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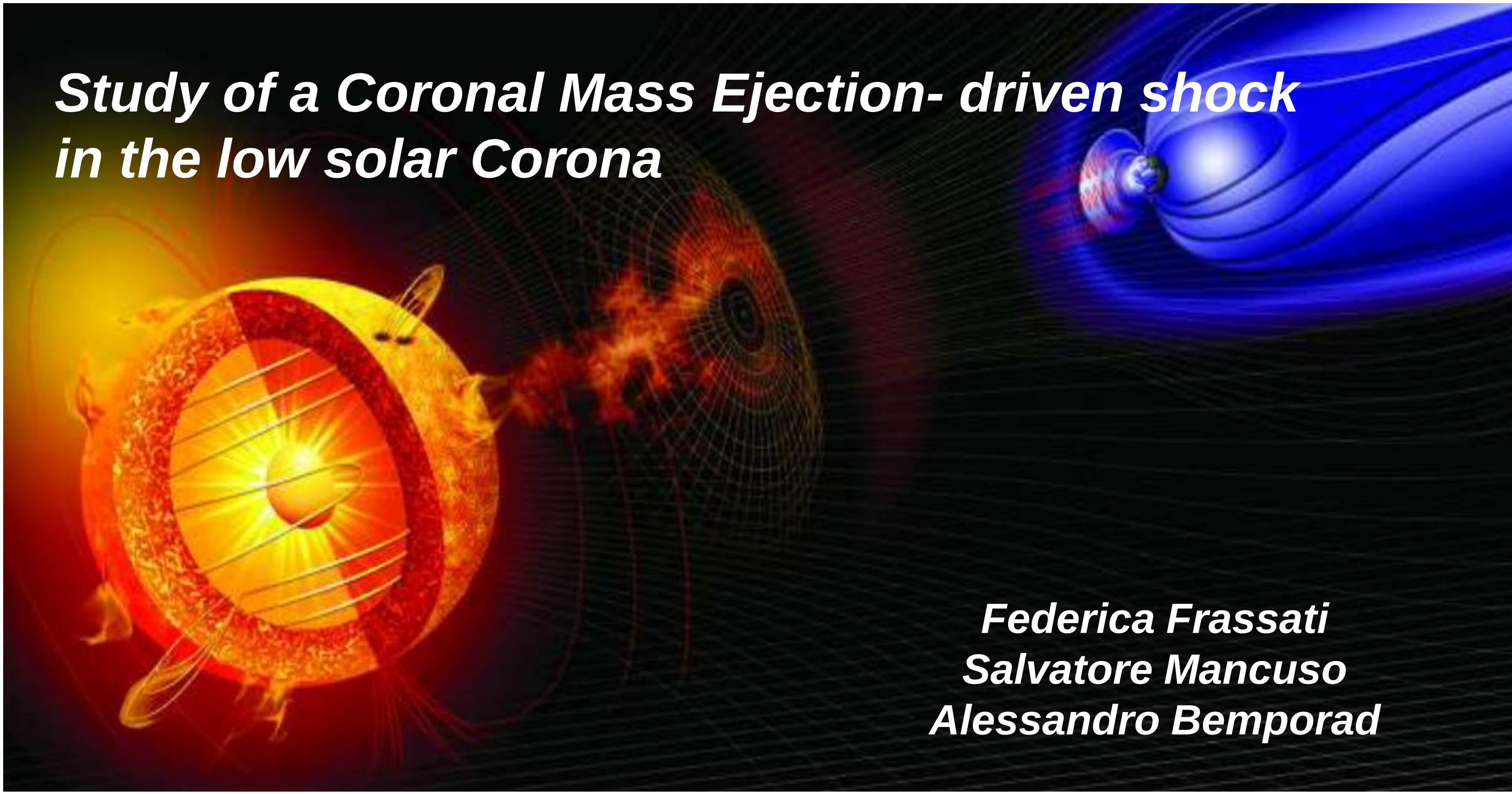

