Structure and Evolution of Stars

Solar corona, eruptive activity

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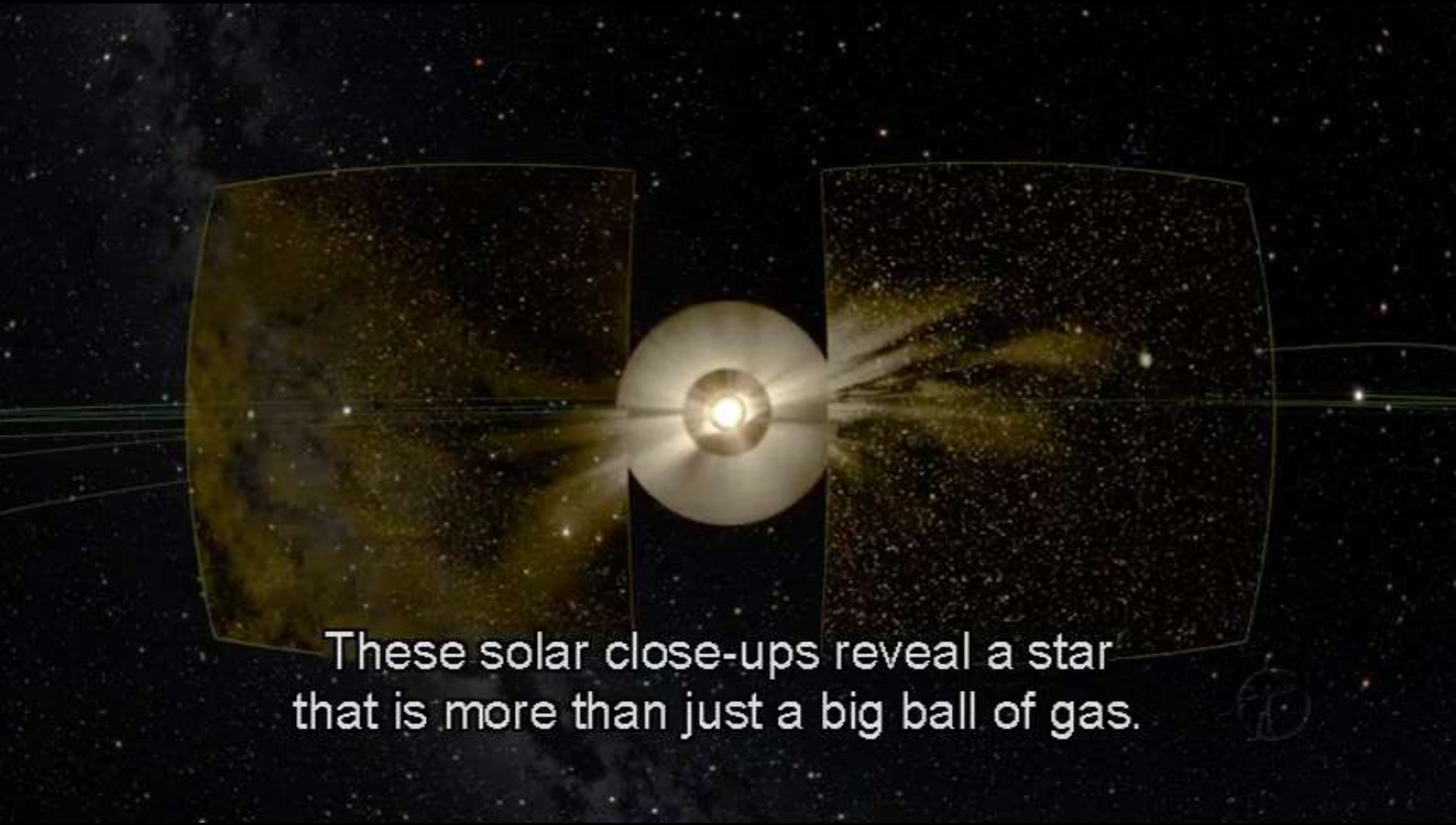
Travel around the close environment of our star



Jouney to the stars movie

Lecture Plan

I. Photosphere, chromosphere and transition region
- Sunspots
- Eruptive phenomena

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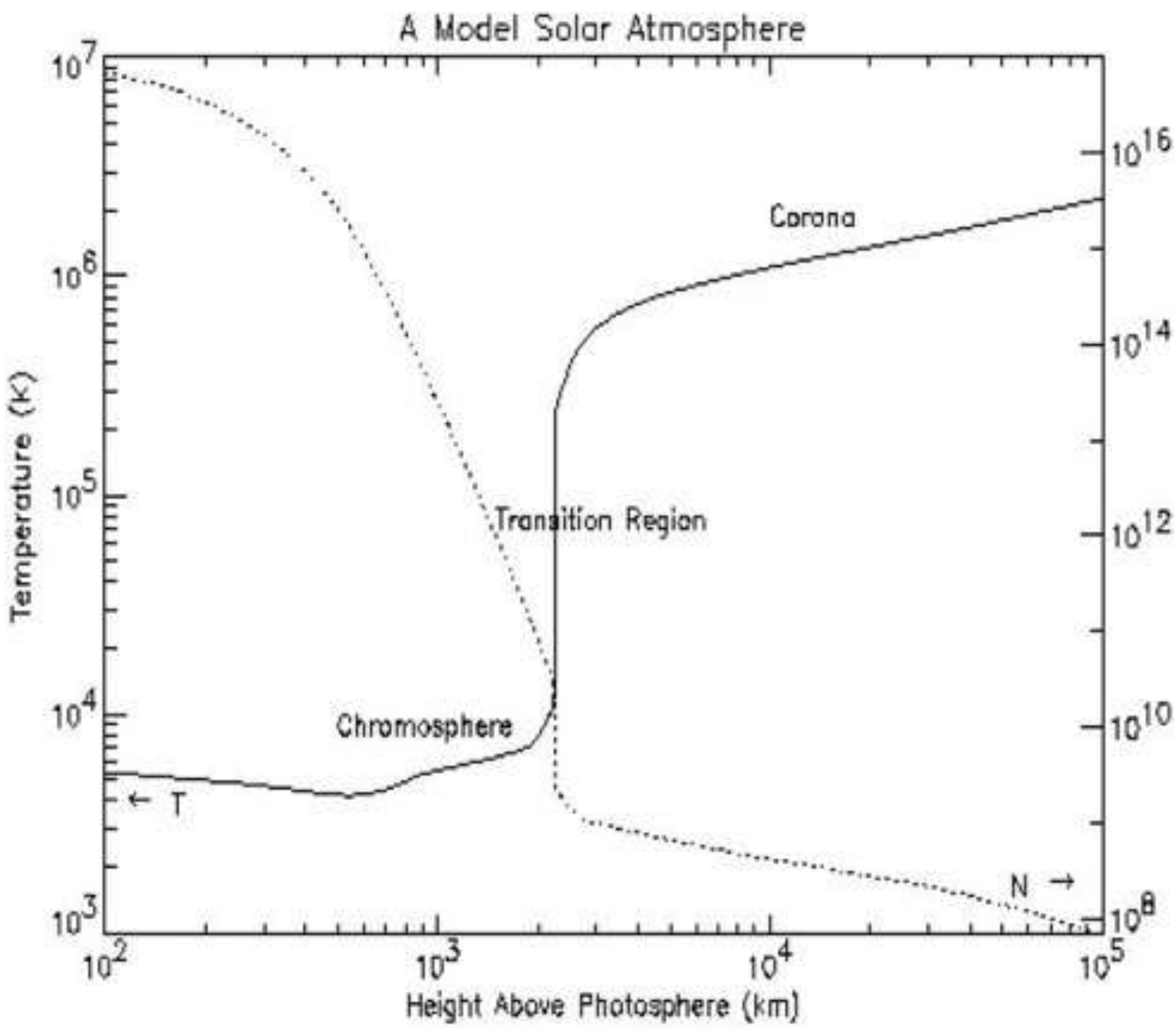
- Coronal mass ejection
- Soland and stellar wind
- Interaction between the host star stellar wind and surounding planets

III. Heliosphere in a galactic context

Solar atmosphere structure (I)



Recall:

$$R_\odot = 7 \times 10^5 \mathrm{km}$$

Solar atmosphere structure (II)

$$\beta = \frac{8\pi n k_B T}{B^2}$$

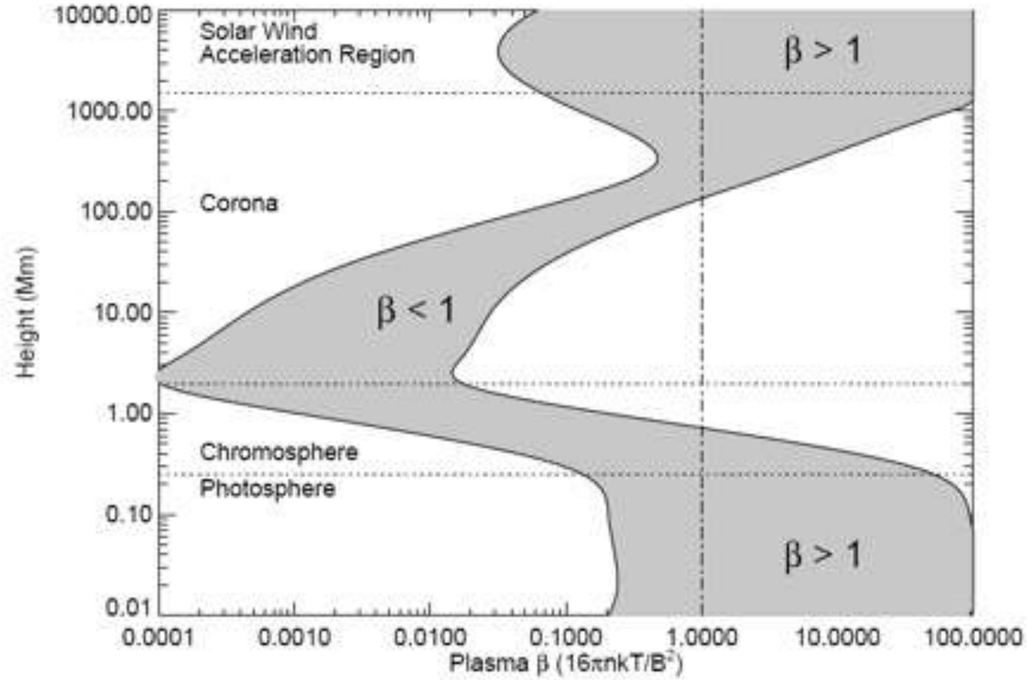


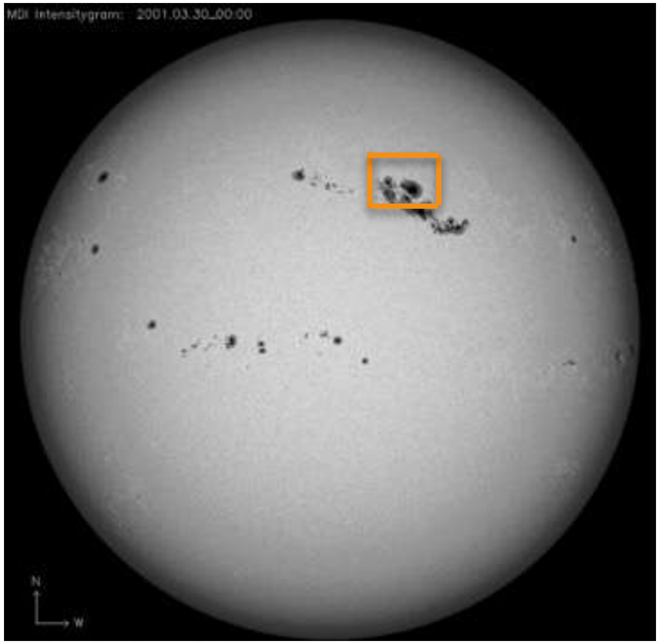
Figure 1.22: Plasma β in the solar atmosphere for two assumed field strengths, 100 G and 2500 G. In the inner corona ($R \lesssim 0.2 R_\odot$), magnetic pressure generally dominates static gas pressure. As with all plots of physical quantities against height, a broad spatial and temporal average is implied (Gary, 2001).

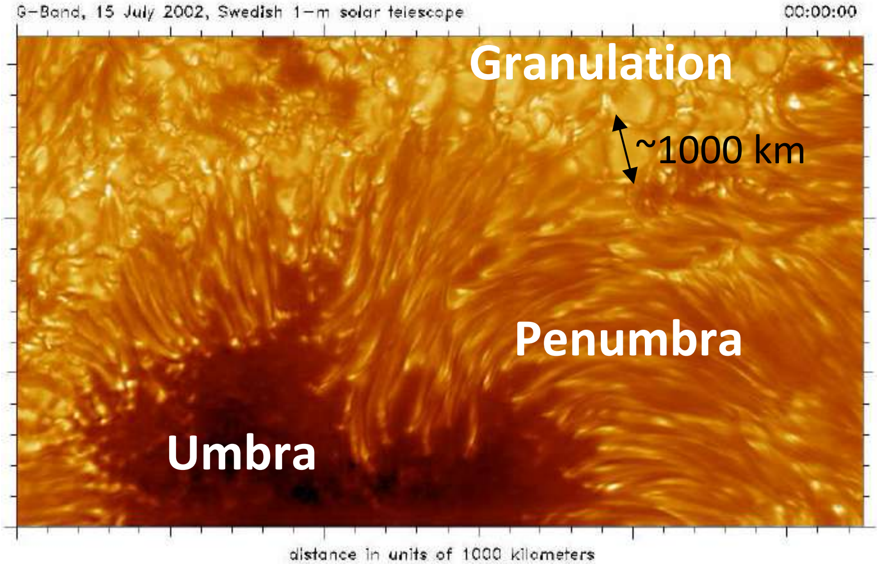
10 dyne/cm^2 = 1 Pascal
10^3 dyne/cm^2 = 1 mbar
1 atm = 1013 mbar

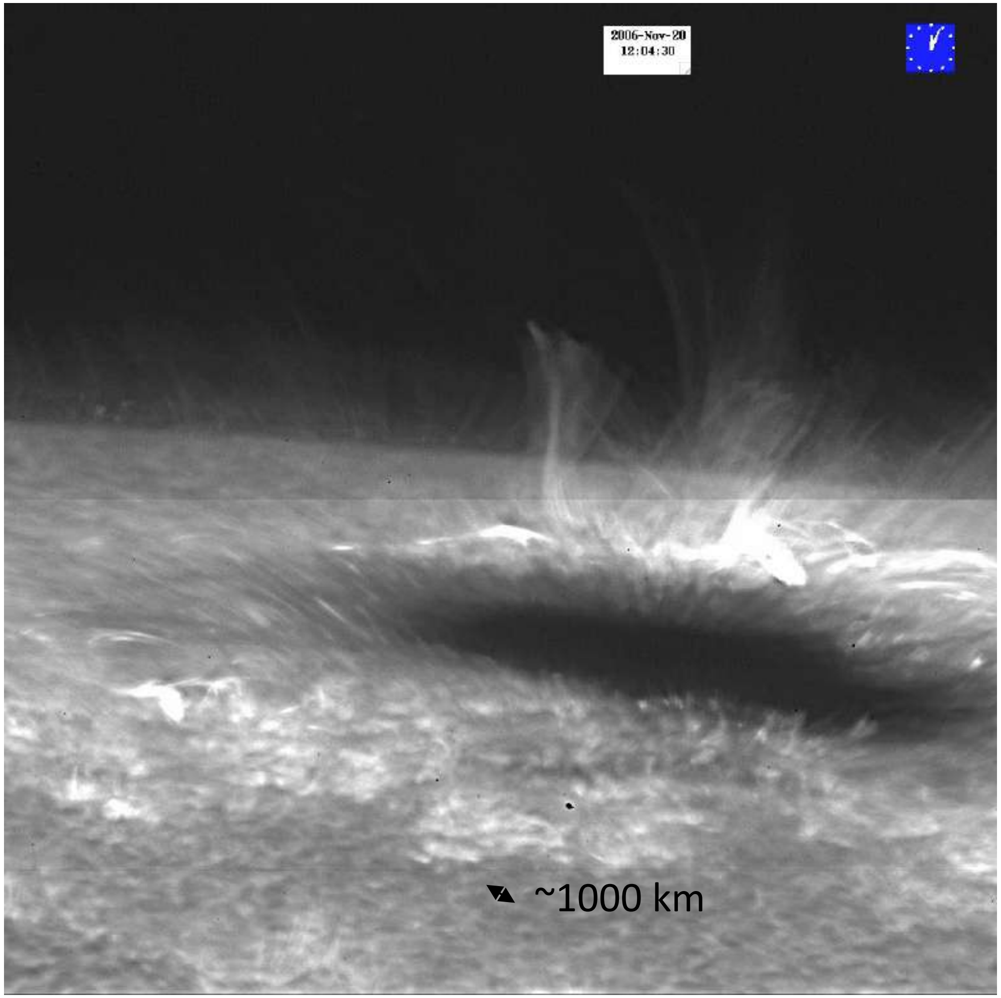
Table 1.1: The plasma-β parameter in the solar atmosphere.

