The Universe is Made of Plasma and Magnetic Field

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Outline

- What is the universe made of ?
- Why plasma ?
- Plasma on the sun
- Plasma in the planetary system
- Plasma in other stars, the interstellar medium and the Galaxy
- Plasma in other galaxies and the intergalactic medium

What is the Universe made of ?

Sugar and spice
And everything nice ?

Not applicable to the universe !

Snips and snails
And puppy-dogs' tails ?

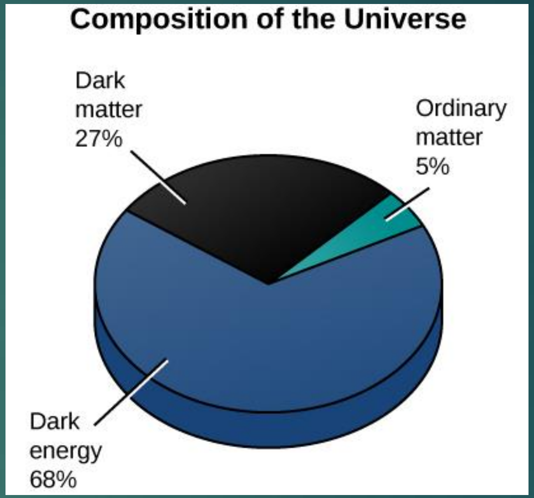
Not applicable to the universe either !

The Universe is made of ...

Contribution to the parameter $\Omega=\rho/\rho_c$:

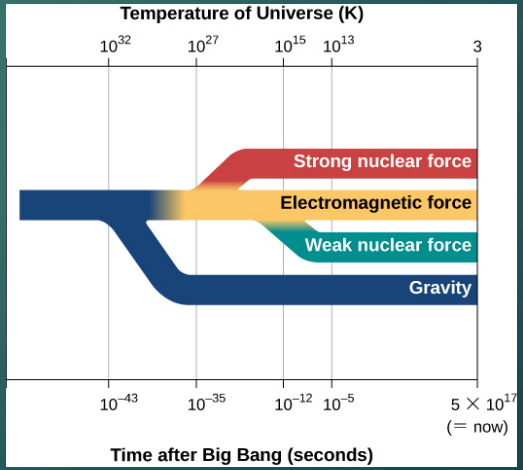
- Ordinary matter (5%)
- Dark matter (27%)
- Dark energy (68%)

(ΛCDM model)



Fundamental forces :

- Gravity
- Electromagnetic force
- Strong interaction
- Weak interaction



For our approach we retain the *ordinary matter*, the *electromagnetic force* and *gravity*

Conditions for plasma

- Charged particles
- Efficient charge shielding: Characteristic size > Debye $\lambda_D^2 = \frac{kT}{8\pi e^2 n_o}$
- Many particles inside a Debye sphere: $g = (n\lambda_D^3)^{-1} \ll 1$
- Dynamic energy << kinetic energy; minimum approach distance $b_o = \frac{e^2}{kT} \ll n^{-1/3}$
- Put together: $b_o \ll n^{-1/3} \ll \lambda_D \ll L$

These conditions are satisfied for most of the ordinary matter in the universe

Description of the plasma (statistical)

- Full statistical description: distribution function, *F*, Liouville equation

$$F = F(\boldsymbol{x}_1, \boldsymbol{x}_2, \ldots, \boldsymbol{x}_N, \boldsymbol{v}_1, \boldsymbol{v}_2, \ldots, \boldsymbol{v}_N, t)$$

$$dF = \frac{\partial F}{\partial t} + \sum_{i=1}^{N} \left(\frac{\partial F}{\partial \boldsymbol{x}_i} \cdot \boldsymbol{v}_i + \frac{\partial F}{\partial \boldsymbol{v}_i} \cdot \boldsymbol{a}_i \right) = 0$$