Study of a Coronal Mass Ejection- driven shock in the low solar Corona

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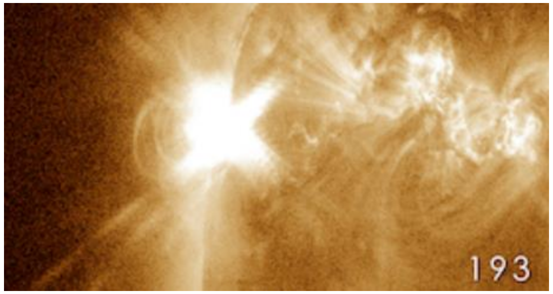
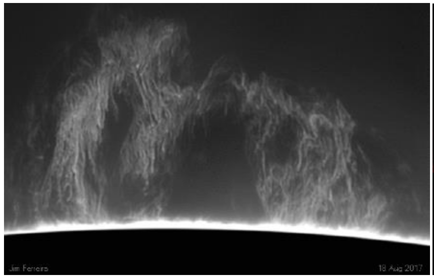
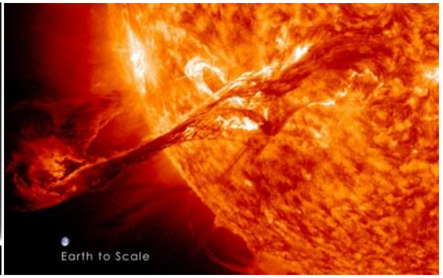
Solar transient phenomena



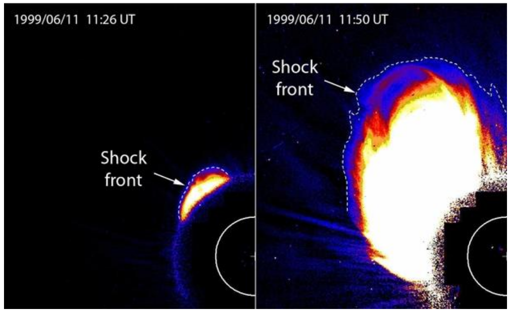
Solar flares are sudden increases in brightness well observed at all wavelengths, but particularly in the X-ray band. During a flare an enormous amount of energy is released (up to 10^{32} erg) and a shock wave can be generated





Prominences: bright structures extending hundreds of thousands of kilometers above the solar limb and composed by high density and low temperature chromospheric material.

Coronal Mass Ejections (CMEs): expulsions of huge quantities of magnetized plasma (up to 10^{16} g) with speeds from 100 km/s to 2500 km/s and temperatures ranging from 10^4 to almost 10^7K.



Shock wave: if a CME is faster than the magnetosonic velocity of the ambient medium, it can drive a shock where the electrons, protons and heavy ions can be accelerated to near-relativistic energies.

Solar Energetic Particles (SEPs) are electrons, protons and heavier ions traveling at near-relativistic speed with energy ranging from keV to GeV.

Solar type II radio bursts

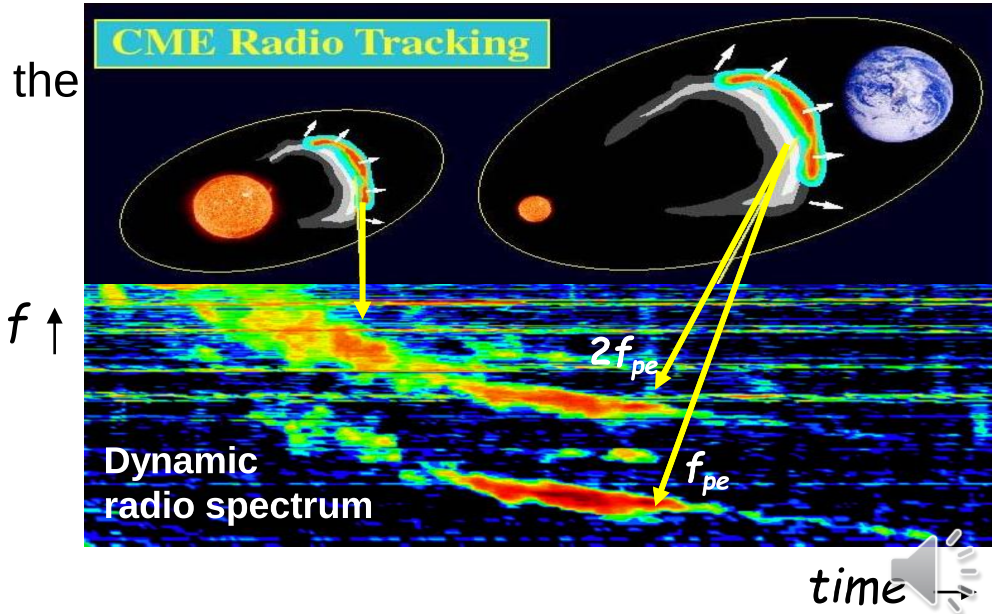
A **type II radio burst** is due to plasma emission that occurs following the passage of a **shock wave** propagating outward through the corona.
It is emitted at the **local plasma frequency** f_{pe} of the source region in the corona, and/or its first harmonic.