Parameter	Photosphere	Cool corona	Hot corona	Outer corona
Electron density n_e (cm^{-3})	2×10^{17}	1×10^{9}	1×10^{9}	1×10^{7}
Temperature T (K)	5×10^{3}	1×10^{6}	3×10^{6}	1×10^{6}
Pressure p (dyne cm^{-2})	1.4×10^{5}	0.3	0.9	0.02
Magnetic field B (G)	500	10	10	0.1
Plasma-β parameter	14	0.07	0.2	7

Chromospheric magnetic phenomenom







Coronal loops emergence (TRACE satellite)

Classification of magnetic active region (Mt. Wilson)

α:A dominant spot, often linked to a range of opposite magnetic polarity

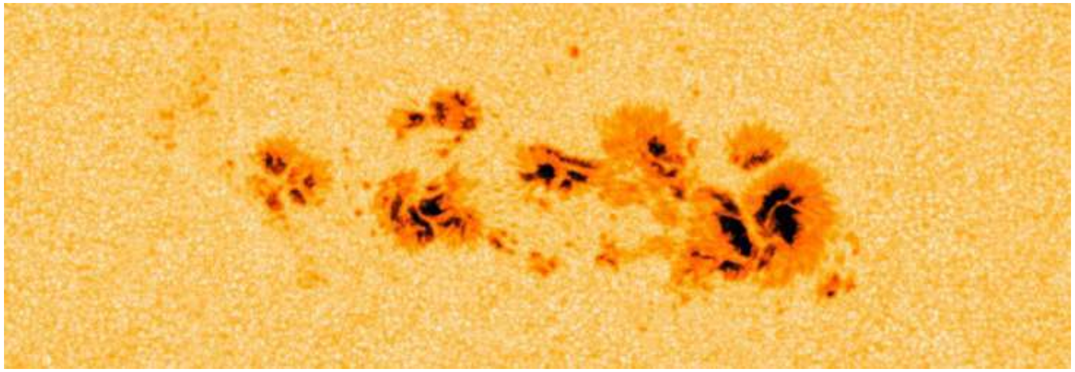
β: A pair of dominant spots of opposite polarity (bipolar)

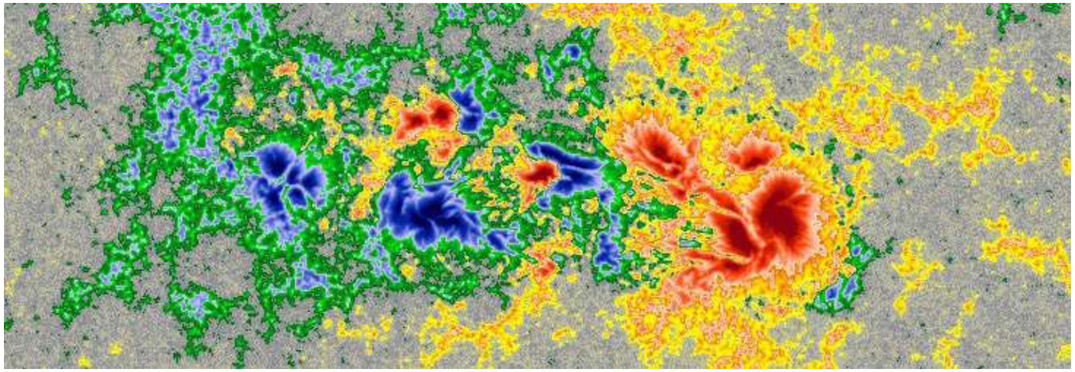
γ: Complex group of spots with irregular polarity distribution

δ: Umbra of opposite polarity in a single penumbra

Mixing of above types… for more complex active regions (see image)

Exemple de tache β-γ-δ





The Sun in X-ray (Hinode satellite)

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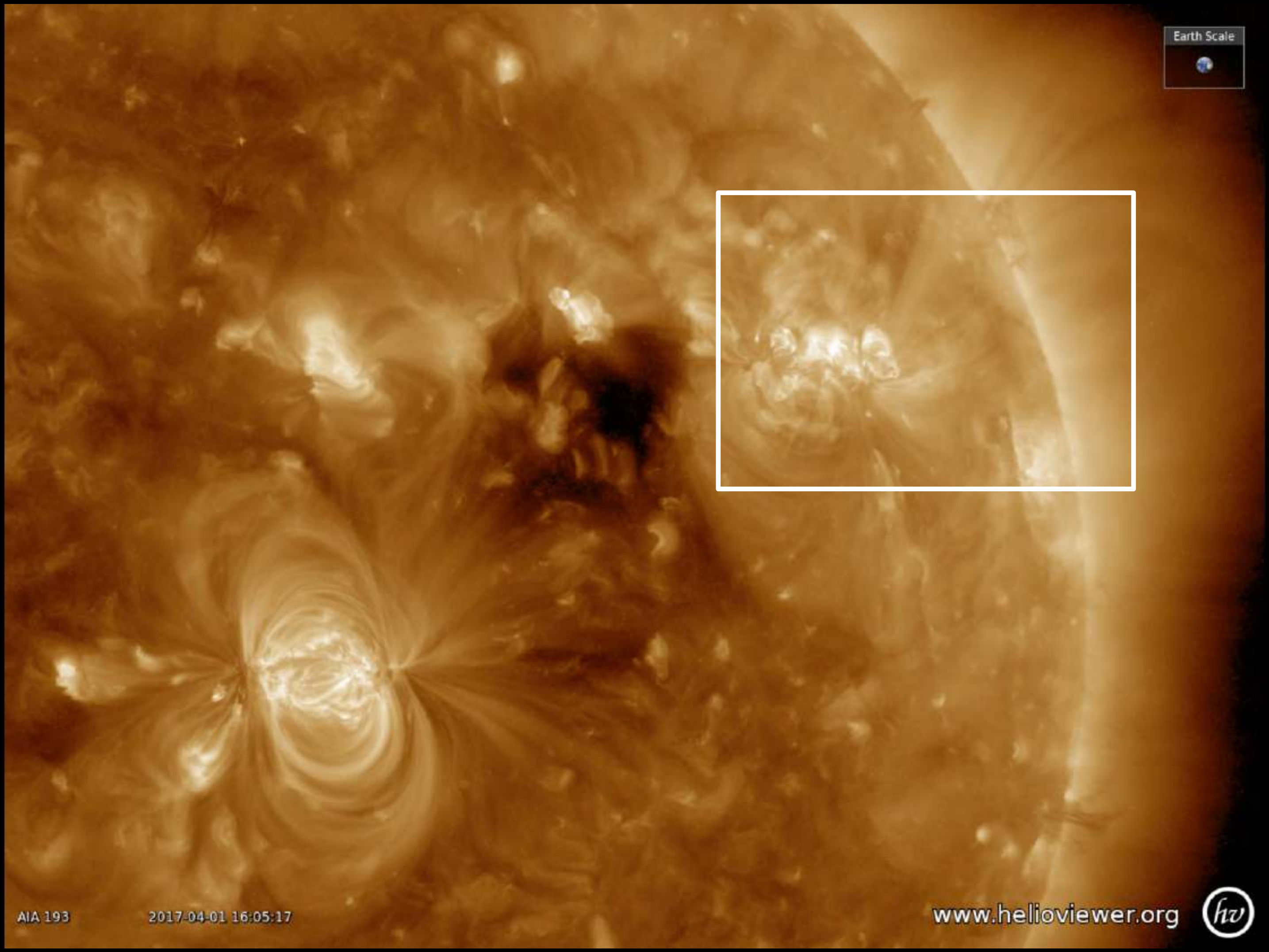
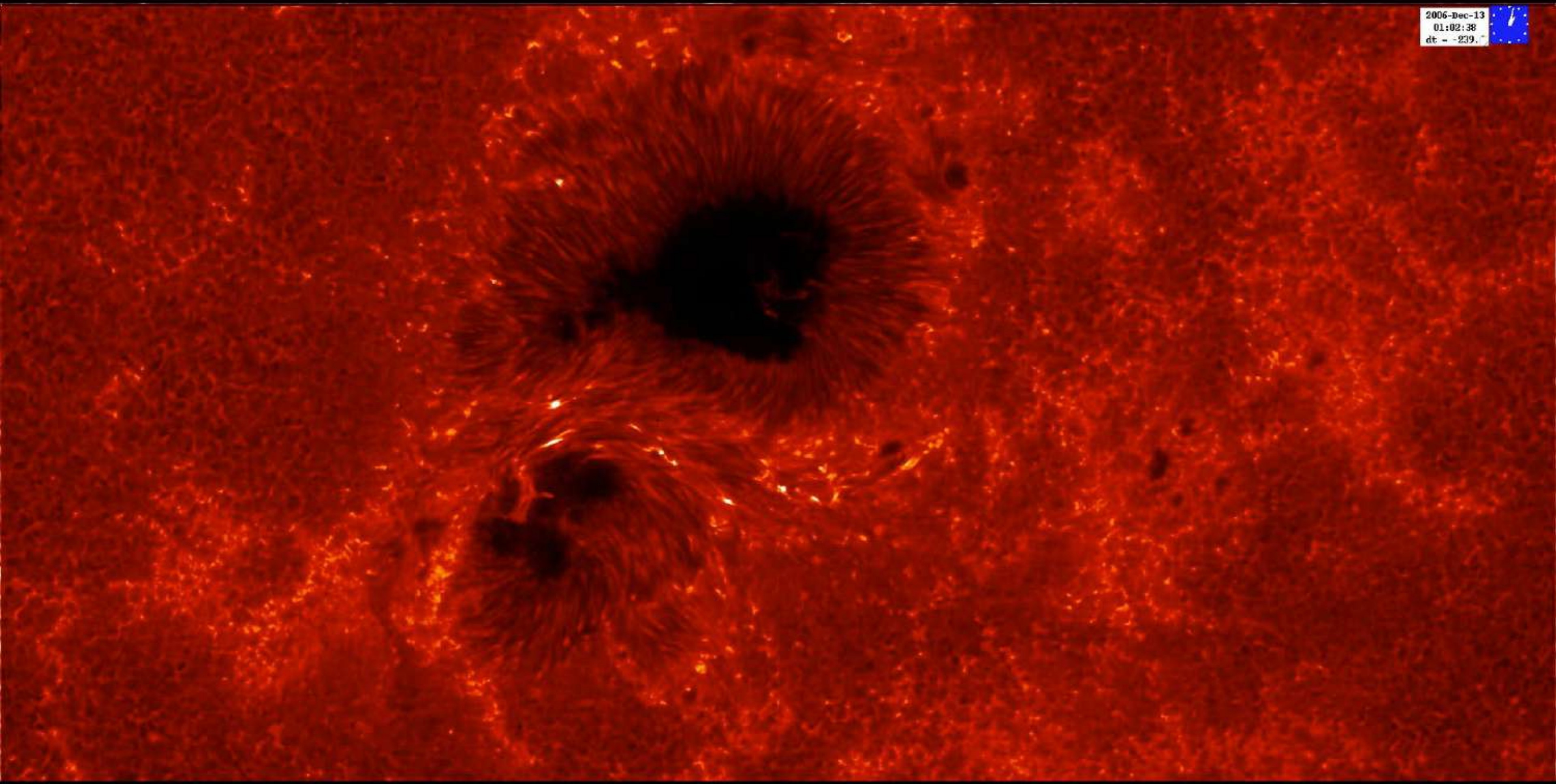
Solar eruptions ('flares'): April 1st 2017

AIA 193
10^6 K

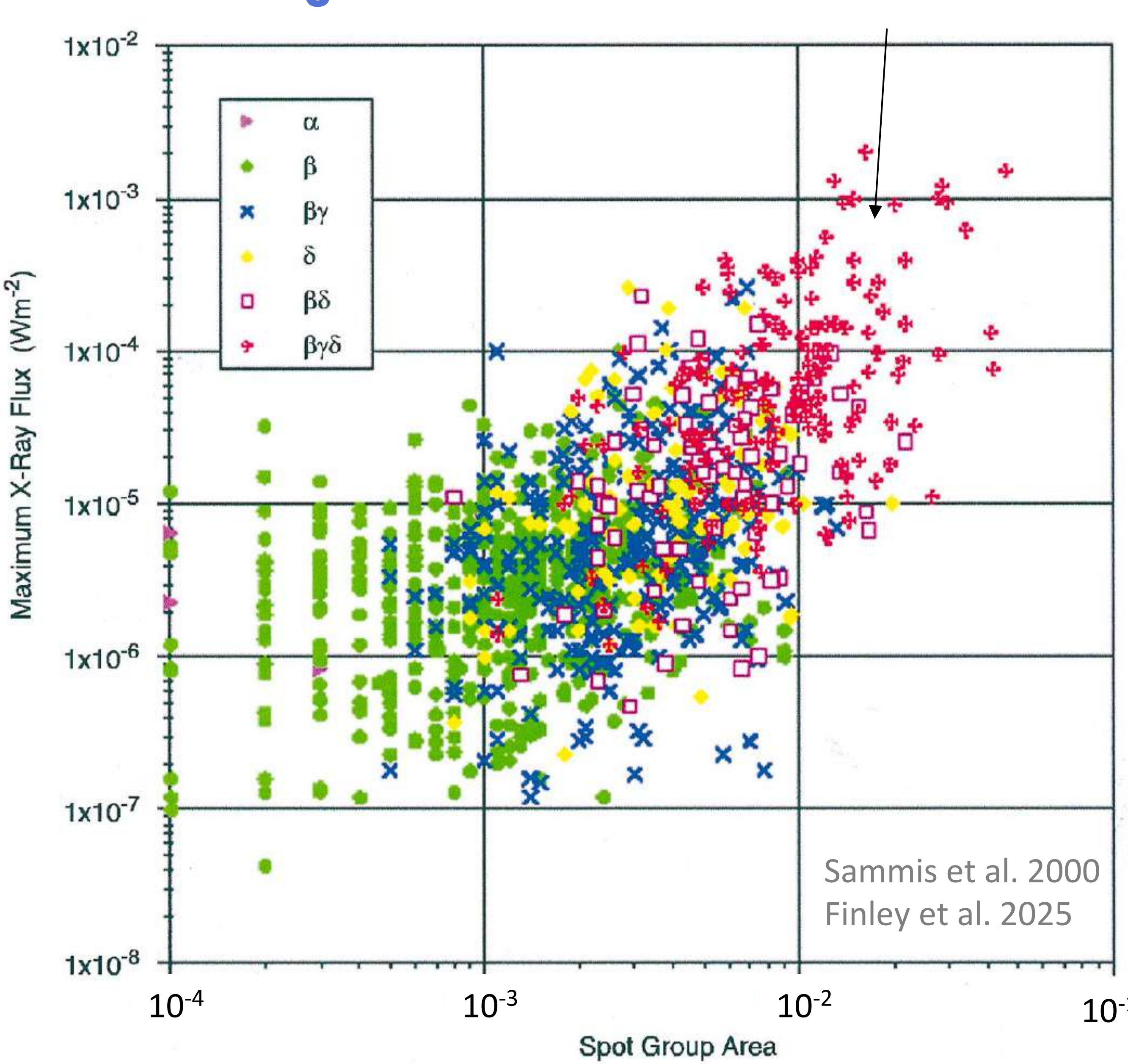


Solar eruptions ('flares') en H_α et CaH (Big Bear + Hinode)



Eruptions vs active region class

High correlation between complexity and flare intensity



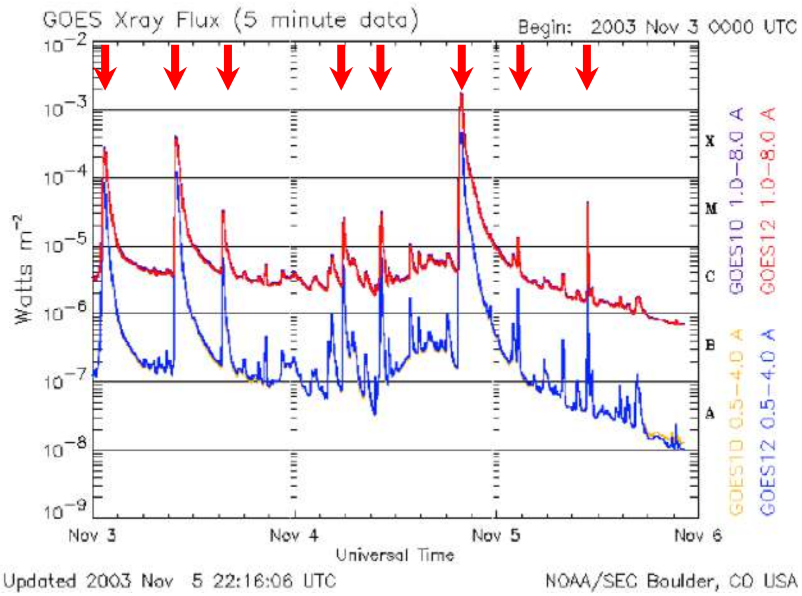
Classification of eruptions

Hα classification			Radio flux at 5000 MHz in s.f.u.	Soft X-ray class	
Importance Class	Area (Sq. Deg.)	Area 10^{-6} solar disk		Importance class	Peak flux in 1-8 Å w/m^2
S	2.0	200	5	A	10^{-8} to 10^{-7}
1	2.0–5.1	200–500	30	B	10^{-7} to 10^{-6}
2	5.2–12.4	500–1200	300	C	10^{-6} to 10^{-5}
3	12.5–24.7	1200–2400	3000	M	10^{-5} to 10^{-4}
4	>24.7	>2400	3000	X	$>10^{-4}$

1 s.f.u. = 10^4 jansky = 10^{-2} W m^{-2} Hz^{-1}

Éruptions les plus intenses

Eruptions during solar cycle



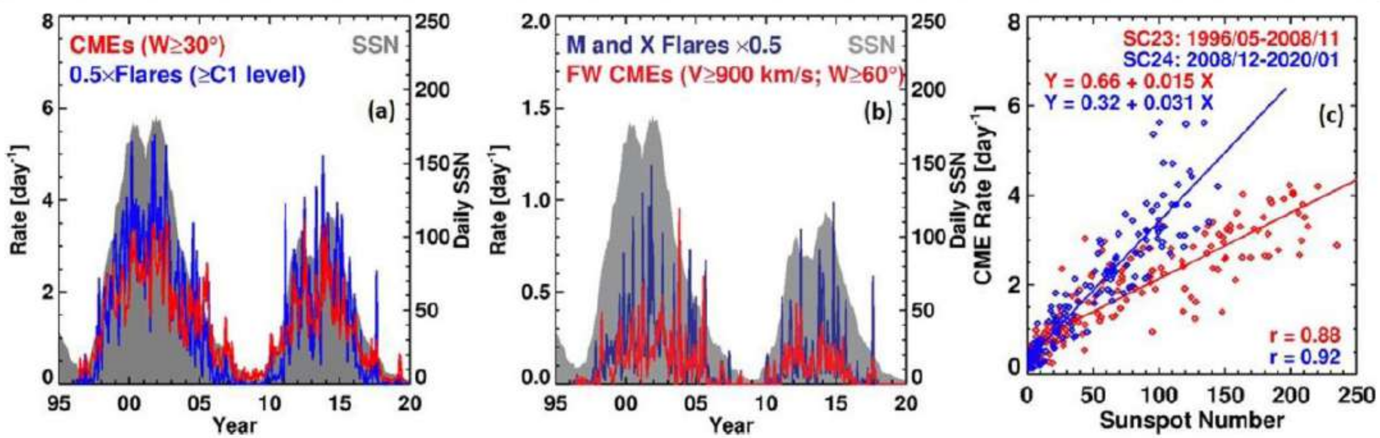


Fig. 5 Solar cycle variation of eruptive phenomena (flares and CMEs): **a** daily CME rate for the general population (width ≥30°) in red and the number of soft X-ray flares with size ≥C1.0 in blue, **b** fast and wide CMEs (speed ≥ 900 km/s; width ≥ 60°) in red and major (M- and X-class) soft X-ray flares in blue, and **c** scatter plots between the sunspot number (SSN, V2.0) and the daily CME rate (general population) for cycle 23 (red) and 24 (blue). In (**a**) and (**b**), SSN is shown in gray background. The CME and flare rates are averaged over the Carrington rotation (CR) periods. The flare rates are multiplied by 0.5 to fit the scale. Updated from Gopalswamy et al. (2020a); Gopalswamy et al. (2020b)

Eruptions during solar cycle

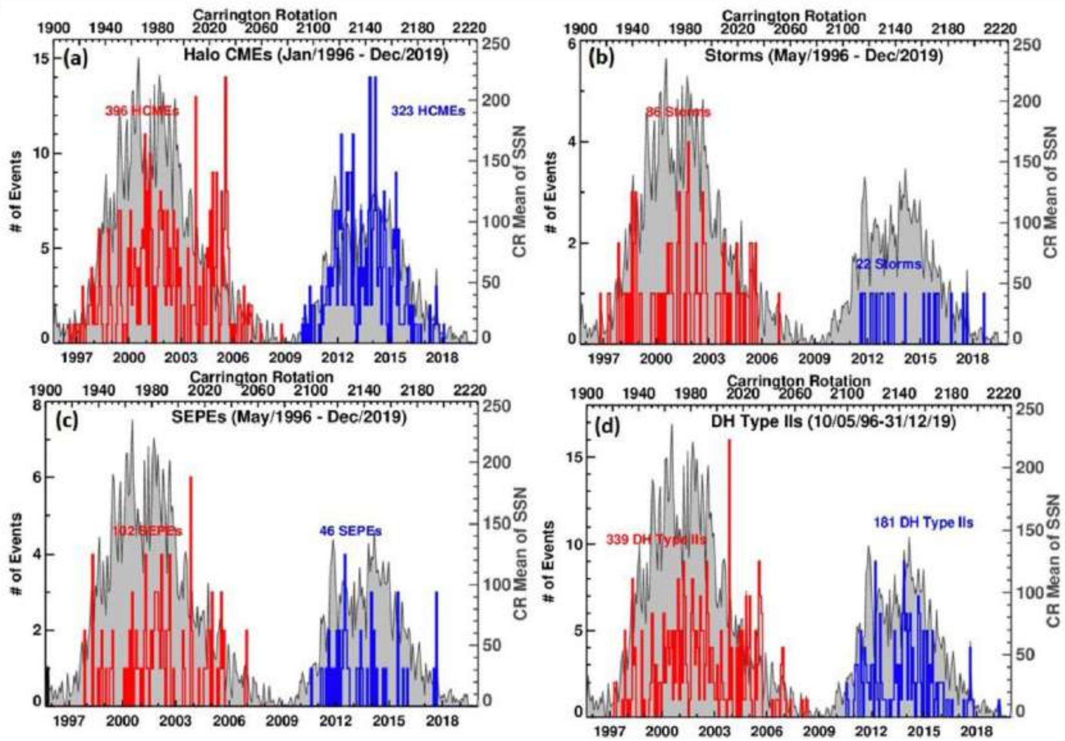


Fig. 6 Solar cycle variation of the key CME-related phenomena during cycles 23 and 24 (from 1996 to the end of 2019): **a** SOHO/LASCO halo CME number from https://cdaw.gsfc.nasa.gov/CME_list/halo/halo.html. **b** the number of large geomagnetic storms (Dst ≤ − 100 nT), **c** the number of large solar energetic particle events (SEPEs) detected in the > 10 MeV GOES channel with intensity exceeding 10 pfu, and **d** the number of decameter-hectometric (DH) type II radio bursts from Wind/WAVES. For comparison with the solar cycle, the sunspot number averaged over Carrington rotation (CR) periods is also shown. Updated from Gopalswamy et al. (2015a, b, c)