- Reduced statistical description: single-particle distribution function, *f*, kinetic equation, Vlassov equation

$$f^{(1)}(\boldsymbol{x}_1, \boldsymbol{v}_1, t) = \int F(\boldsymbol{x}_1, \ldots, \boldsymbol{v}_N, t)\, d\boldsymbol{x}_2 \ldots d\boldsymbol{x}_N\, d\boldsymbol{v}_2 \ldots d\boldsymbol{v}_N$$

$$\frac{\partial f}{\partial t} + \boldsymbol{v} \cdot \frac{\partial f}{\partial \boldsymbol{x}} + \boldsymbol{a} \cdot \frac{\partial f}{\partial \boldsymbol{v}} = \left. \frac{\partial f}{\partial t} \right|_c \qquad \frac{\partial f}{\partial t} + \boldsymbol{v} \cdot \frac{\partial f}{\partial \boldsymbol{x}} + \boldsymbol{a} \cdot \frac{\partial f}{\partial \boldsymbol{v}} = 0$$

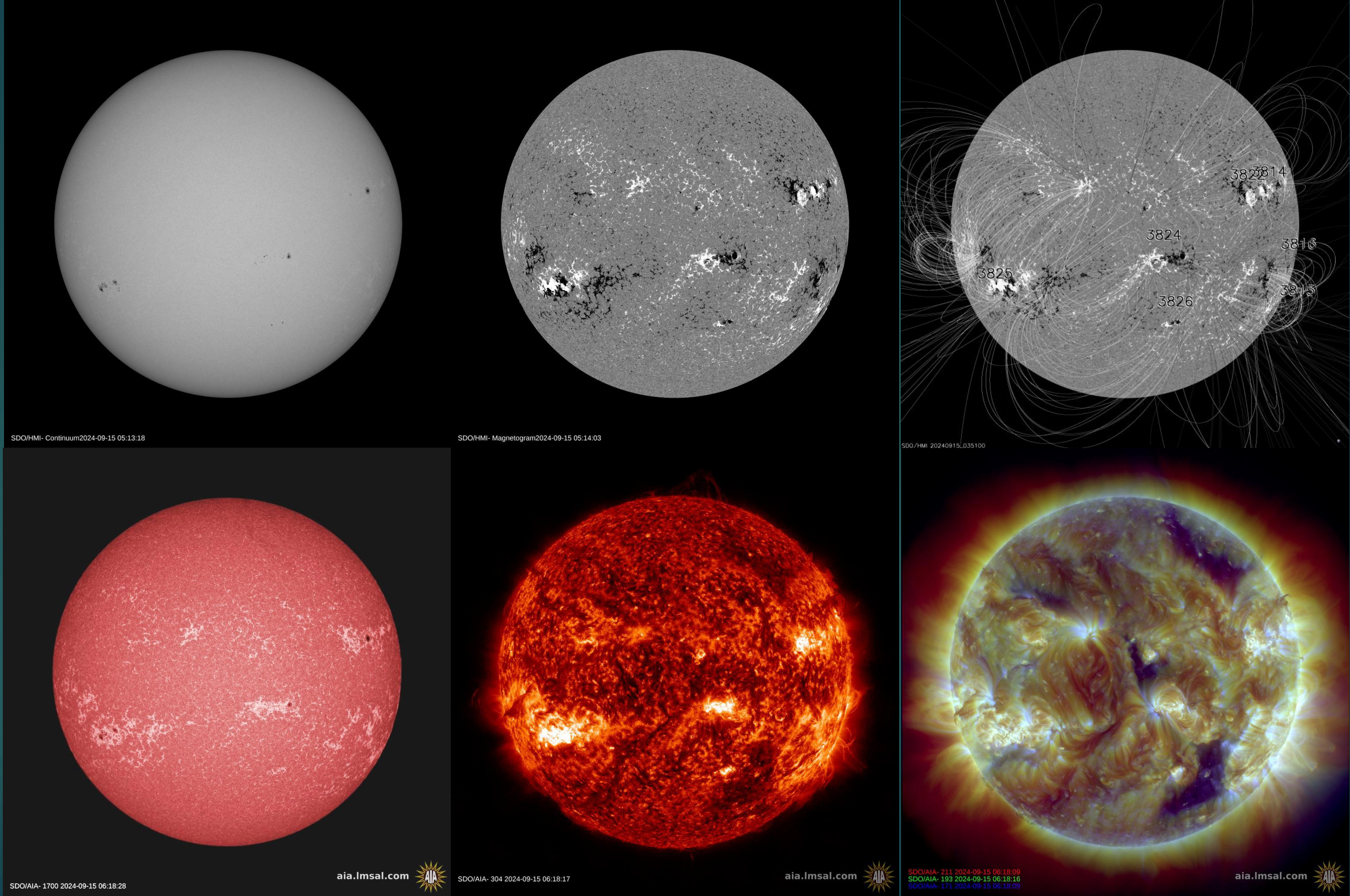
- Multi-fluid description, after definition of macroscopic parameters (density, velocity, pressure…) for each species (electrons, ions…); fluid equations (continuity, momentum, …)
- Single fluid approximation, with appropriate macroscopic parameters and the equations that they obey
- Magnetohydrodynamics

What is Magnetohydrodynamics (MHD) ?

