x plane → free parameters

→ We determined the five parameters that minimized the least-square difference between calculated and observed locations of the type II radio sources in the (x-z) plane.

Time-evolving 3D geometry of the CME/shock and the spatial location of the two streamers axes.



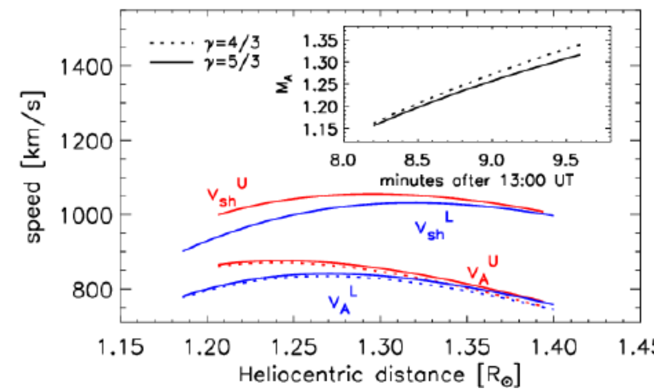
Coronal magnetic field

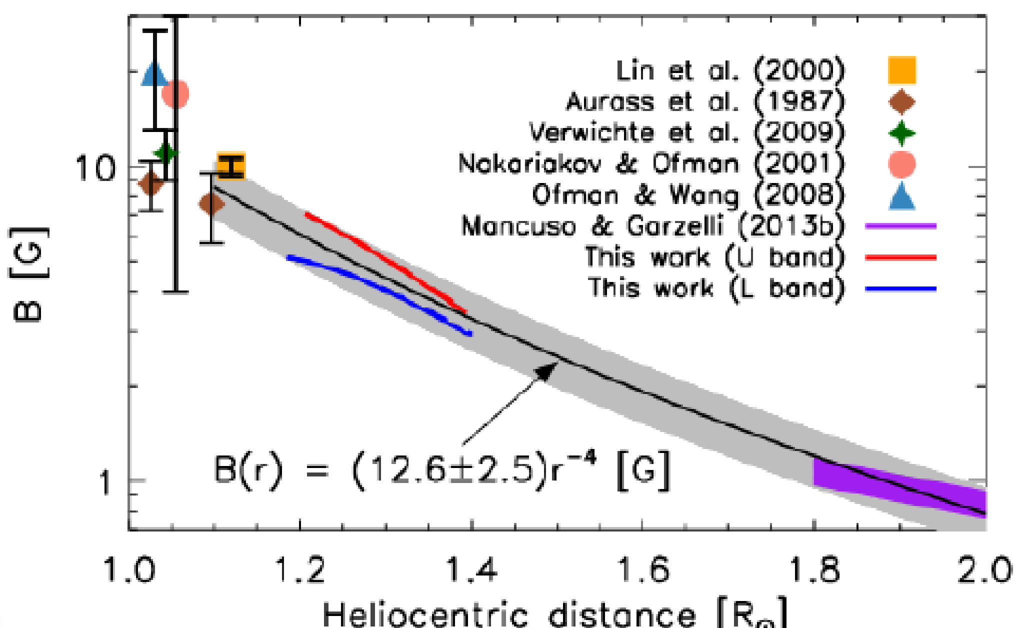
Standoff distance $\Delta r \equiv r_{sh} - r_{cme}$ → $\delta \equiv \frac{\Delta r}{r_{cme}} = 0.81 \frac{(\gamma - 1) M^2 + 2}{(\gamma - 1)(M^2 - 1)}$

Inner corona: $v_A >> c_s \rightarrow$ M replaced by M_A

$$M_A^2 = 1 + \left[\frac{\delta}{0.81} - \frac{(\gamma - 1)}{(\gamma + 1)} \right]^{-1}$$

→ Pre-shock $v_A = v_{sh}/M_A$ along the two streamers





$\mathbf{B(r) = 4.92 \cdot 10^{-7}\, v_A\, n_e^{0.5}}$ [Gauss]

r = heliocentric distance

$n_e(r) = \alpha \cdot 10^{\beta/r}$ Newkirk-like function

Conclusion

- **Analysis of Intensity EUV profiles →** slow increase above the 3σ level of the unperturbed plasma preceding the CME transit;
- **Onset Type II radio Burts** → same temporal range → shock evidence in SDO/AIA FOV;
- **Density compression ratio** → Assuming the secondary band splitting due to simultaneous emission from plasma upstream and downstream : X_{EUV} and X_{radio} are comparable (X~ 1.3 → weak shock, plasma temperature ~ [2 - 4] MK) → Assuming a perpendicular shock and T_U ~ 1.85 MK→ T_D ~ 2.76 MK;
- **3D shock front reconstruction →** Assuming the primary band-splitting due to intersection between the expanding shock surface and two adjacent low-Alfvén speed coronal streamers → 3D shock front reconstruction without stereoscopic observations;
- **Magnetic field strength B and its profile →** represented by a power law of the form
- $B(r) = (12.6 \pm 2.5)\, r^{-4}$ [G] in the heliocentric distance range [1.1 − 2.0] $R_{\odot}$.

Metis:
Future opportunities

- A similar analysis could be performed by Metis (UV + WL) and EUI on Solar Orbiter mission with the advantage of bigger field of view (at perihelion) compared with SDO/AIA instrument used in this work.
- The 3D reconstruction will be possible by combining Metis and EUI images to those of other spacecraft (SOHO, SDO, PROBA2, Parker Solar Probe, etc…).
- During the nominal and extended mission the spacecraft will operate out of the ecliptic plane (> 24° and > 33°) allowing us the observation of structures (as streamers) interacting with expaning shock from a new point of view.