CME

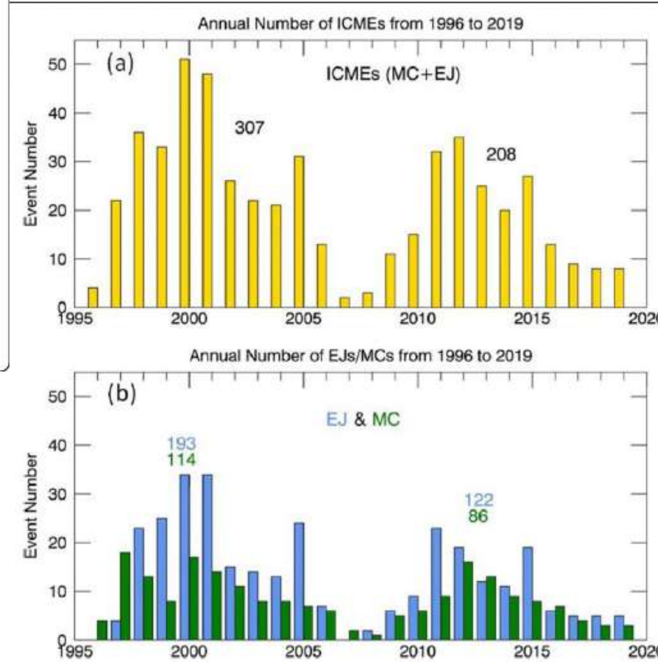
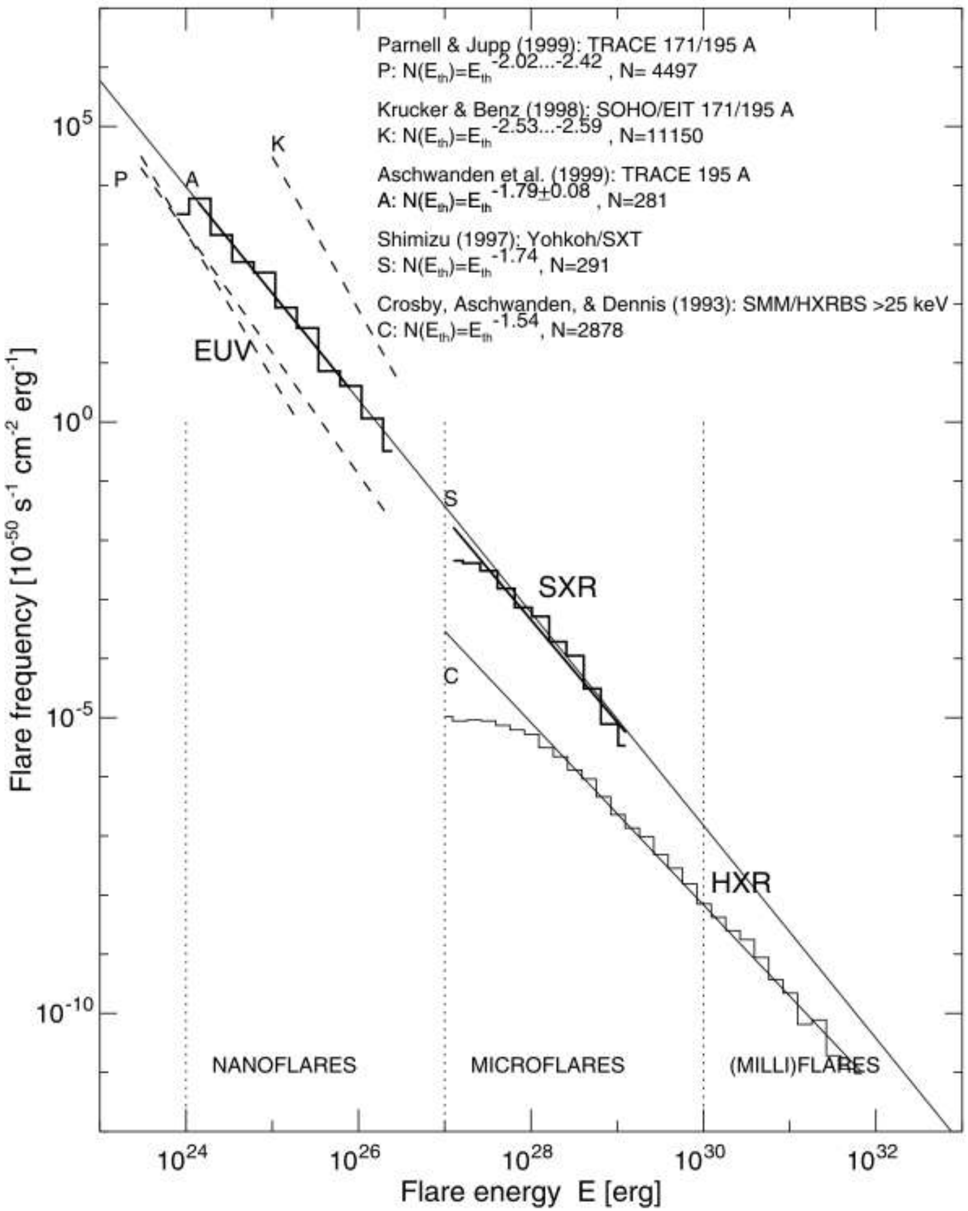


Fig. 7 a Solar cycle variation of the annual number of ICMEs (magnetic clouds—MCs and non-cloud ejecta—EJs) observed near Earth as compiled in http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm. The total number of ICMEs in cycles 23 (307) and 24 (208) are noted on the plot. **b** Annual number of EJs and MCs shown separately. The number of EJs and MCs is noted on the plot

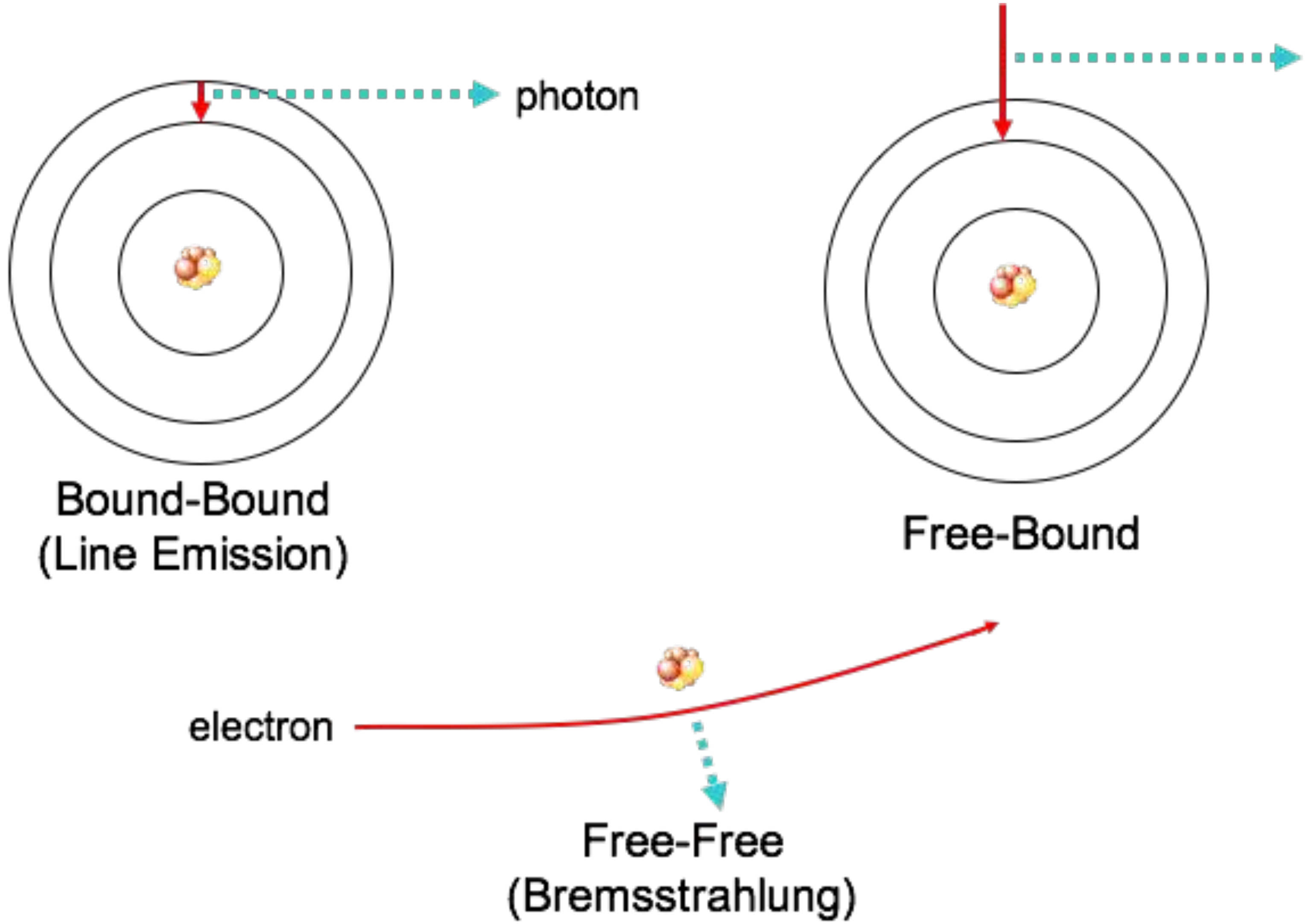
Solar eruption statistics: loi auto-similaire!



[Aschwanden+, 2014]

$$N(E_{th}) \sim E_{th}^{-n}$$

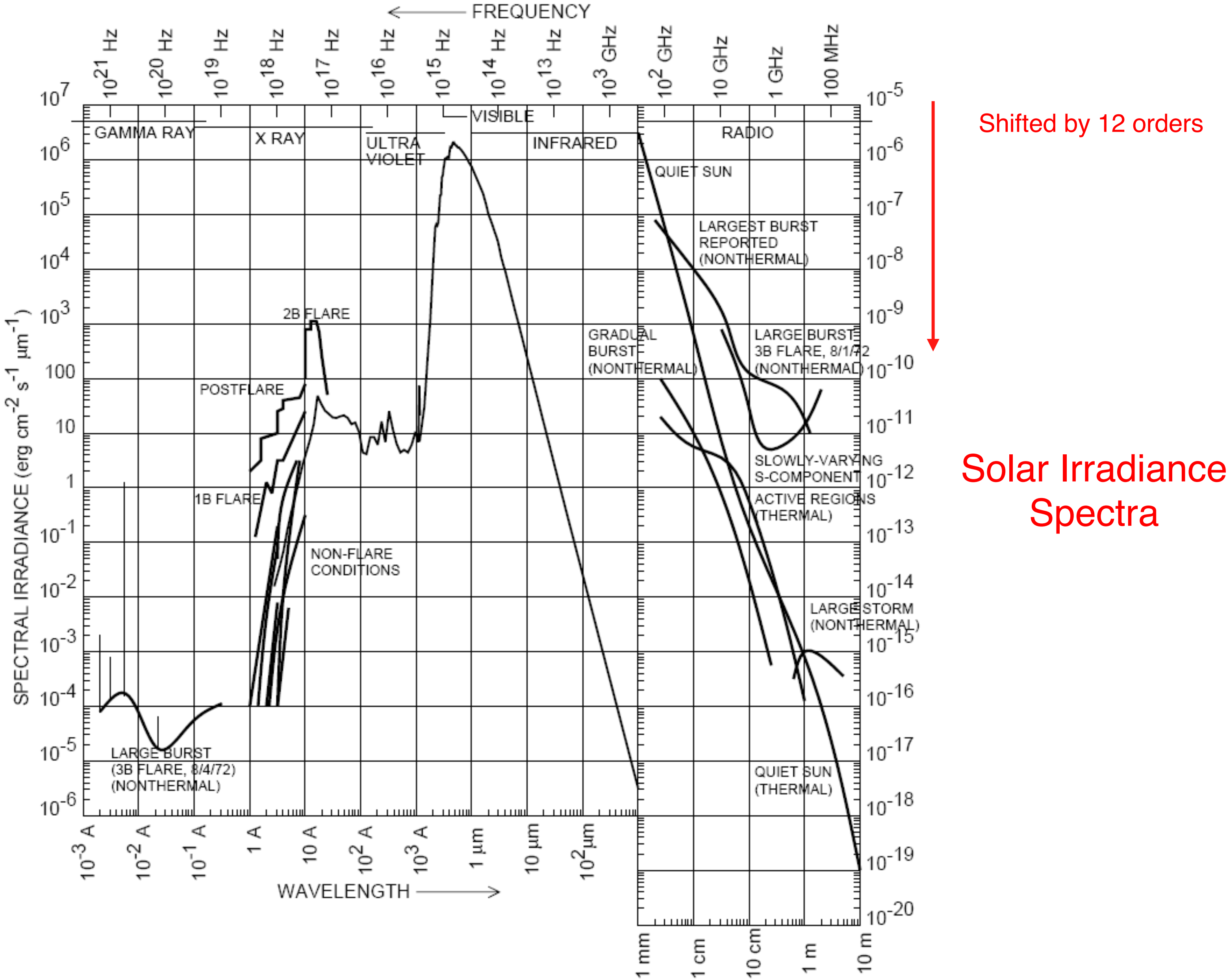
Radiation Mecanisms



Mécanismes d’accélération de particules

Table VI. Overview of Particle Acceleration Mechansims in Solar Flares

Acceleration Mechanisms	Electromagnetic £elds
DC Electric Field Acceleration:	
– Sub-Dreicer £elds, runaway acceleration[1]	$E < E_D$
– Super-Dreicer £elds[2]	$\mathcal{E} > \mathcal{E}_D$
– Current sheet (X-point) collapse[3]	$\mathcal{E} = -u_{inflow} \times B$
– Magnetic island (O-point) coalescence[4]	$\mathcal{E}_{conv} = -u_{coal} \times B$
– (£lamentary current sheet: X- and O-points)	
– Double layers[5]	$\mathcal{E} = -\nabla V$
– Betatron acceleration (magnetic pumping)[6]	$\nabla \times \mathcal{E} = -(1/c)(dB/dt)$
Stochastic Acceleration:	
Gyroresonant wave-particle interactions (weak turbulence) with:	
– whistler (R-) and L-waves[7]	$k \parallel B$
– O- and X-waves[8]	$k \perp B$
– Alfvènic waves (transit time damping)[9]	$k \parallel B$
– magnetoacoustic waves[10]	$k \perp B$
– Langmuir waves[11]	$k \parallel B$
– Lower hybrid waves[12]	$k \perp B$
Shock Acceleration:	
First-order Fermi acceleration, Shock-drift acceleration[13]	
– Fast shocks in reconnection out□ow[14]	
– Mirror-trap in reconnection out□ow[15]	
– Diffusive-shock acceleration[17]	
Second-order Fermi acceleration[16]	
– Strong turbulence scattering[18]	



Solar Irradiance Spectra

Figure 1.25: The solar irradiance spectrum from gamma-rays to radio waves. The spectrum is shifted by 12 orders of magnitude in the vertical axis at $\lambda = 1$ mm to accommodate for the large dynamic range in spectral irradiance (after Zombeck, 1990 and Foukal, 1990).

Emissions of thermal and non-thermal electrons (ions)