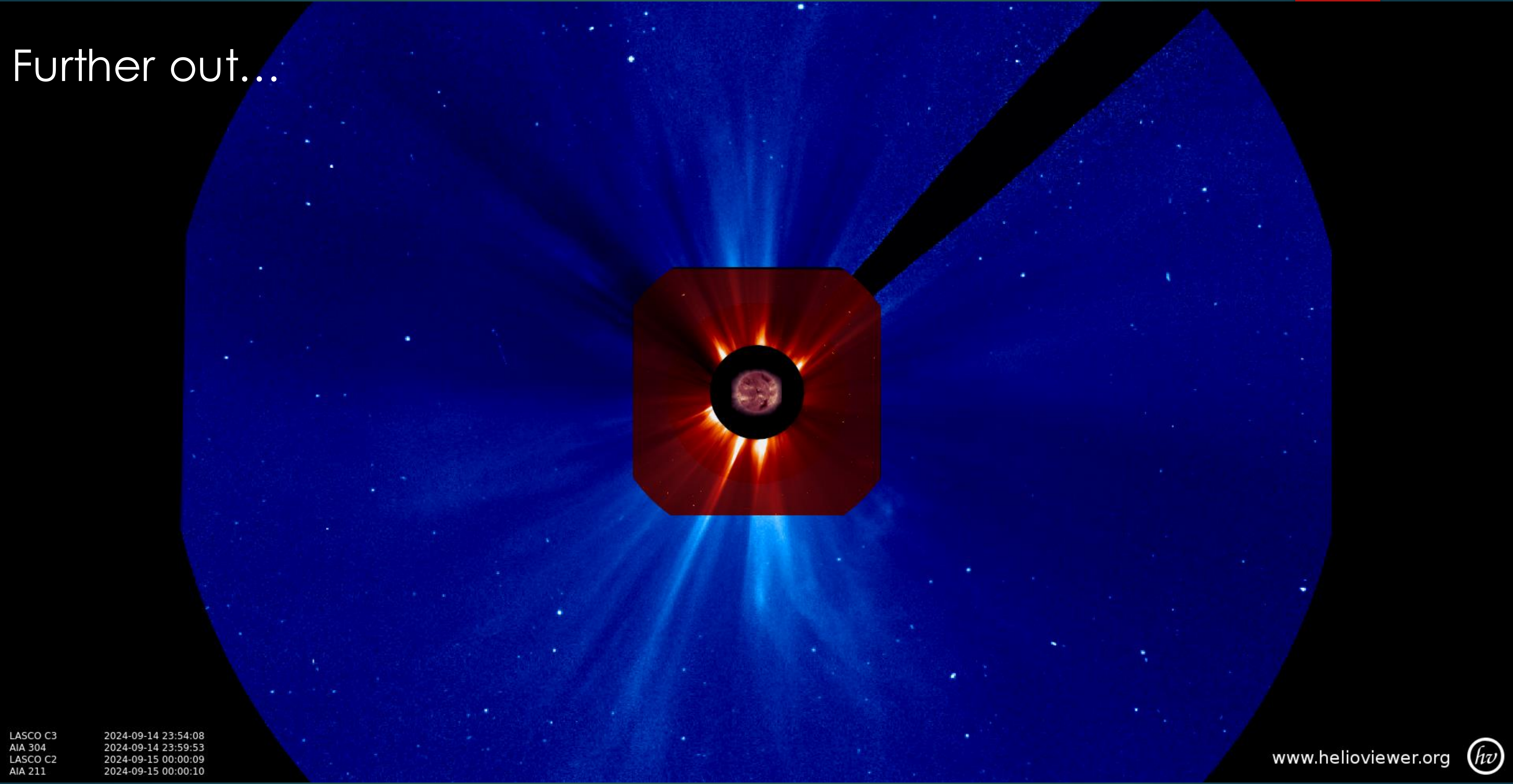
- Single fluid description
- Use $m_e << m_i$
- Charge neutrality
- Scalar pressure
- Fluid velocity << c
- Large spatial scale, small characteristic frequency
- If the electrical conductivity, σ, is so high that the magnetic Reynolds number, $R_m \equiv \frac{4\pi\sigma LV}{c^2} \gg 1$ => *Ideal MHD*