$$f \approx f_{pe} \equiv \sqrt{\frac{e^2 n_e}{m_e \pi}} \propto \sqrt{n_e}$$

Emissions at different frequencies thus come from different layers of the corona (the **electron density** n_e decreases with altitude): the longer the wavelength, the higher the coronal layer. In **dynamic radio spectra**, type IIs radio bursts appear as stripes of enhanced radio emission slowly drifting from high to low frequencies.

Physical mechanism:

- Fast CMEs (or powerful flares) drive shocks in the corona.
- Shocks accelerate energetic electrons beams
- Electron energy is converted to plasma waves at the local plasma frequency f_{pe} that scatter off of ions or combine to produce e.m. radio emission at frequencies f_{pe} (fundamental) and/or $2f_{pe}$ (harmonic)



Why is it important to study Interplanetary Shocks?

The study of Interplanetary Shocks (ISs) associated with major solar eruptions is very important for scientific and technological reasons:

1 – to provide a better understanding of fundamental plasma physical processes and acceleration of energetic particles at collisionless shock waves.

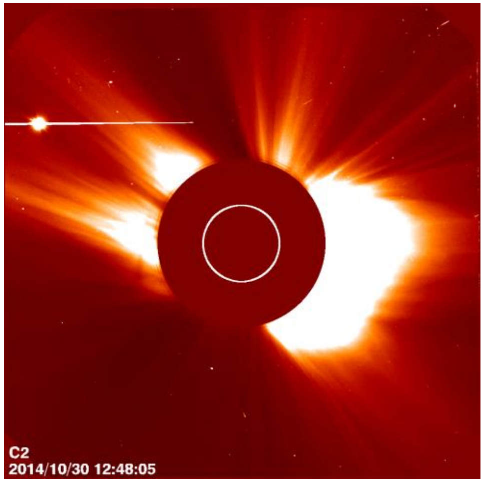
2 – SEPs accelerated by CME-driven shock constitute an important hazard for satellites and astronauts; they may affect the ionosphere around polar caps and disturb the system and producing severe geomagnetic storms.

Understanding the origin, propagation and physical properties of Interplanetary Shocks is crucial for future developments of our capabilities of **forecasting** possible **Space Weather effects** of solar activity.

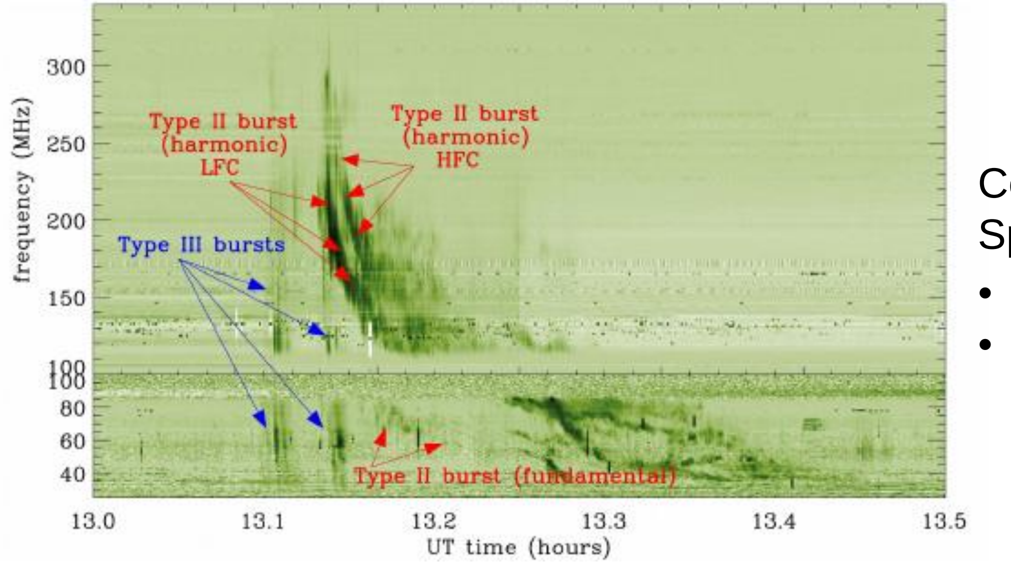
A study case

Observations

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 radio burst** starting at 13:08 UT was the evidence of a shock formation.