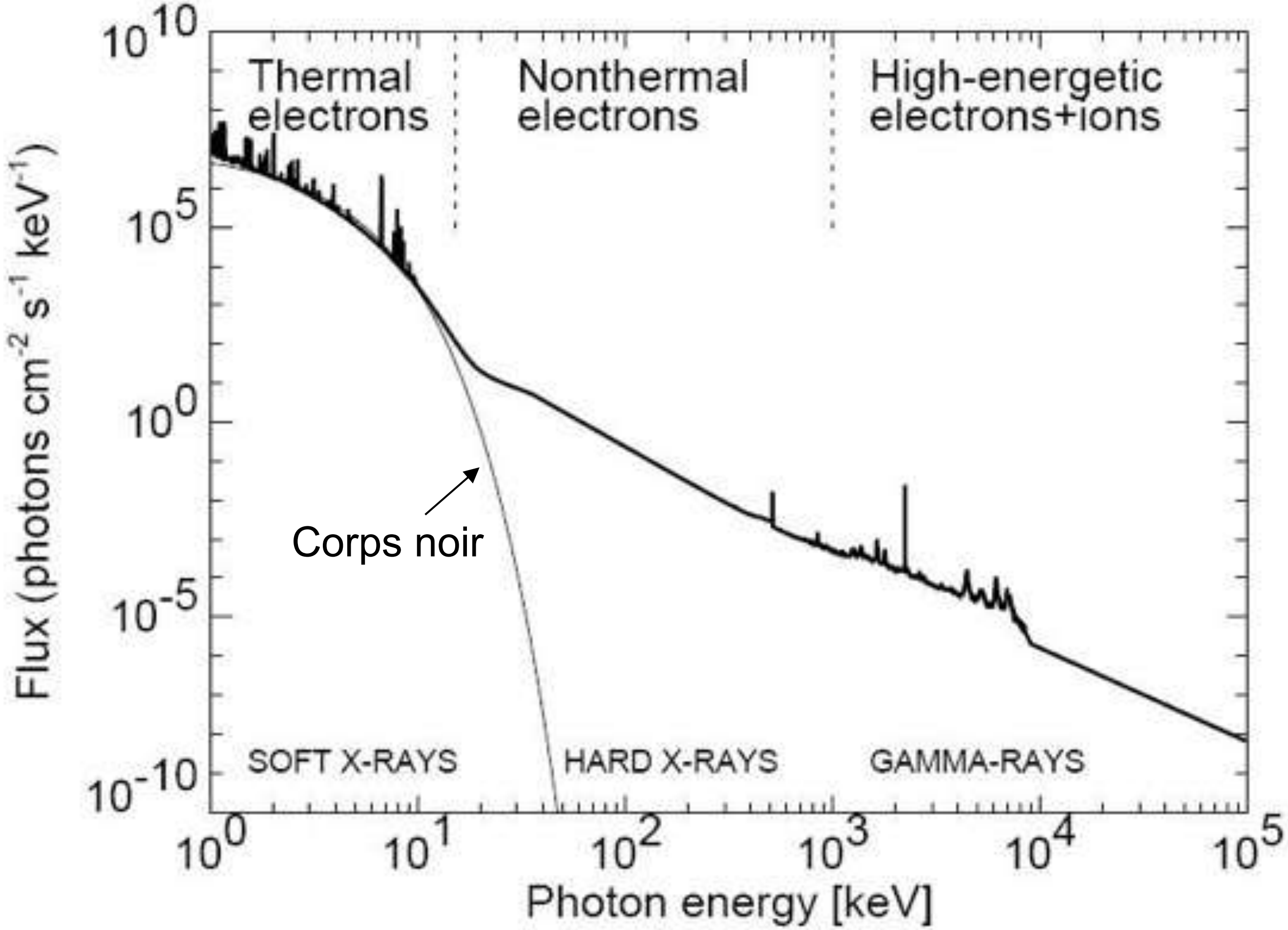
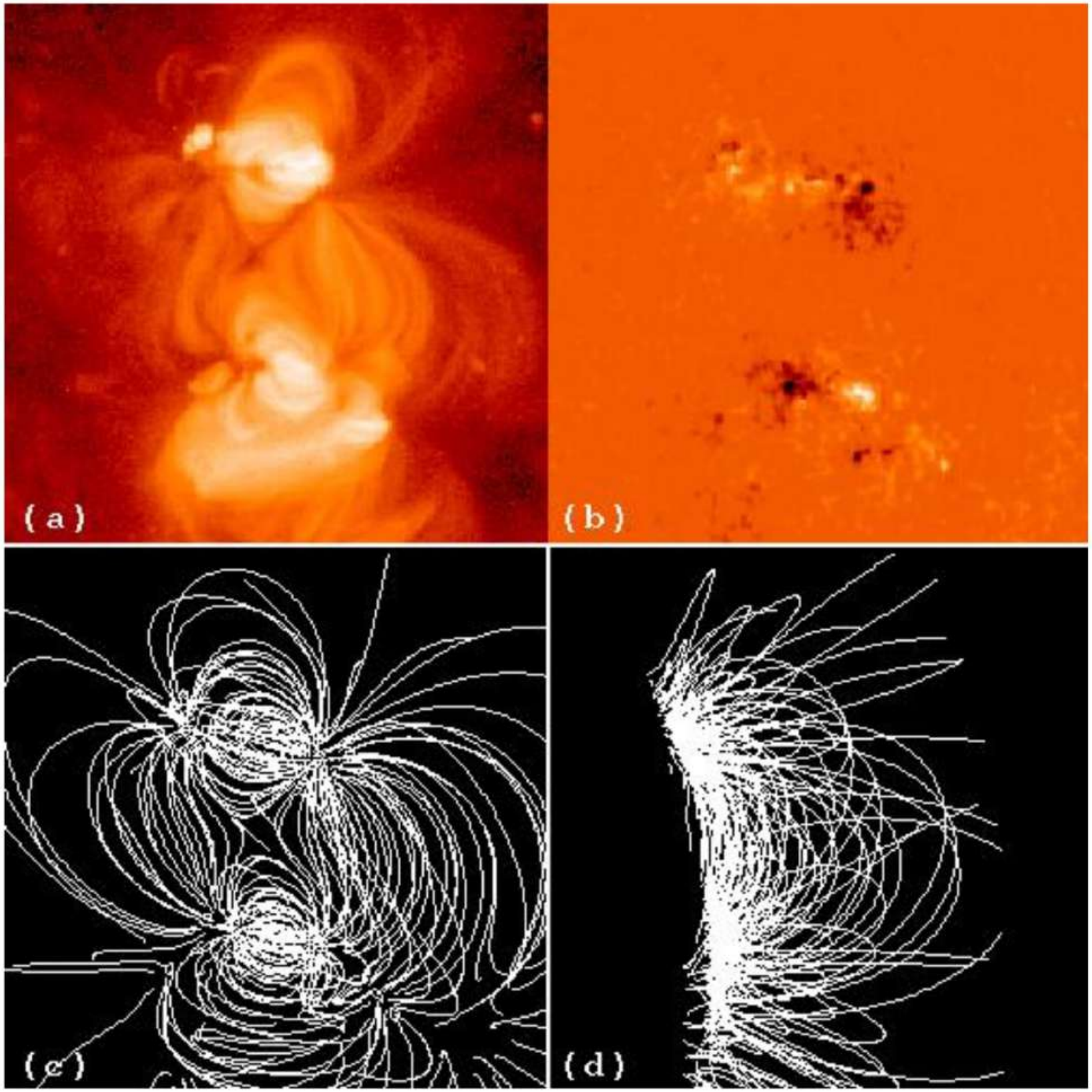
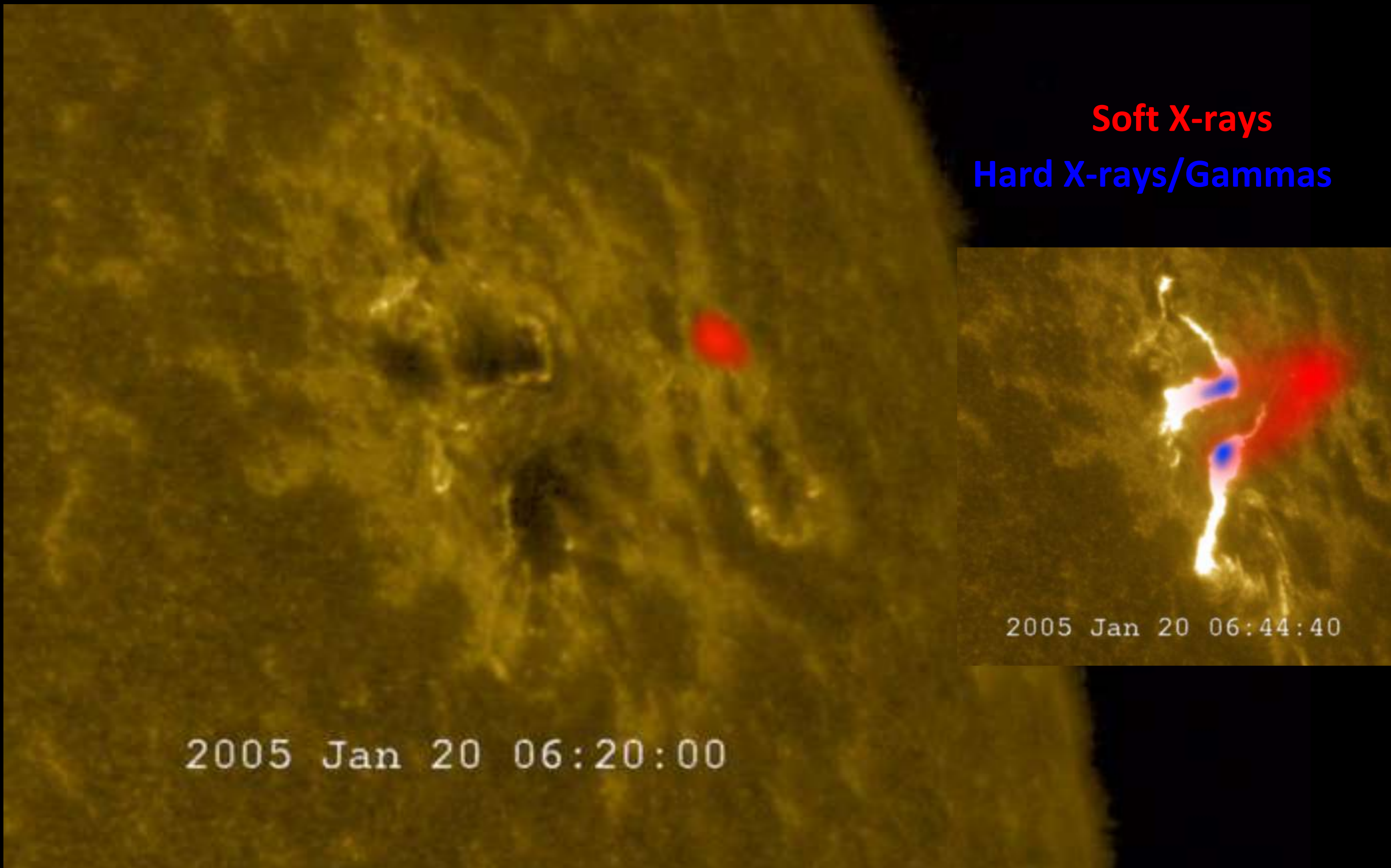


Figure 94. Composite photon spectrum of a large ▫are, extending from soft X-rays (1-10 keV), hard X-rays (10 keV-1 MeV), to gamma rays (1 MeV-10 GeV), mostly produced by thermal, nonthermal (energetic), or high-energetic electrons. Gamma-ray line emission and parts of the gamma-ray continuum is produced by interactions of protons, neutrons, ions, and pion decay.

Magnetic field lines reconstruction



Multiwavelength observation of an eruption/flare



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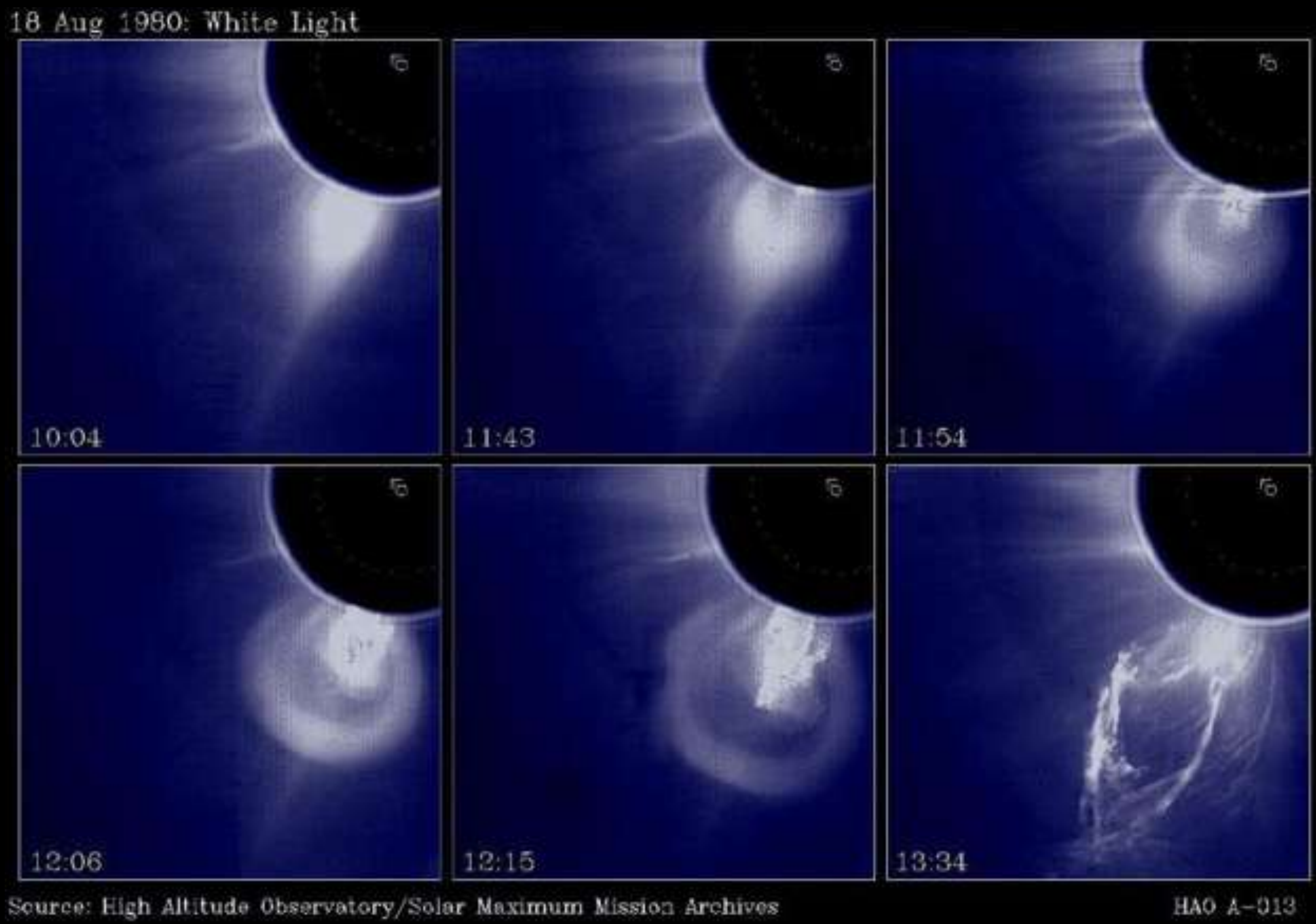
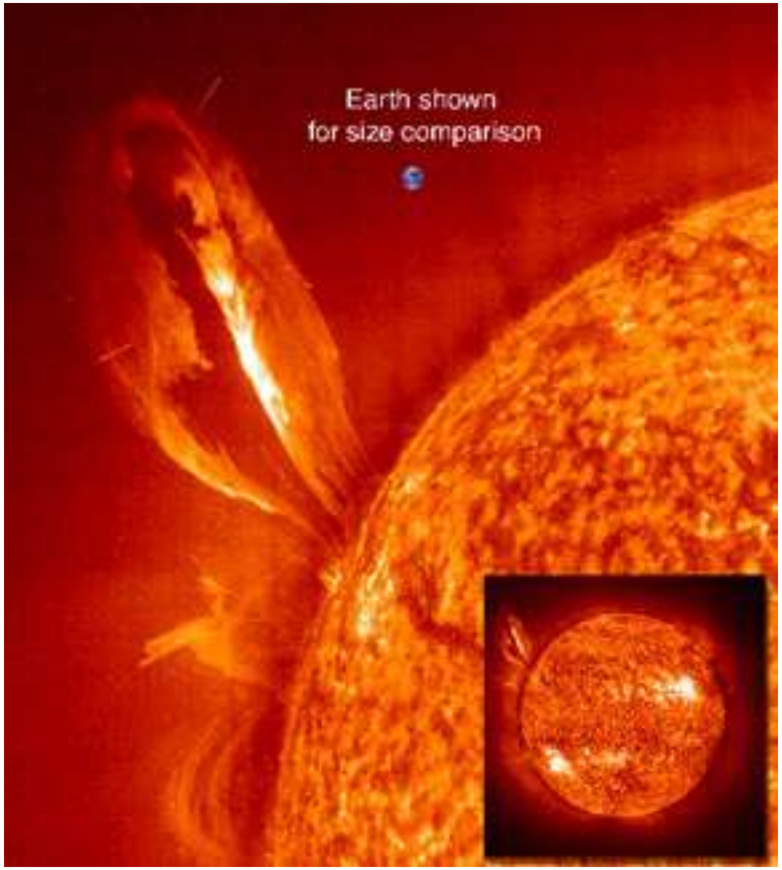
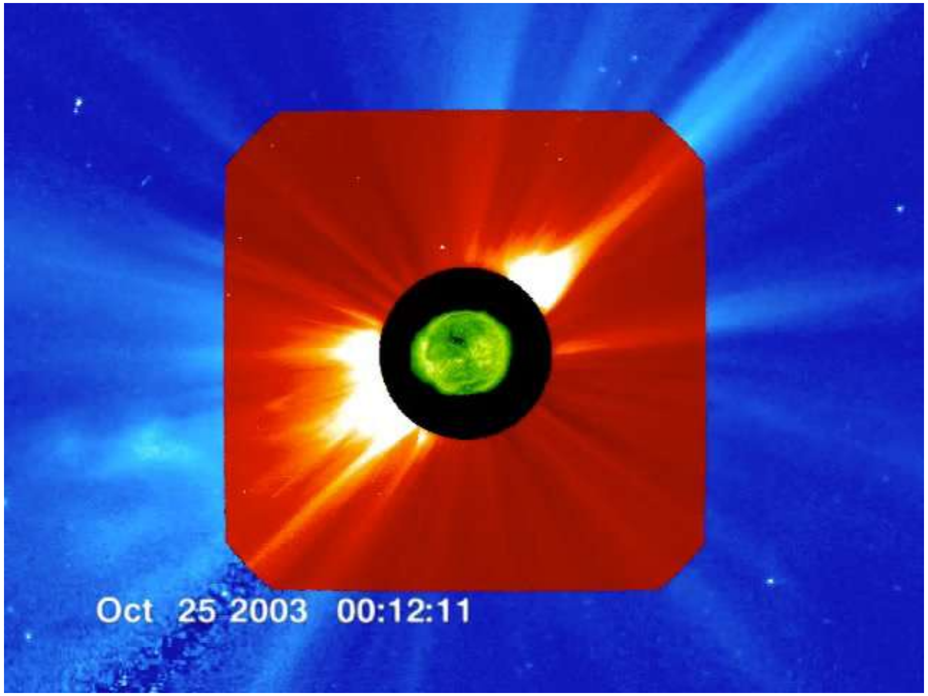
Coronal mass ejection (I)



Coronal mass ejection + flares





SoHO-EIT & LASCO

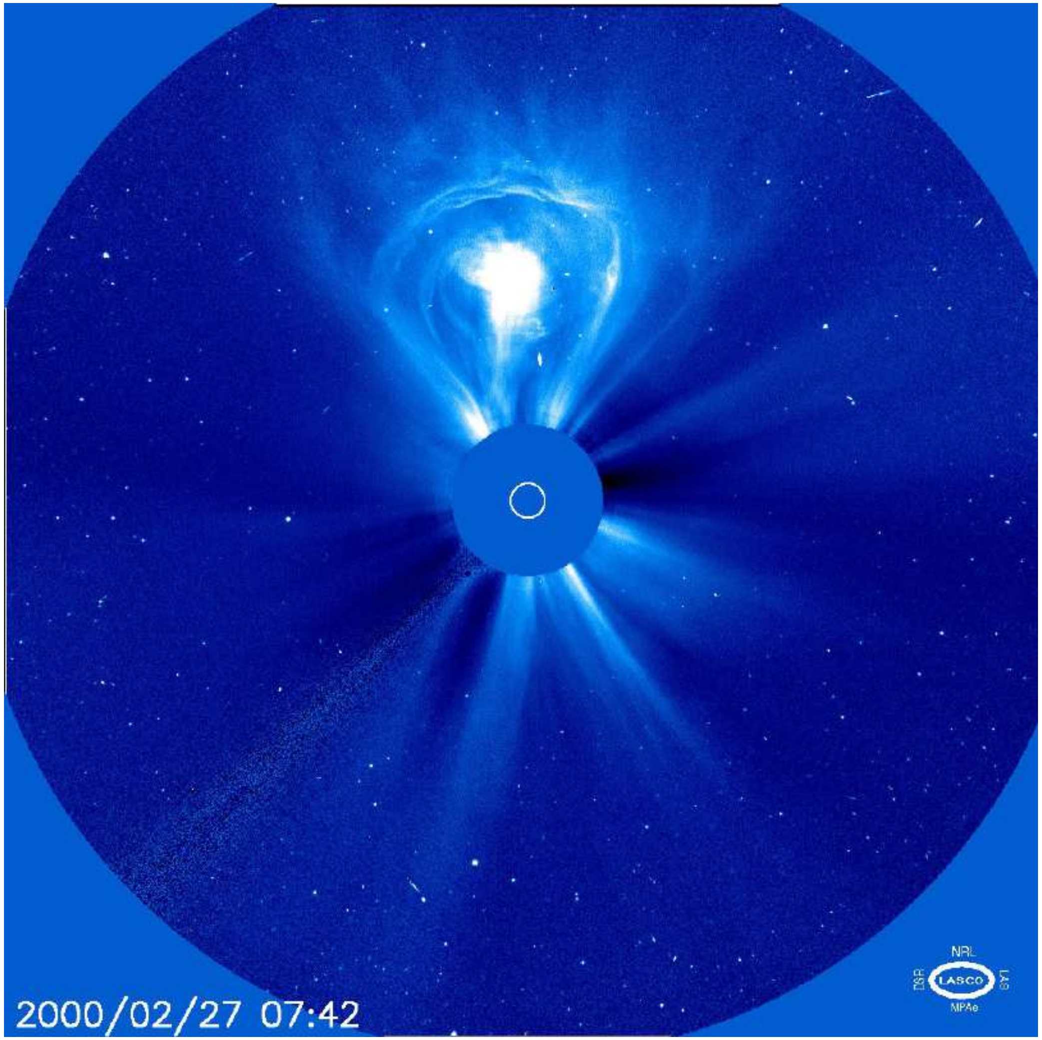
Some numbers about CMES

The energy of medium to large eruptive flares is generally distributed roughly equally between radiated energy (flare) and the kinetic energy of the ejected plasma (CME), for a total energy of around **4×10^{25} J**

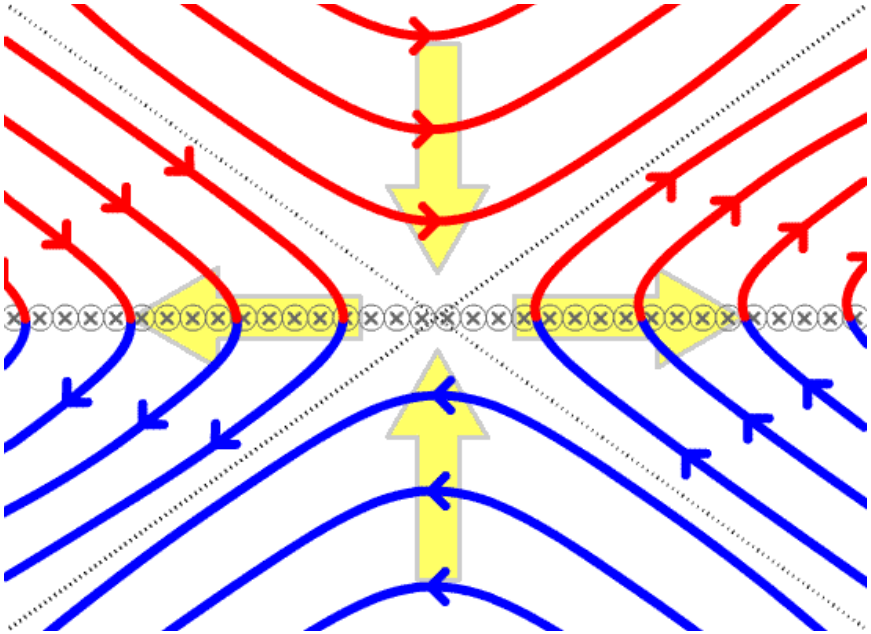
The only sufficient source of eneegy is the **magnetic energy**

They can reach up to **4×10^{13} kg**

They are accelerated to approximately 2 solar radii, then propagate through the interplanetary medium at speeds ranging from **20 to 2000 km/s**



Magnetic Reconnexion(2D)



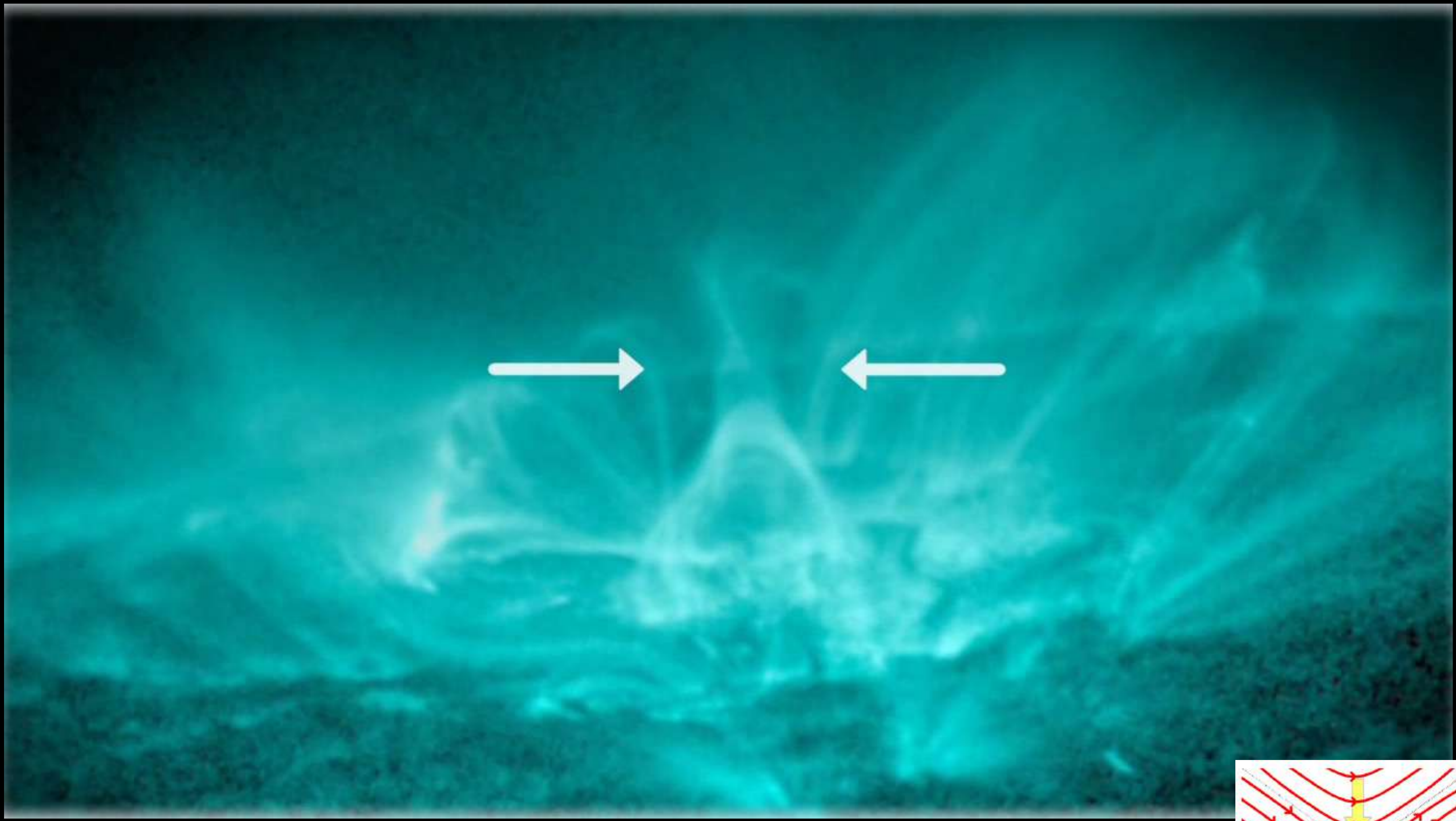
First model for solar flares proposed by Parker-Sweet in the 1960s (resistive current layer). **<u>Problem:</u>** the characteristic time is too long!

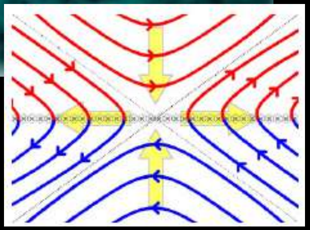
$$\tau = (\tau_\eta \tau_A)^{1/2} \sim 10^7 \; s$$

Petschek then proposed a rapid reconnection mechanism in 1964, based on "increased" ohmic dissipation near the reconnection point. **Problem:** What mechanism is behind this high dissipation?

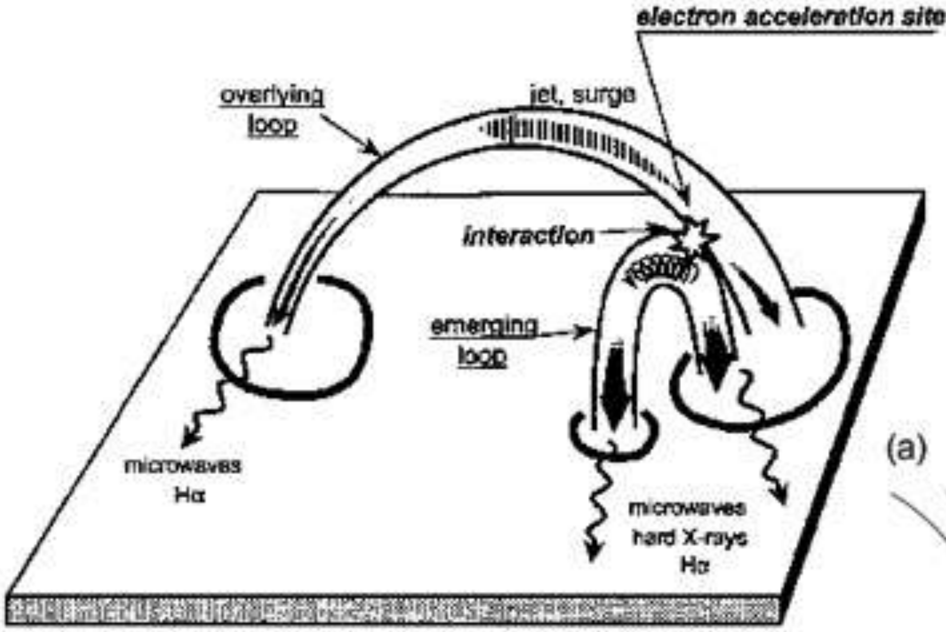
Several solutions exist to achieve such dissipation:
- Shock waves that convert magnetic energy very efficiently
- Non-collisional effects (due to small-scale ionic or electronic effects)

Reconnexion in solar courona



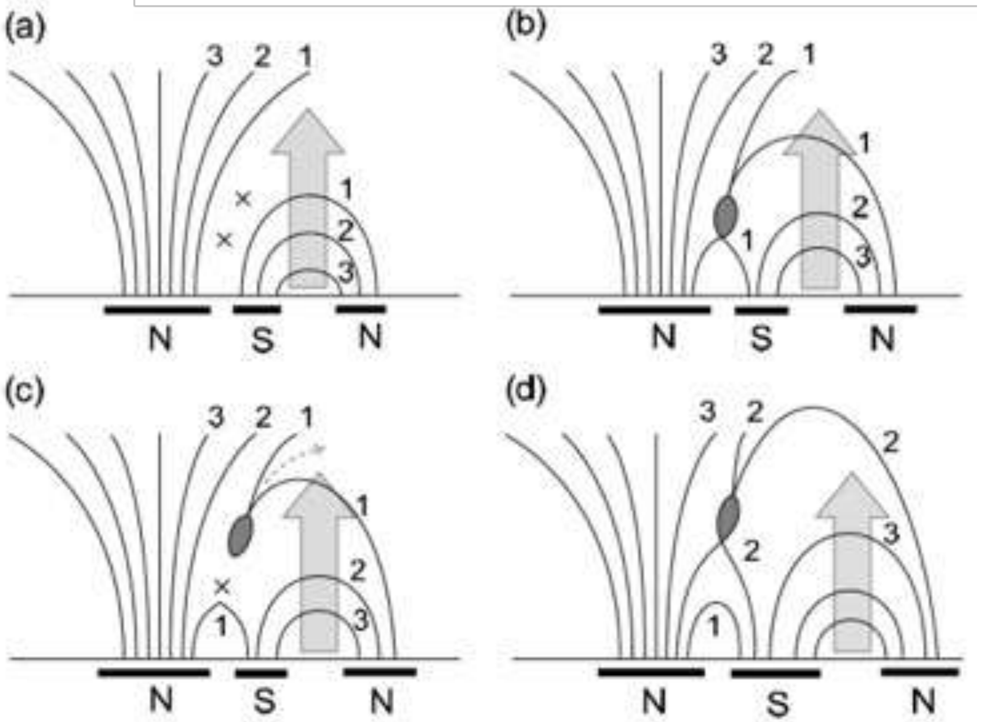


Interacting magnetic loops



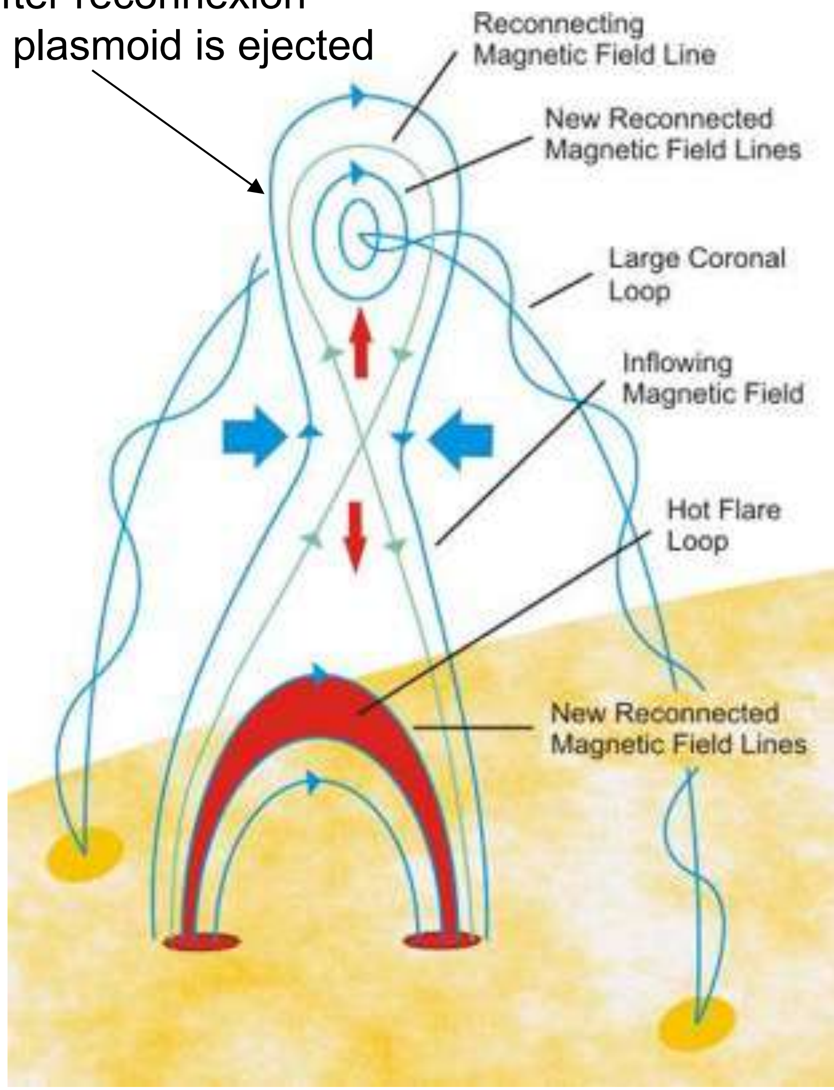
Hanaoka, Publications of the Astronomical Society of Japan, 1999

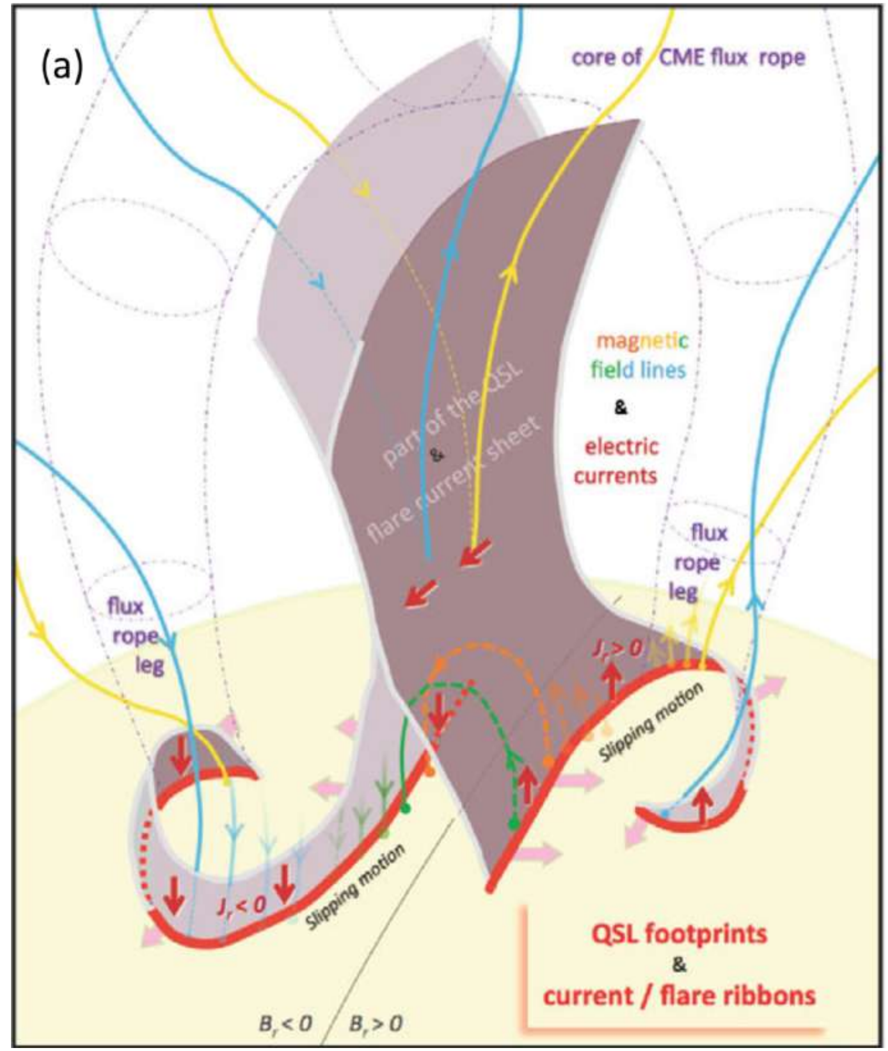
Takasaki et al., The Astrophysical Journal, 2004