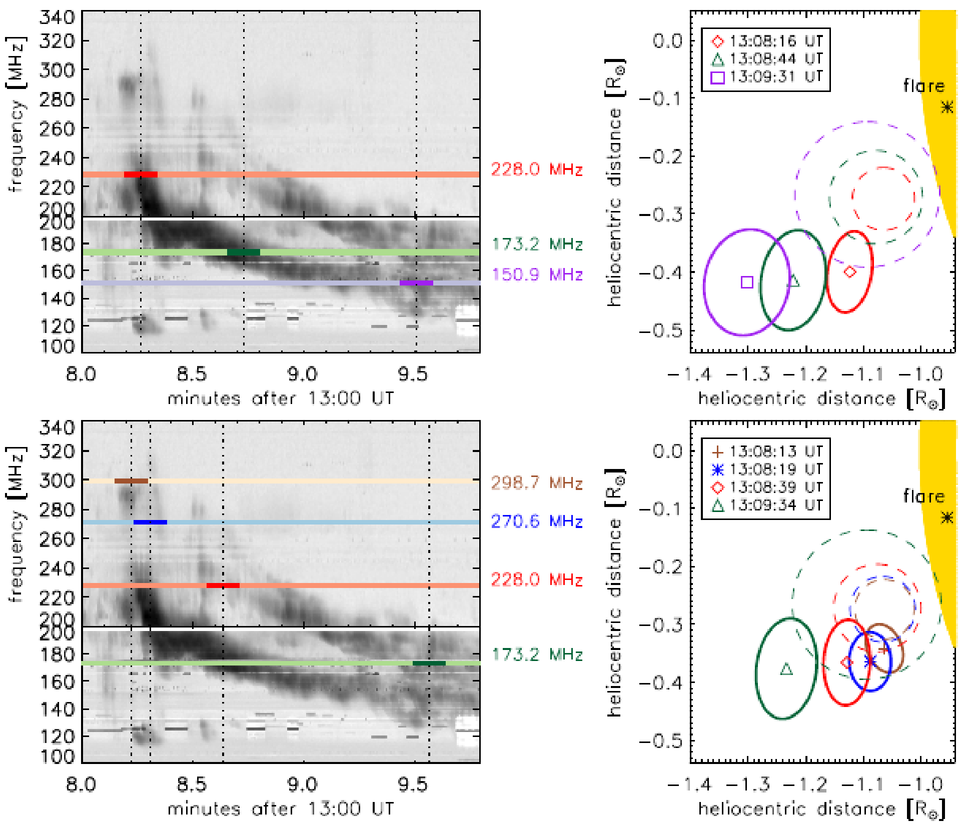


Complex type II radio burst starting at about 13:08 UT. Splitting into sub-bands→

- Shock/streamer interactions (primary band splitting);
- emission from plasma both upstream and downstream of the shock front (secondary band splitting).

Radio analysis

Primary Band Splitting



- 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 localized at five NRH frequencies: 298.7 MHz - 270.6 MHz - 228.0 MHz - 173.2 MHz - 150.9 MHz.

Time (after 13:00 UT)	U	L
08:13-08:19	298.7 / 270.6	228.0
09:31 – 09:34	173.2	150.9

Not co-spatial radio emission → Band-splitting origin is supposed to be due to emission from two different parts of the same shock front expanding streamers with different electron density and magnetic field distributions.

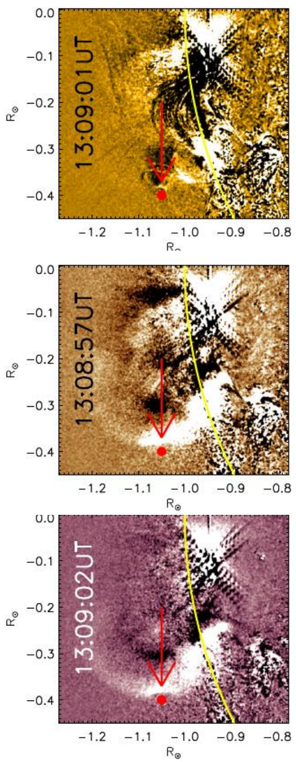
Secondary Band Splitting

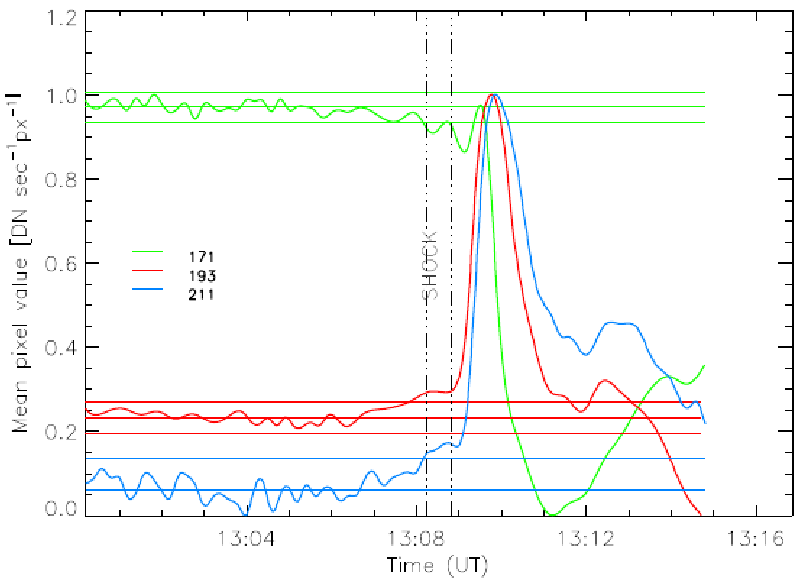
Time interval = [13:08.5 - 13:08.7] UT, the upper splitted harmonic band is further splitted into two sub-components that most probably originate from simultaneous radio emission occurring in the upstream (ahead) and downstream (behind) region of a shock. The compression ratio X is given by:

$$X = \frac{n_{e,D}}{n_{e,U}} = \left(\frac{f_{\mathrm{U}}}{f_{\mathrm{L}}}\right)^2 \approx 1.1 - 1.4 \qquad [f_{pe} \sim 120 \text{ MHz}]$$

Extreme Ultra-Violet analysis

EUV Intensities





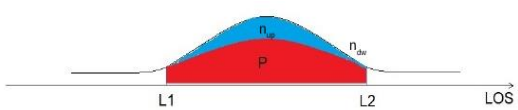
Temporal variations of observed intensities related on the evolution of electron density and ionization state (depending on temperature) of the plasma → useful to infer the presence of the shock from the observed images

Estimated temperature of the emitting plasma : T ~1.75 – 4 MK

Emission Measure (EM) represents the amount of the emitting material as a function of coronal plasma temperature along the line of sight (LOS) and was calculated by using 6 SDO/AIA filter images (94-131-171-194-211-335 Å).

$$EM(r) = \int \frac{dEM(r,T)}{dT} dT = \int_{LOS} n_e^2(r) ds$$

Compression Ratio X estimated across the EUV compression front taking into account the effects of integration along the LOS.



$$P_U = L \cdot < n_{e,U}^2 >_{LOS}$$

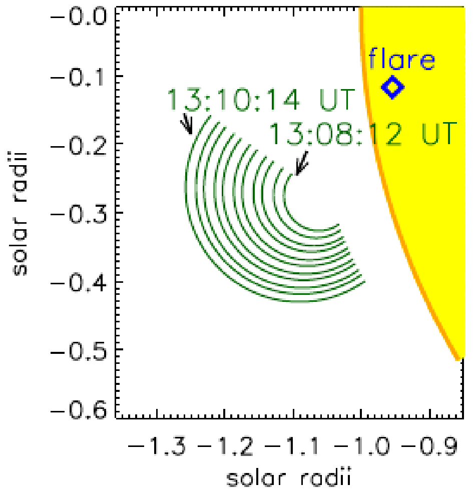
is the contribution to the pre-event EM from the coronal plasma region located between L1 and L2.