Standard model for eruptions and CMEs

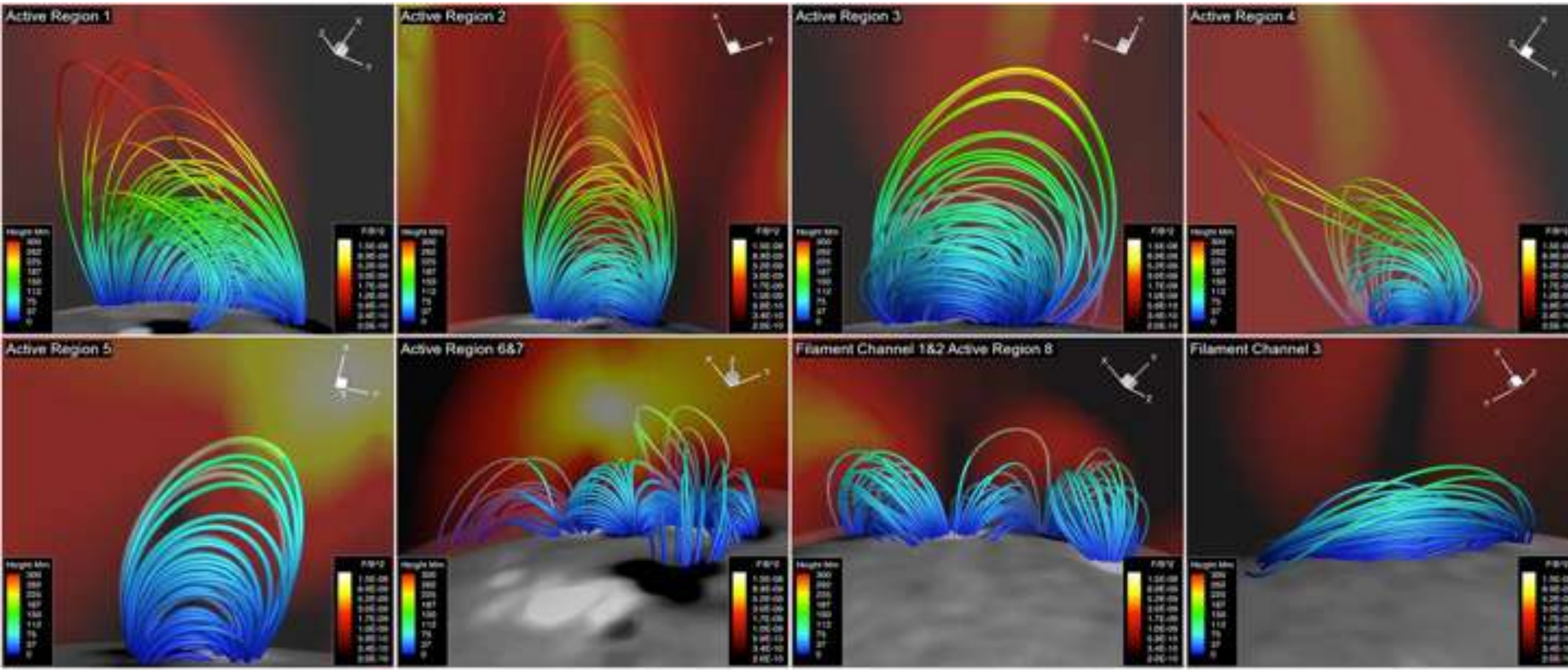
after reconnexion
a plasmoid is ejected





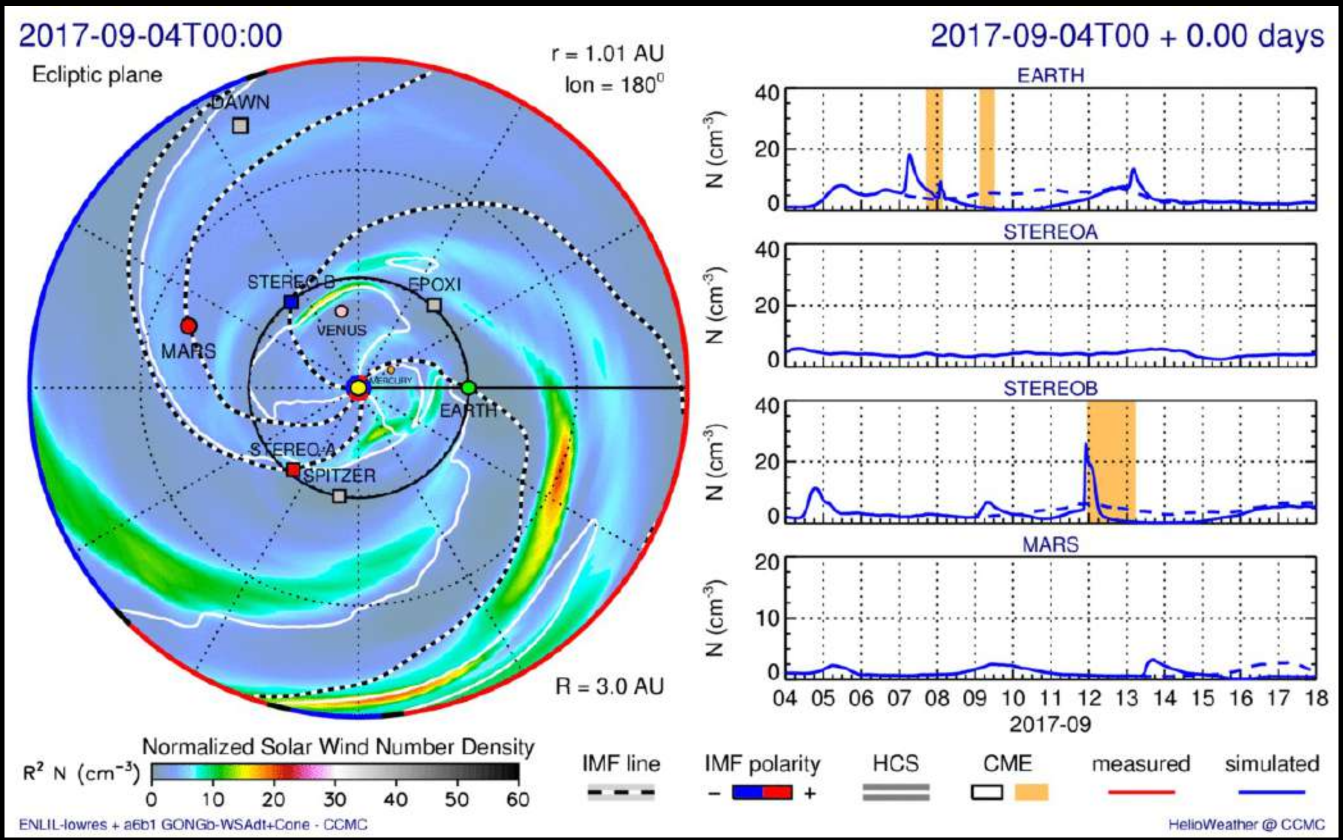
… towards more realistic models

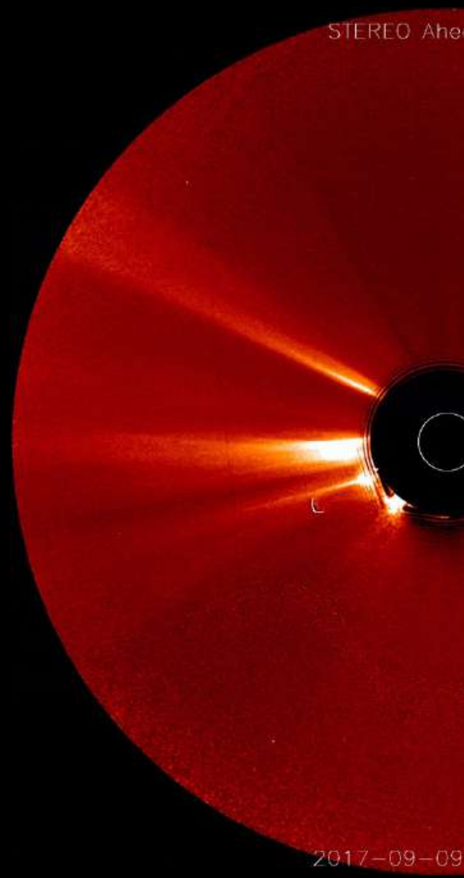
15 février 2011, Jin (LMSAL) & Torok (Predictive Sciences Inc.)

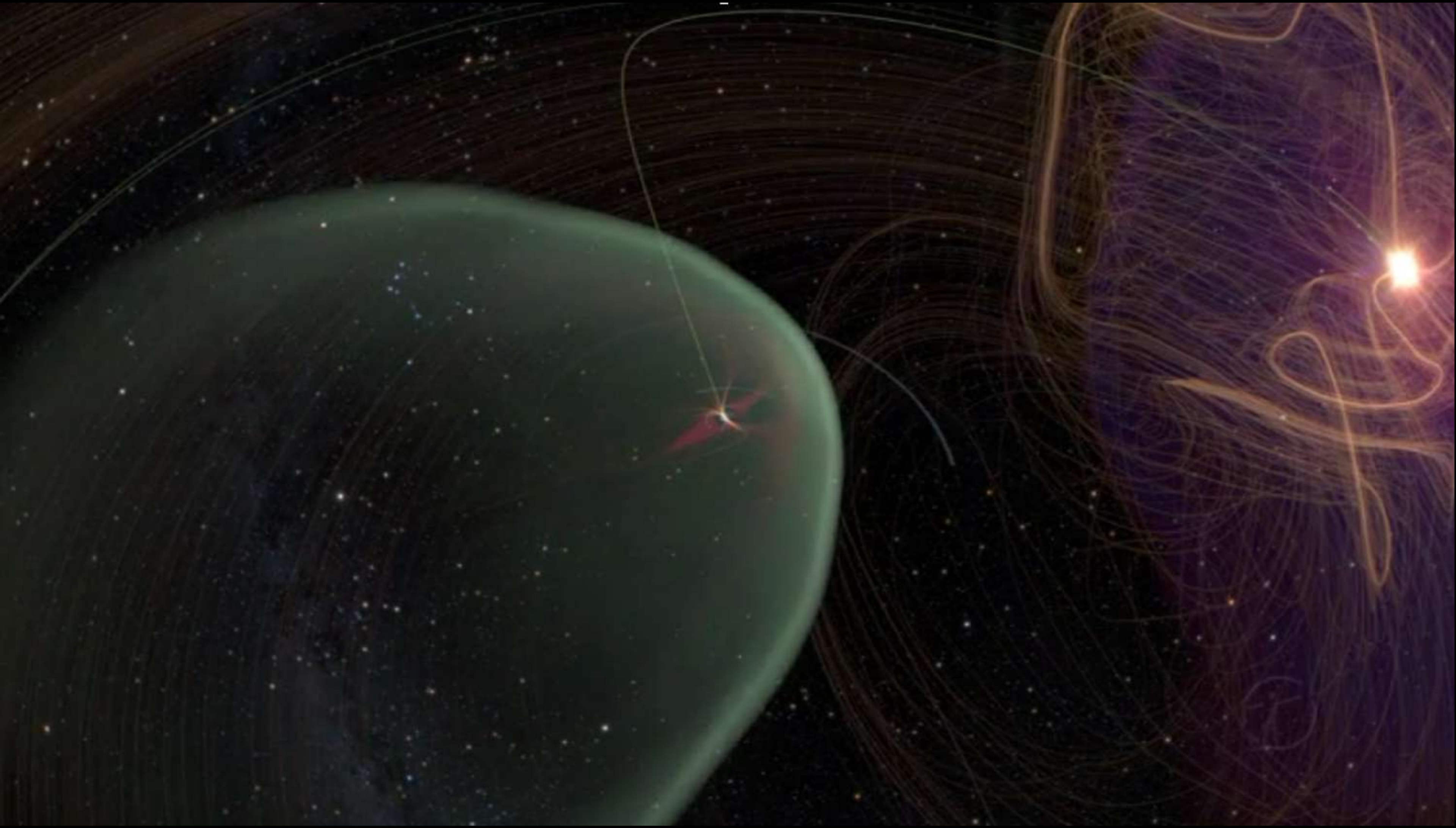


Magnetic clouds propagation (artist view)

Exemple of 10th September 2017



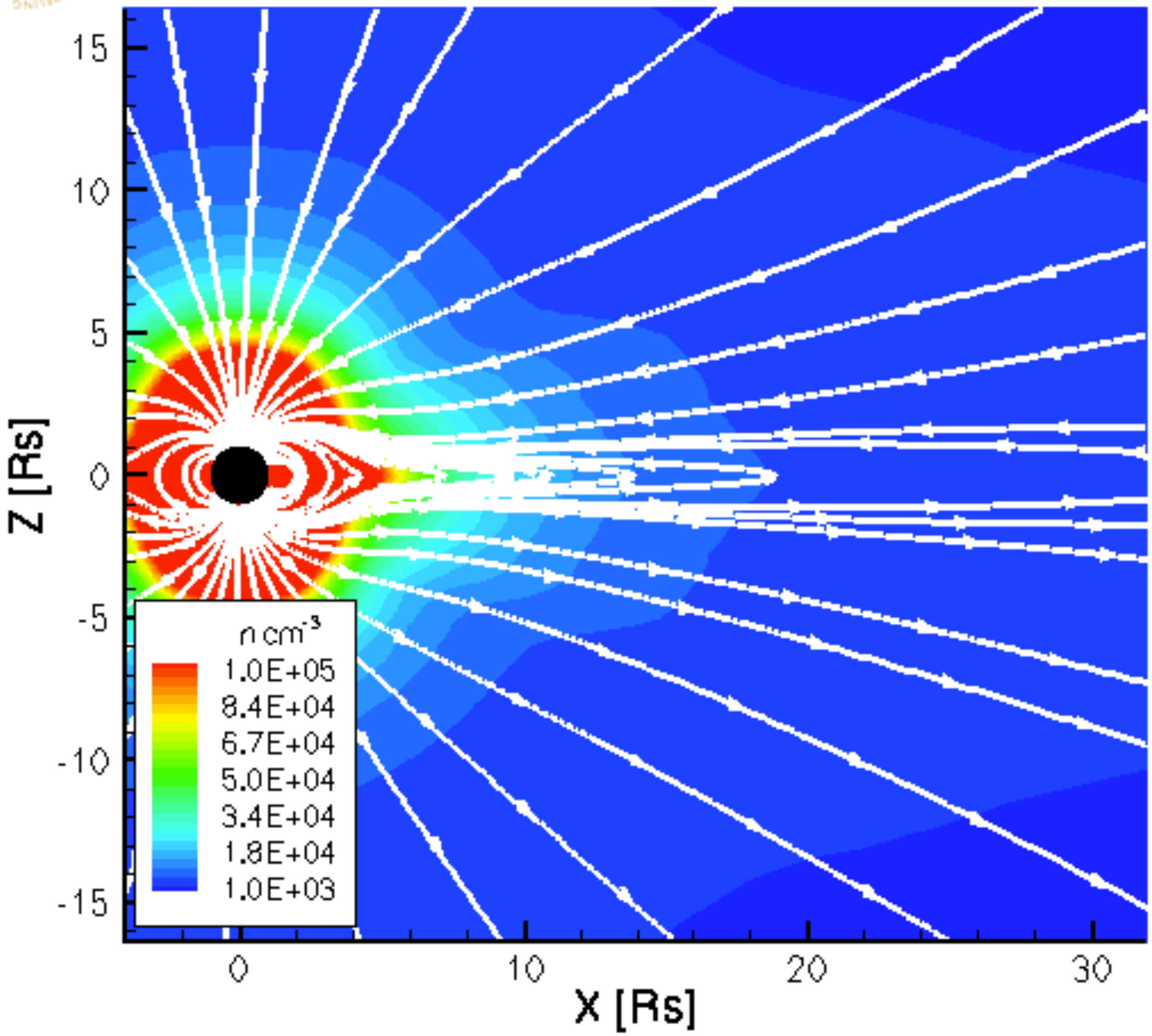




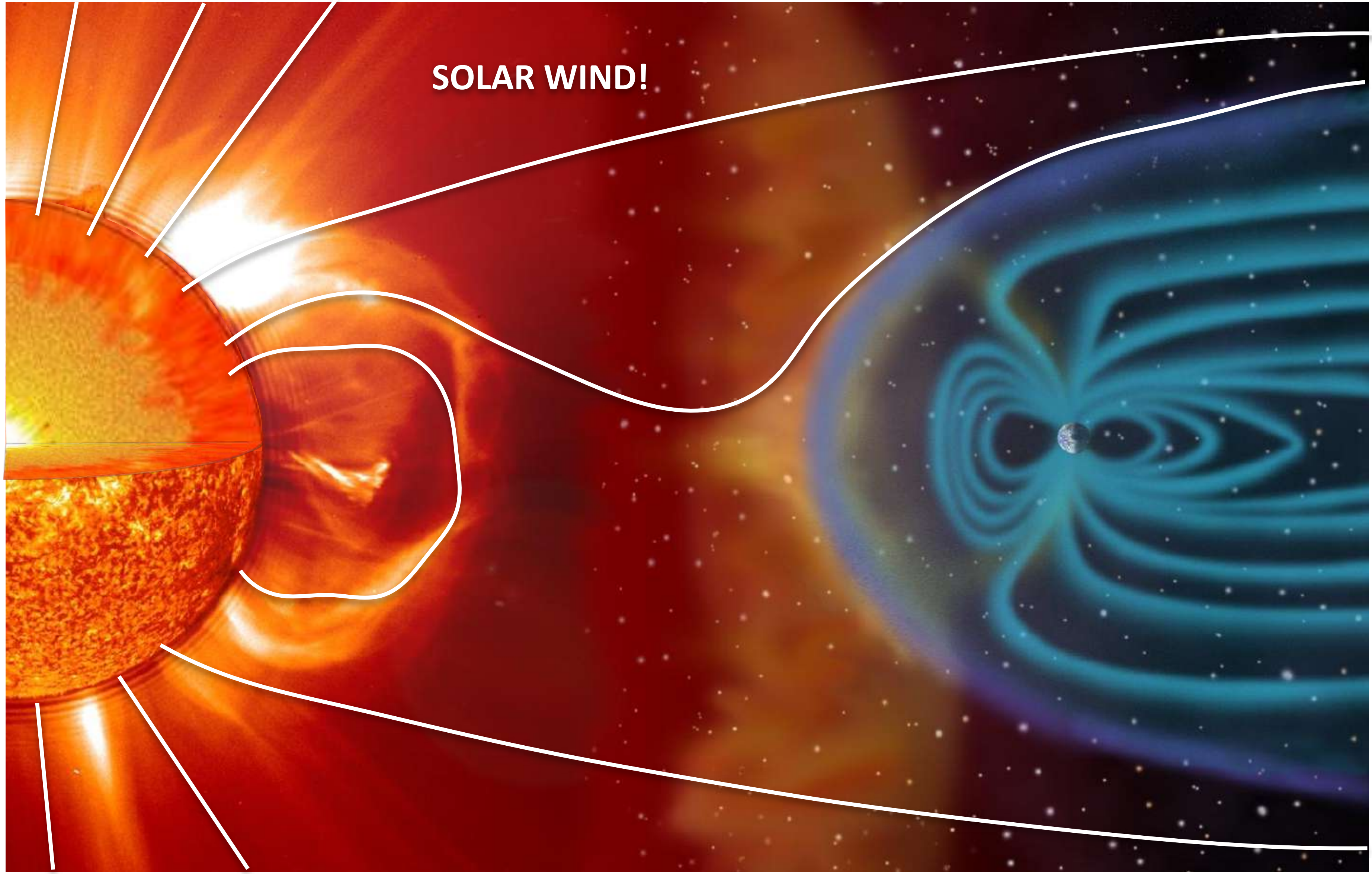
Jouney to the stars movie

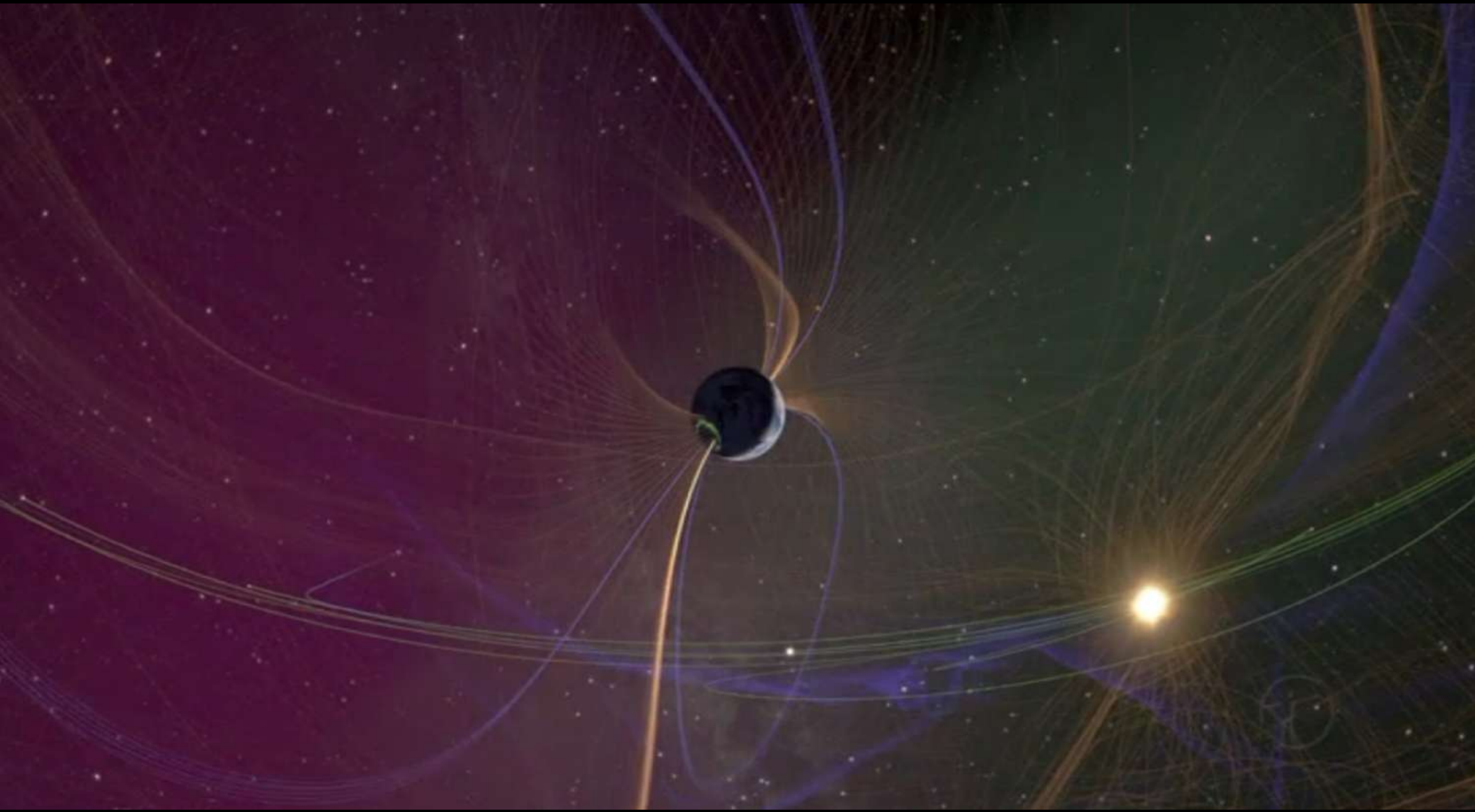
CME and (tiny!) planet Earth

University of Michigan
Manchester et. al.
2003



These ejections do not propagate in a void medium (next Lecture)





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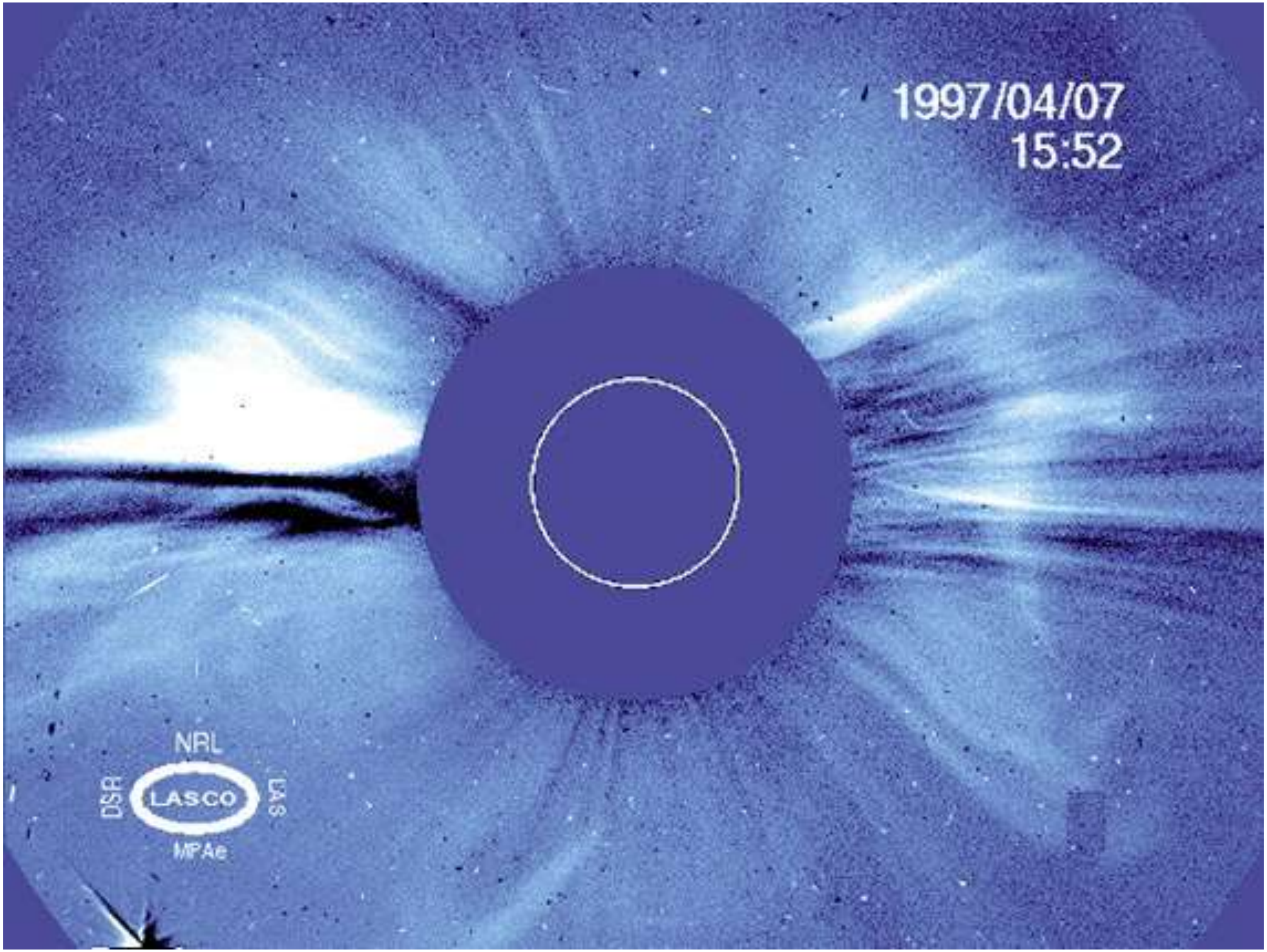
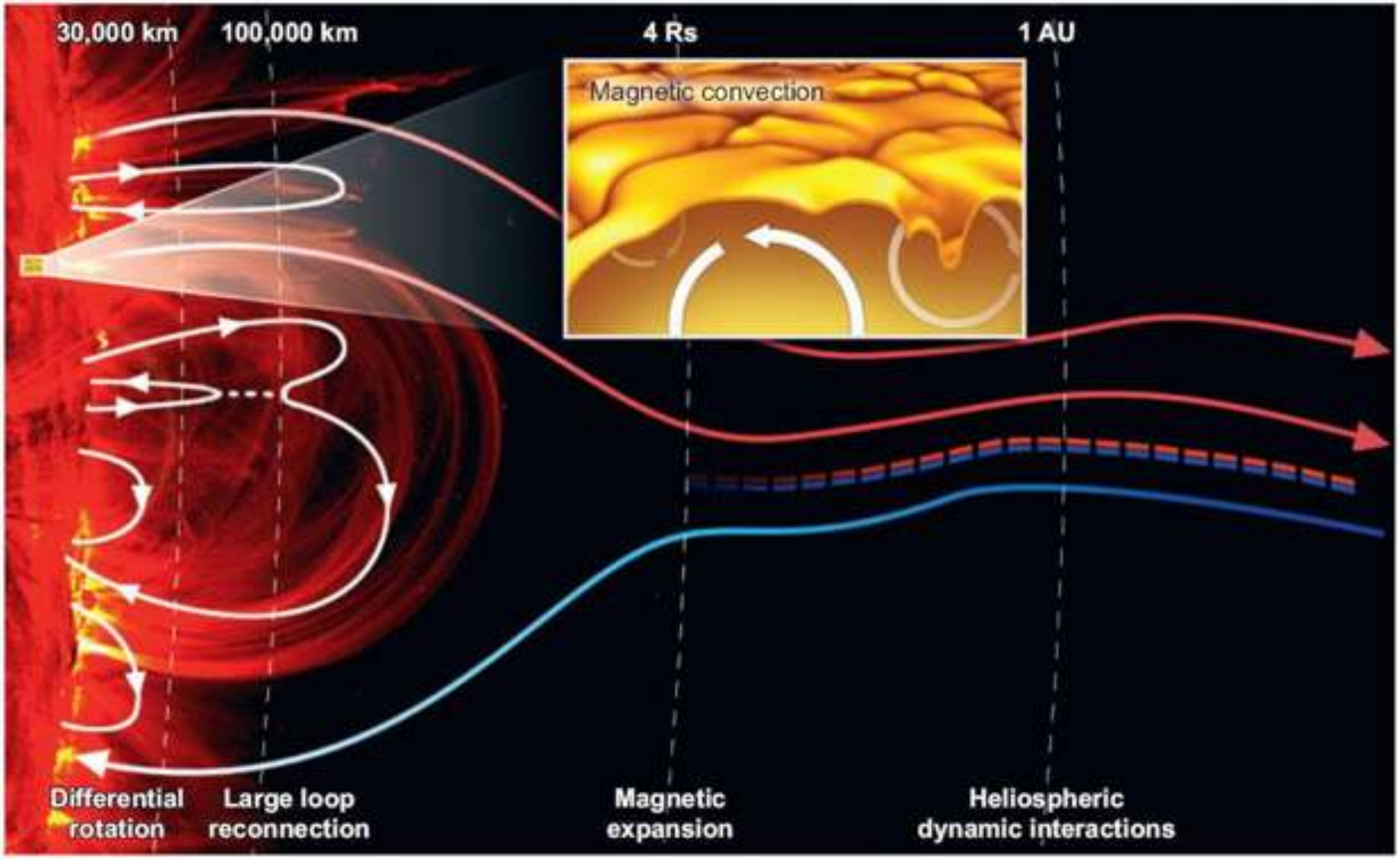
Corona and solar wind



Heliosphere structuration and magnetic field



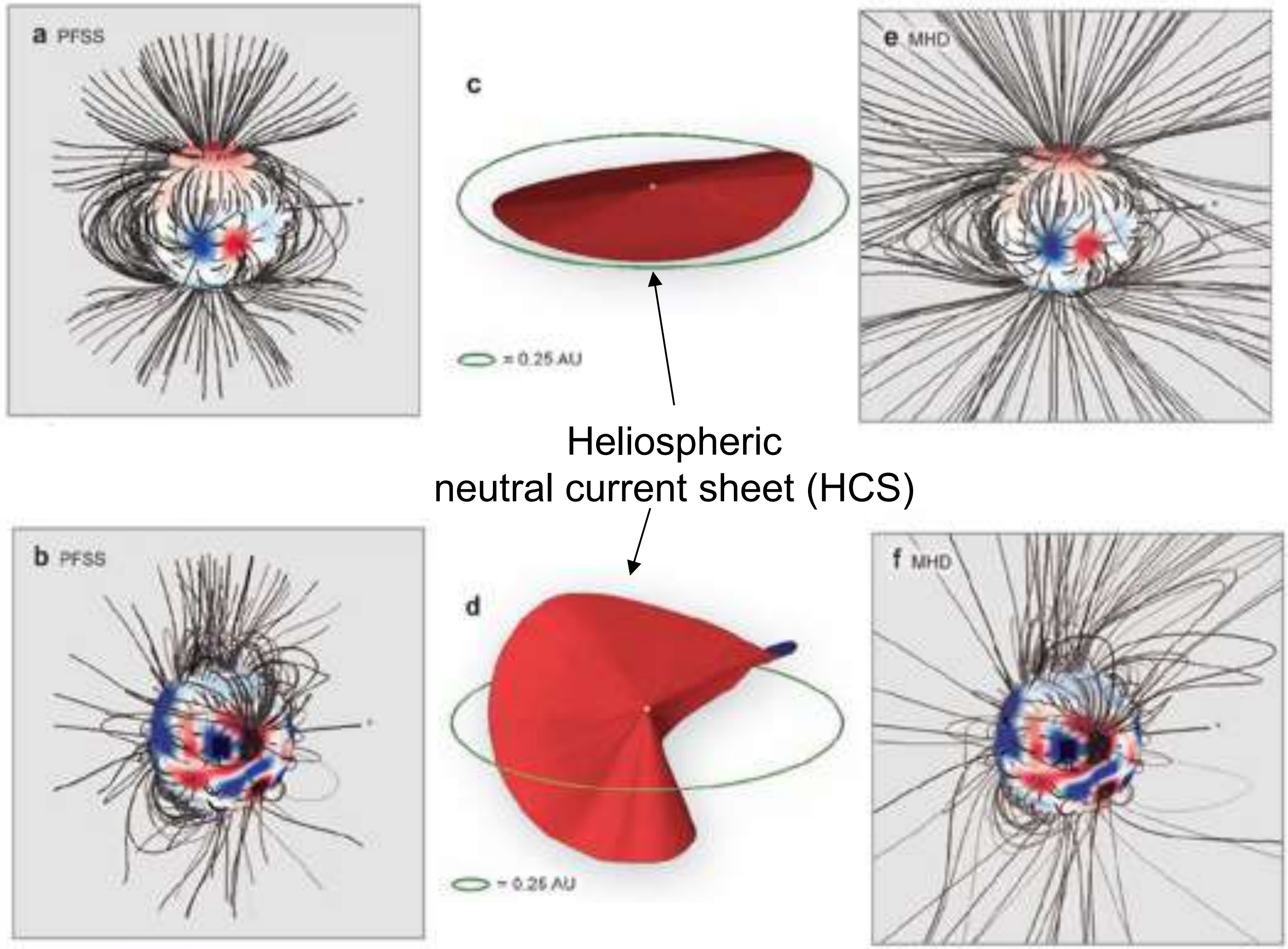
Extrapolation 'Potential Field Source Surface (PFSS)'

Cas Potentiel sans courant

Cas MHD général

Mininum

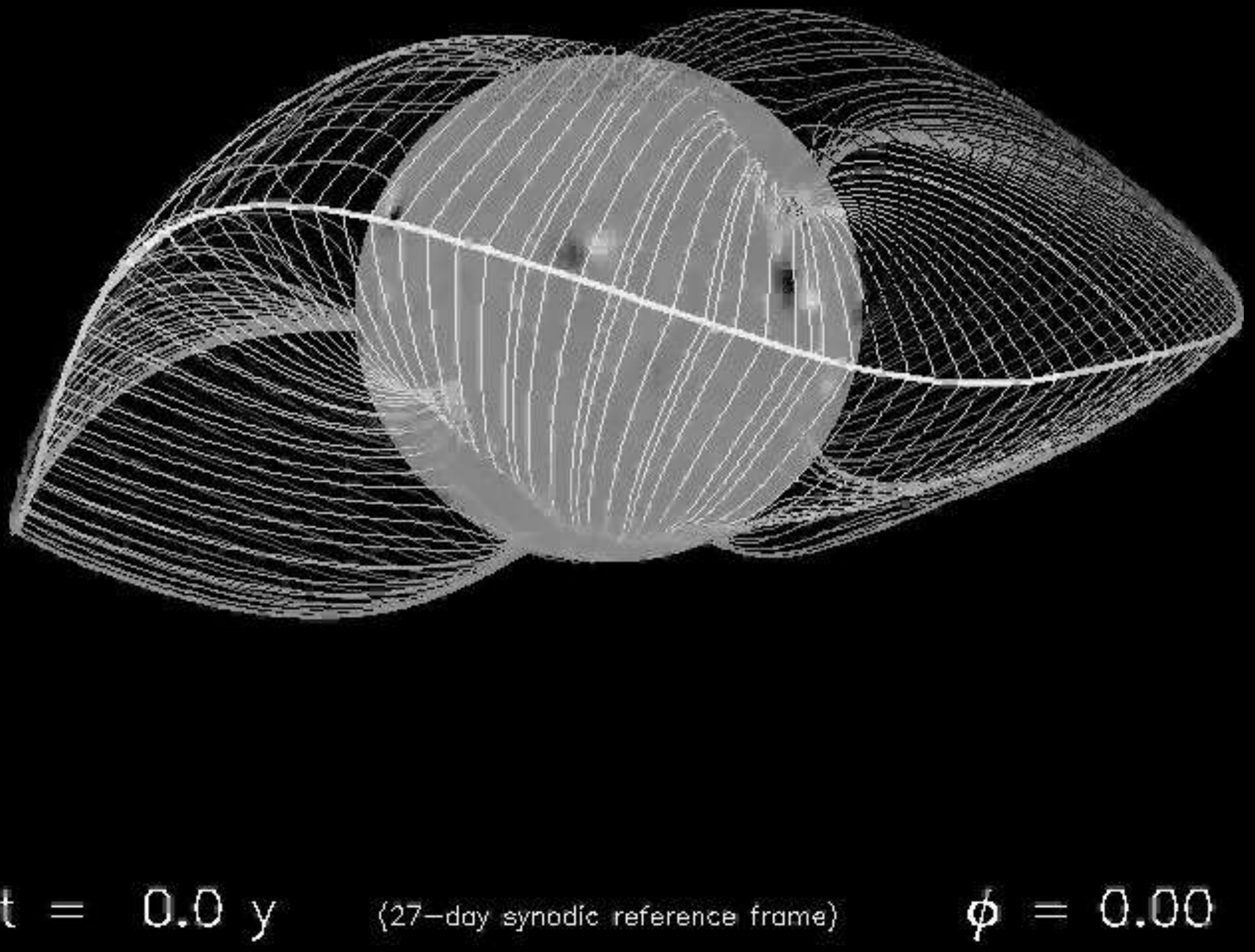
Maximum



Heliospheric
neutral current sheet (HCS)

Field geometry and HCS more complex at maximum

Magnetic field and HCS



Courtesy of Dr. M. Derosa

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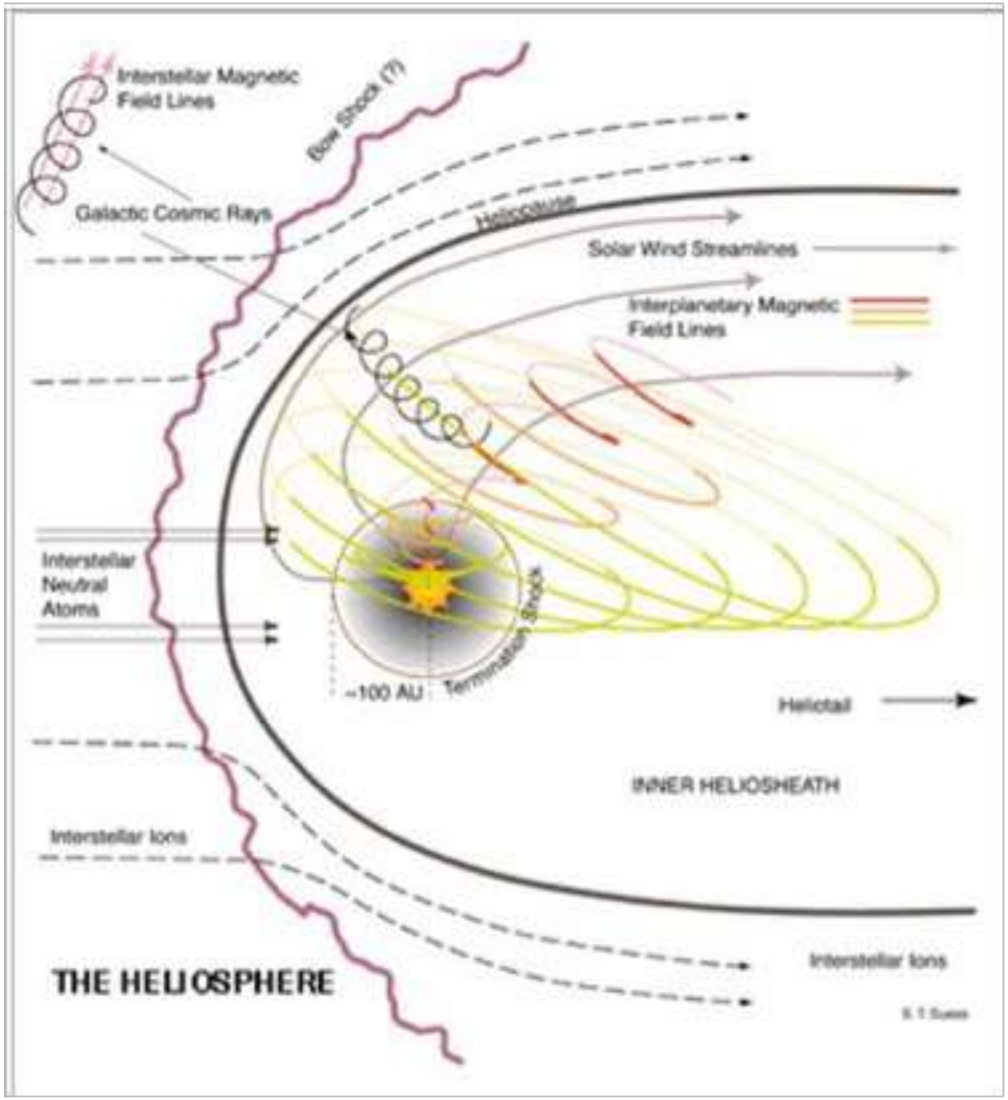
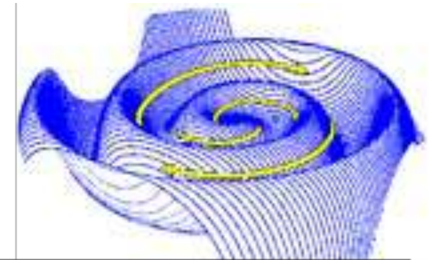
Heliosphere as a whole