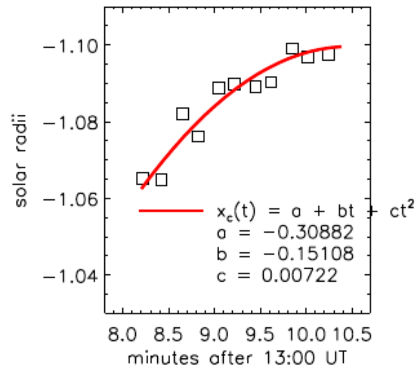
Assuming that an EUV front with thickness L transits on the plane of the sky (POS) induces, on average, an unknown density compression by a factor X :

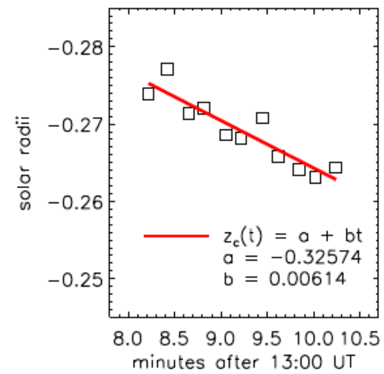
$$X = \sqrt{\frac{(EM_D - EM_U) + P_U}{P_U}}$$ ≈ 1.23 in temperature range [2 – 3] MK

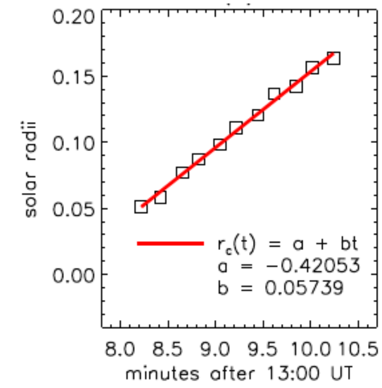
Temporal Evolution of the CME front

The observed EUV front can; (1) be produced by an expanding quasi-circular loop or (2) represent the projection of a bubble-like structure on plane of sky POS.

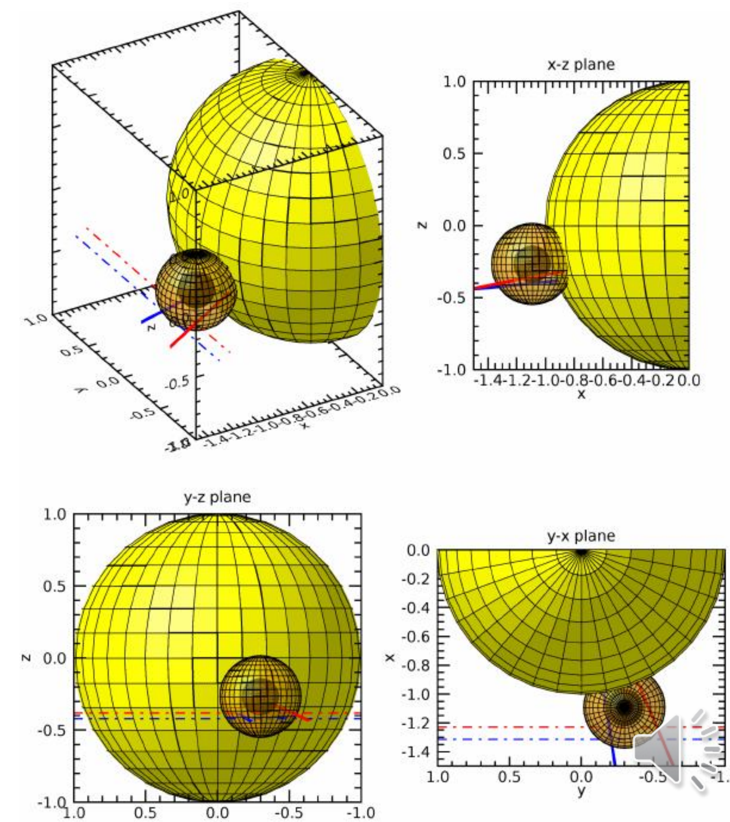








The model of the evolution of the expanding front obtained by fitting to the data the temporal evolution of the coordinates in the POS (x − z) of the center of the circle $[x_c(t), z_c(t)]$ and of its radius $r_{cme}(t)$ with low-order polynomials.



- 5 parameters to be found minimizing the least-square difference between calculated and observed locations of the type II radio sources in the (x-z) plane:
- $r_{sh}=a_0 + a_1\, r_{cme}$(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

Coronal magnetic field

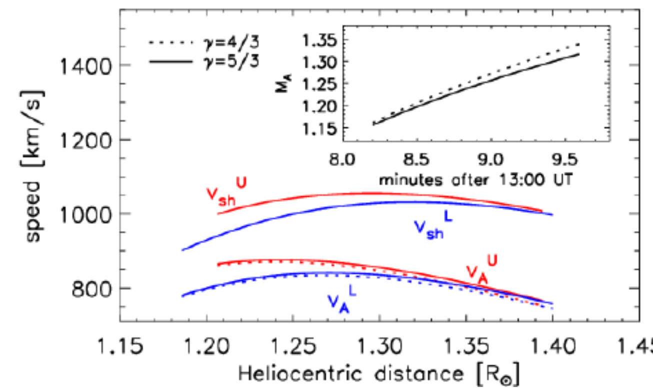
Standoff distance $\Delta r \equiv r_{sh} - r_{cme}$

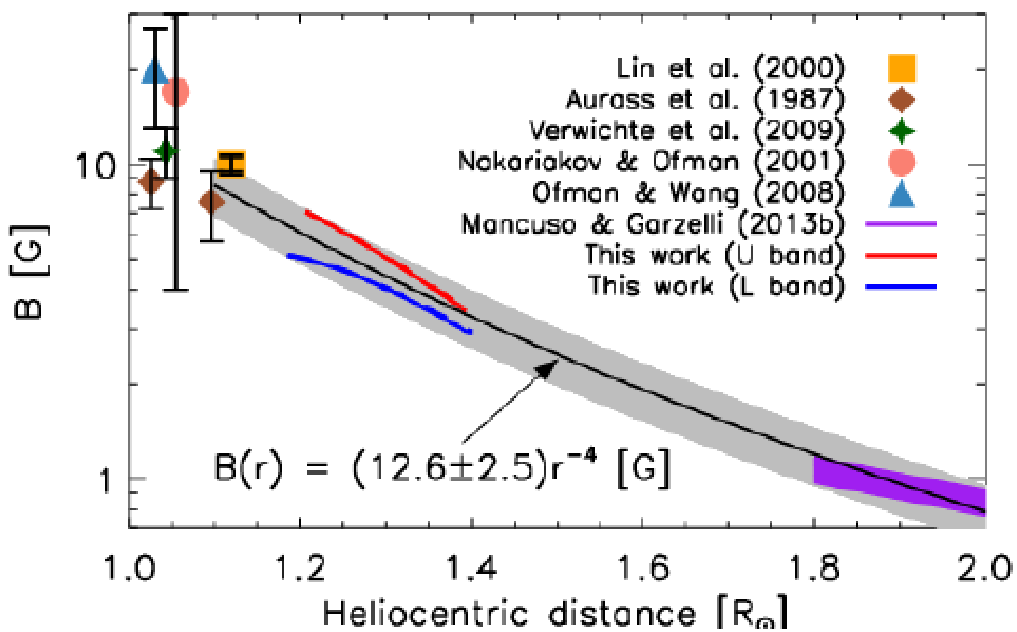
$$\delta \equiv \frac{\Delta r}{r_{cme}} = 0.81\,\frac{(\gamma-1)M^2+2}{(\gamma-1)(M^2-1)}$$

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





Magnetic field strength:

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

r = heliocentric distance

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

$\alpha = 12.6 \pm 2.5$

$\beta = -4$

The work presentend is avaliable on:

- **Three-dimensional reconstruction of CME-driven shock-streamer interaction from radio and EUV observations: a different take on the diagnostics of coronal magnetic fields**, *Mancuso, Salvatore; Frassati, Federica; Barghini, Dario; Bemporad, Alessandro, Astronomy & Astrophysics, Volume 624, id.L2, 5 pp, 2019.*

Estimate of Plasma Temperatures across a CME-driven Shock from a Comparison between EUV and Radio Data, *Federica Frassati, Salvatore Mancuso, Alessandro Bemporad; Sol Phys* **295,** 124 (2020).

Thank you!