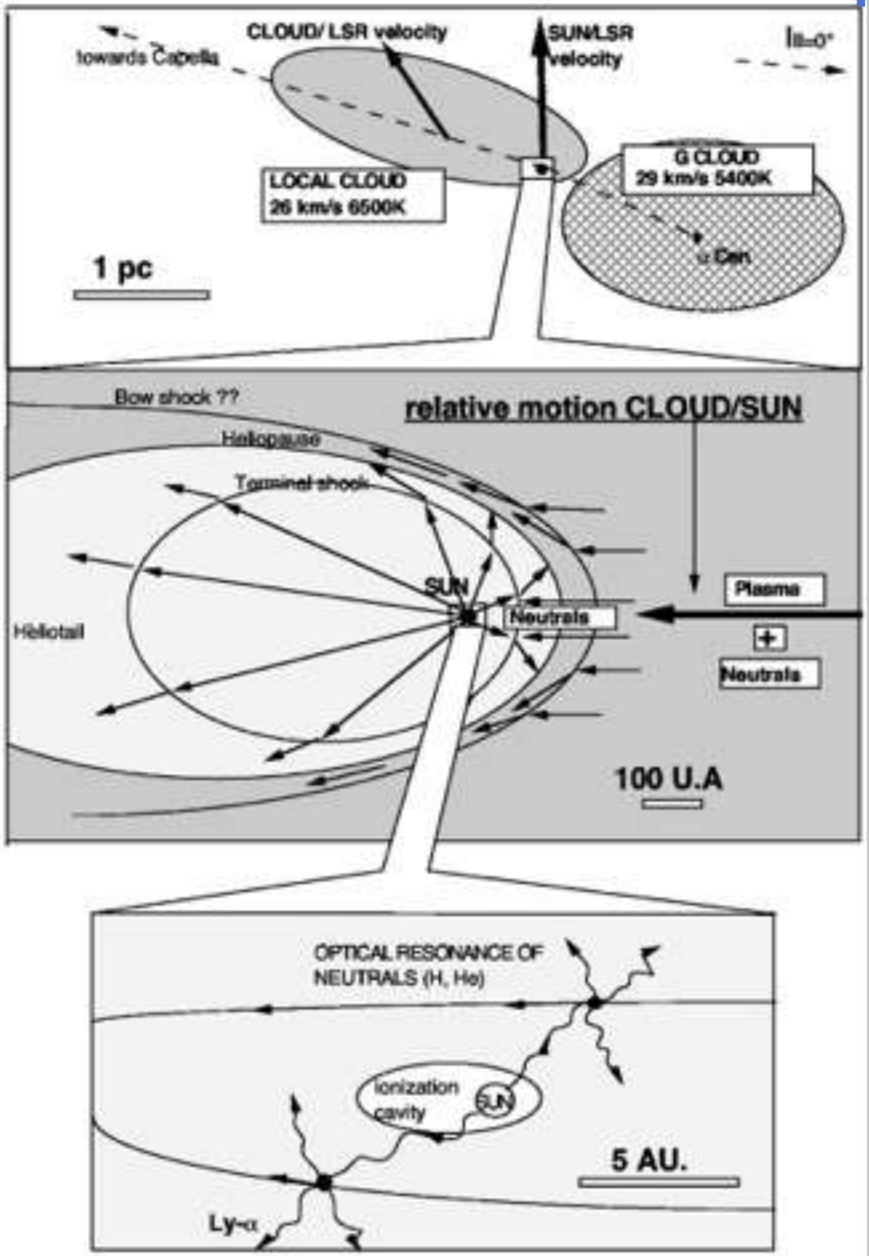


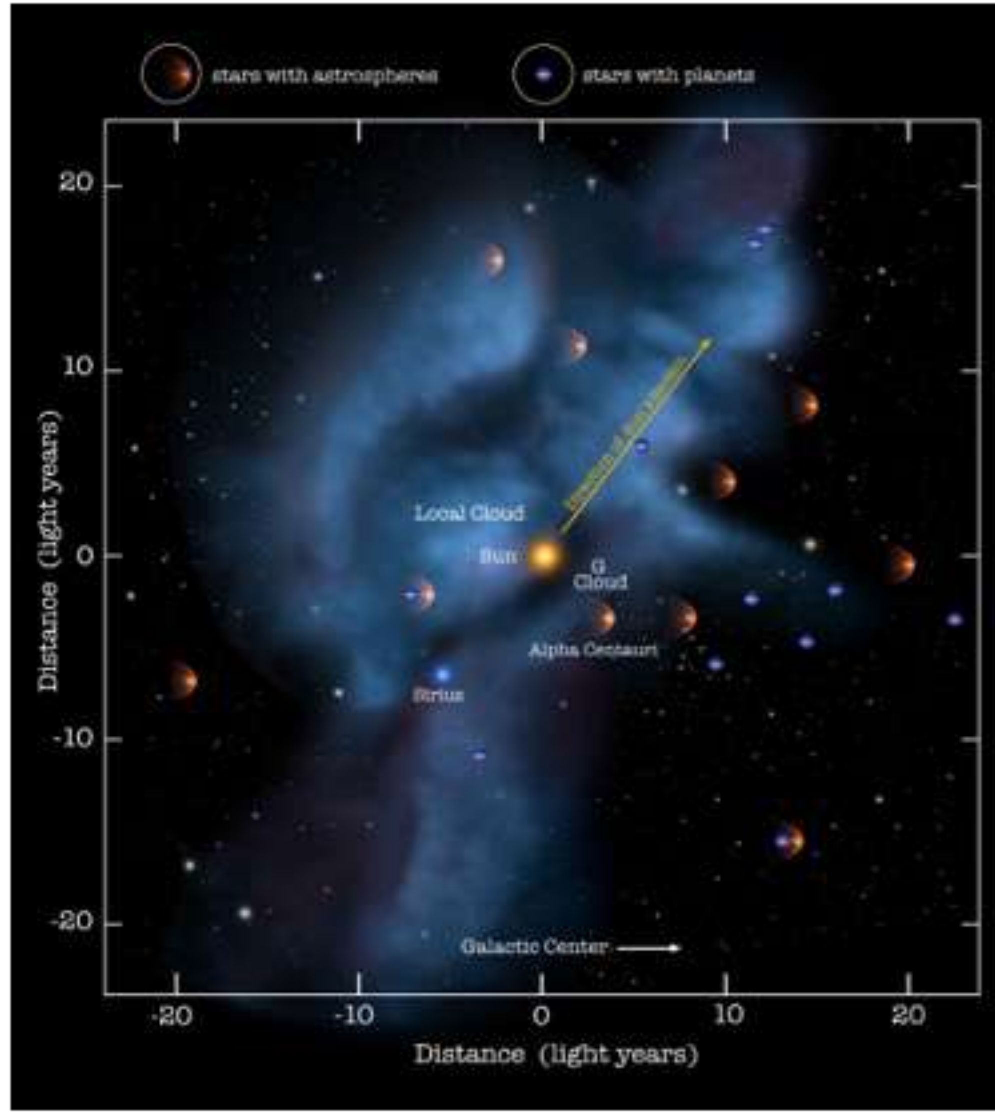


Spirale de Parker et
Couche de Courant Neutre Héliosphérique

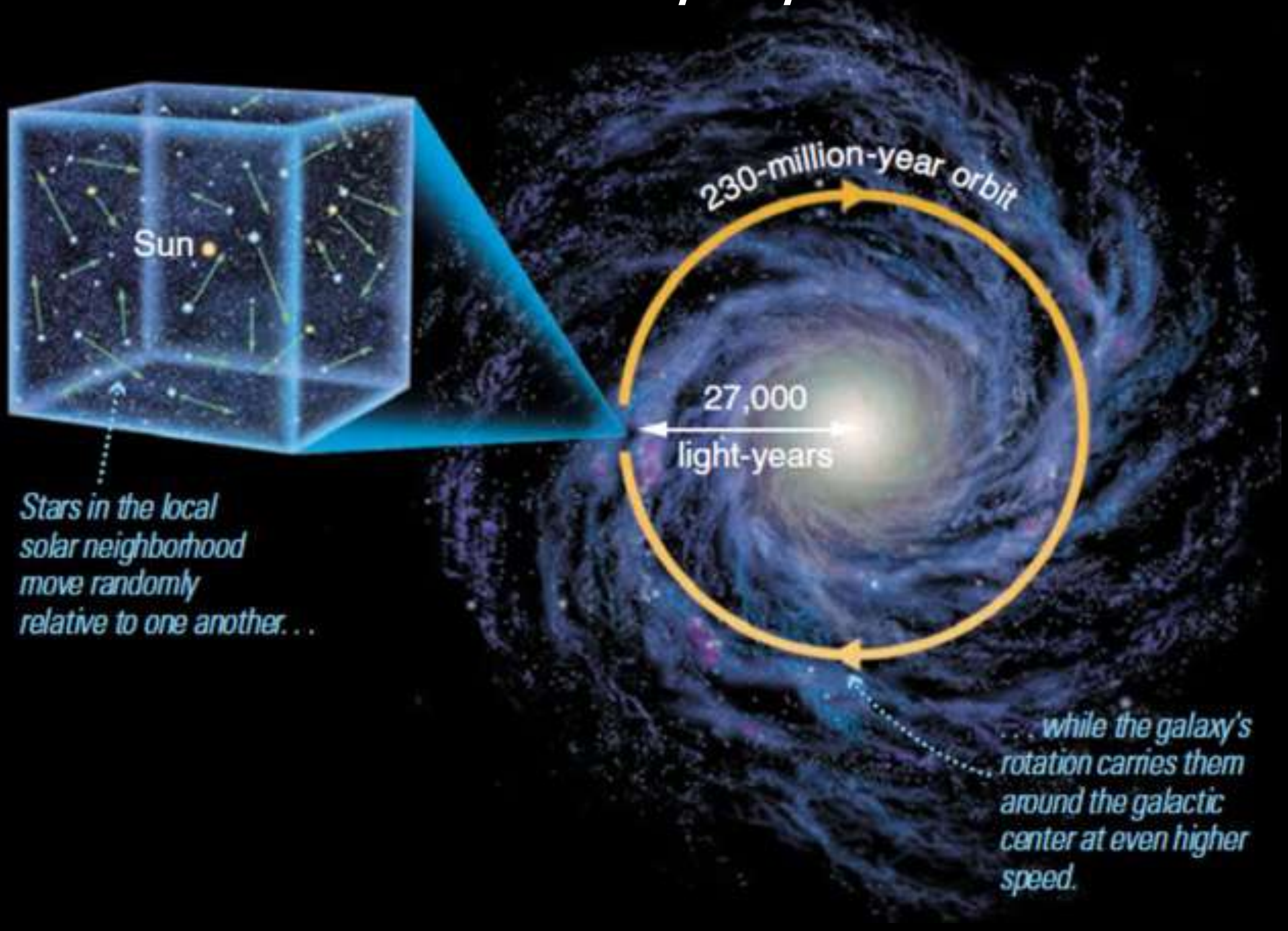
Jouney to the stars movie

Relative motion of the Sun in space





Where is the Sun located in the Milky Way?

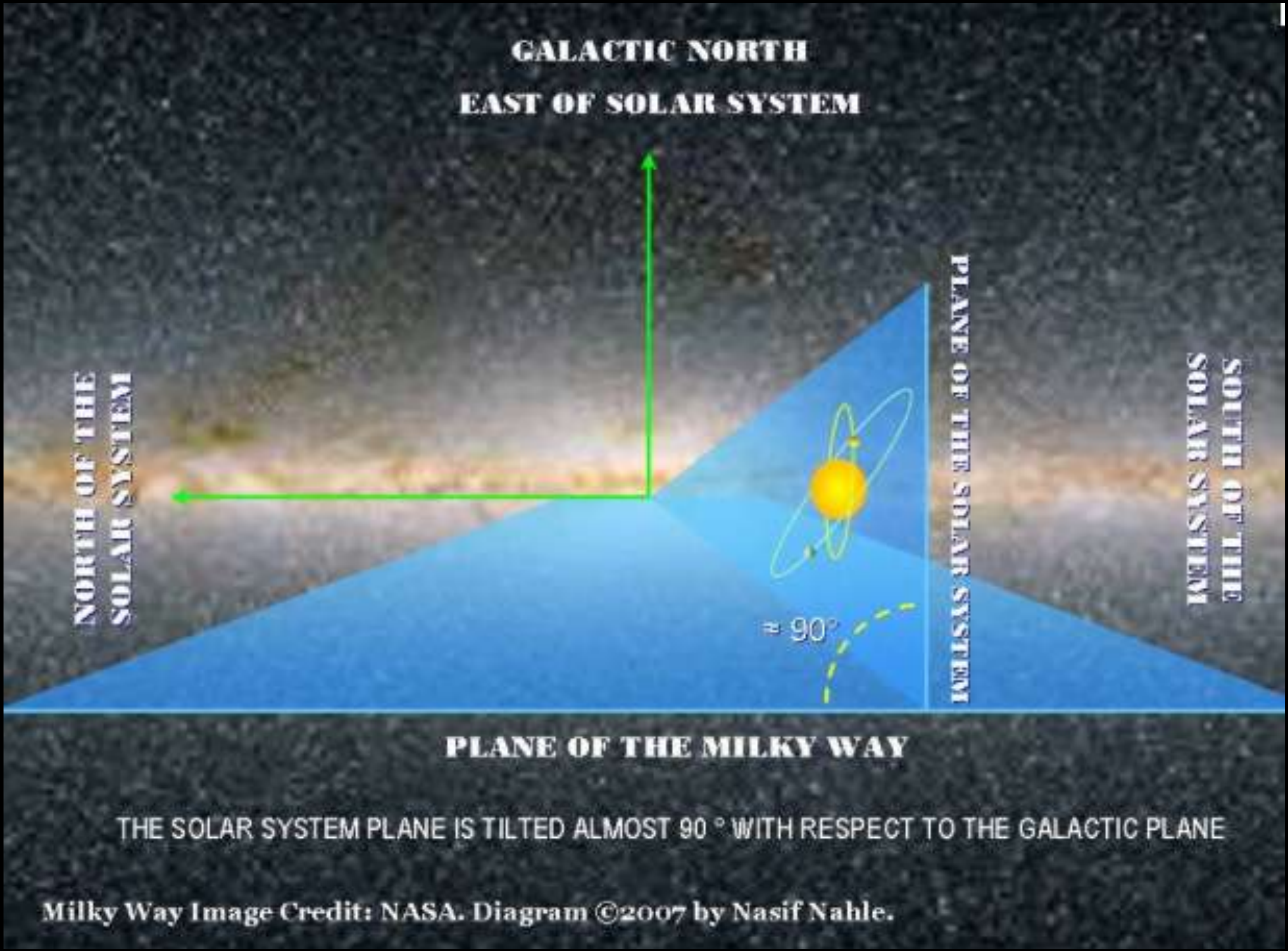


Motions of the Soleil in the Milky Way

The Sun orbits the Milky Way in about 230 Myr and possesses an oscillatory motion

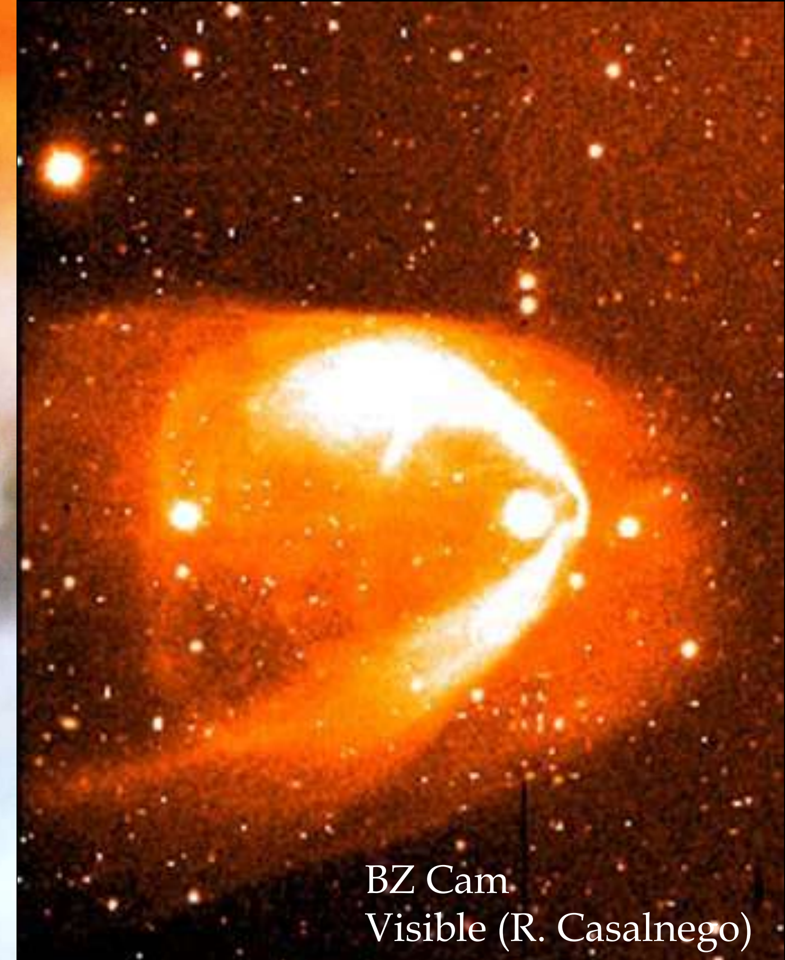
Going above and below the galactic plane with a period of 30 Myr.

Orbital plane of the Sun’s orbit with respect to that of the Galaxy

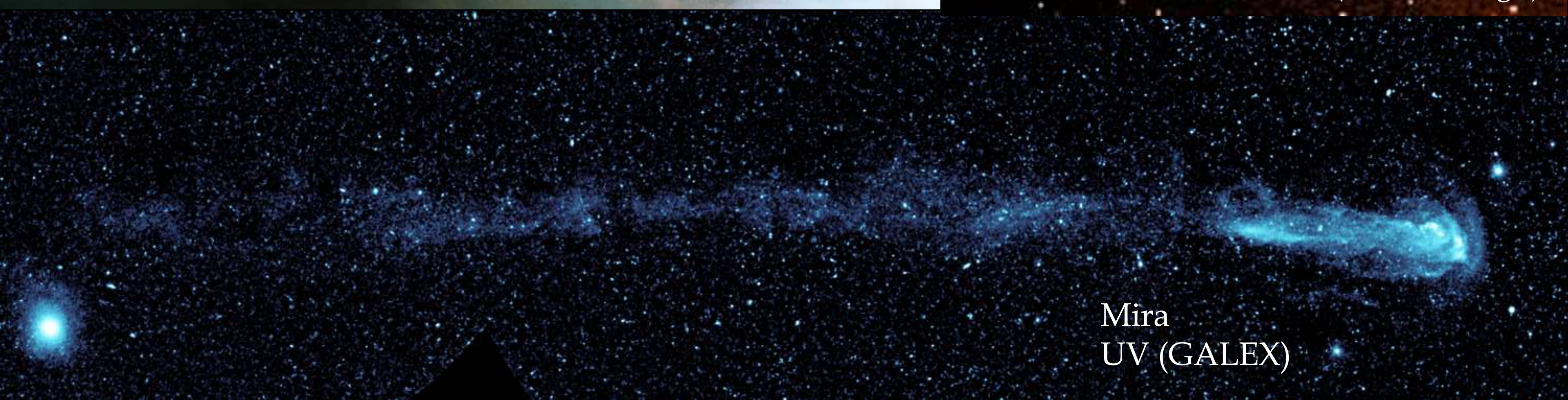


Distant Asterospheres ...

LL Orionis
Visible (Hubble)



BZ Cam
Visible (R. Casalnego)



Mira
UV (GALEX)

Next Lecture:

solar/stellare wind, gyro/magnetochronology