ENOUGH! Let's go back to the universe

Our multi -faced Sun



Further out…



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LASCO C2 2024-09-15 00:00:09
AIA 211 2024-09-15 00:00:10
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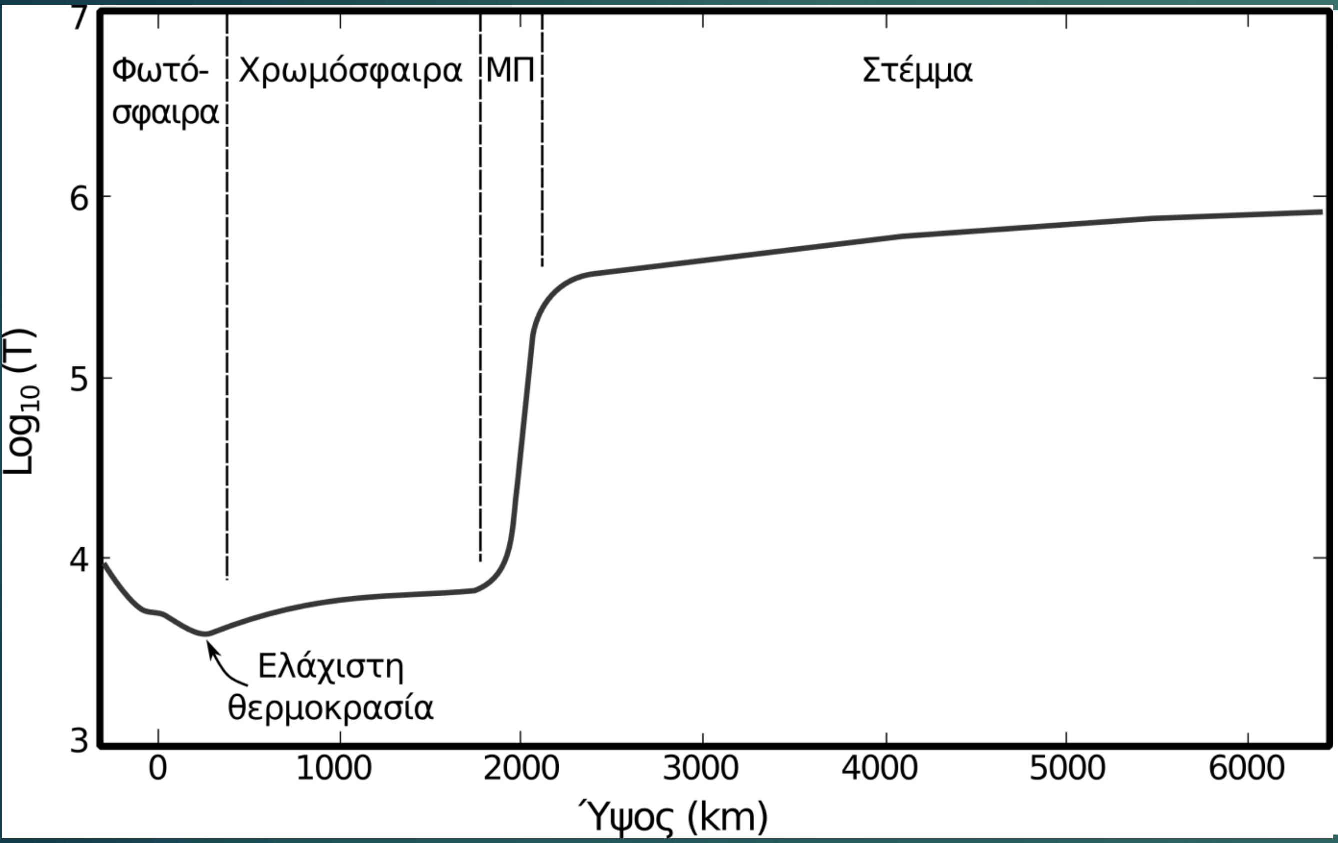
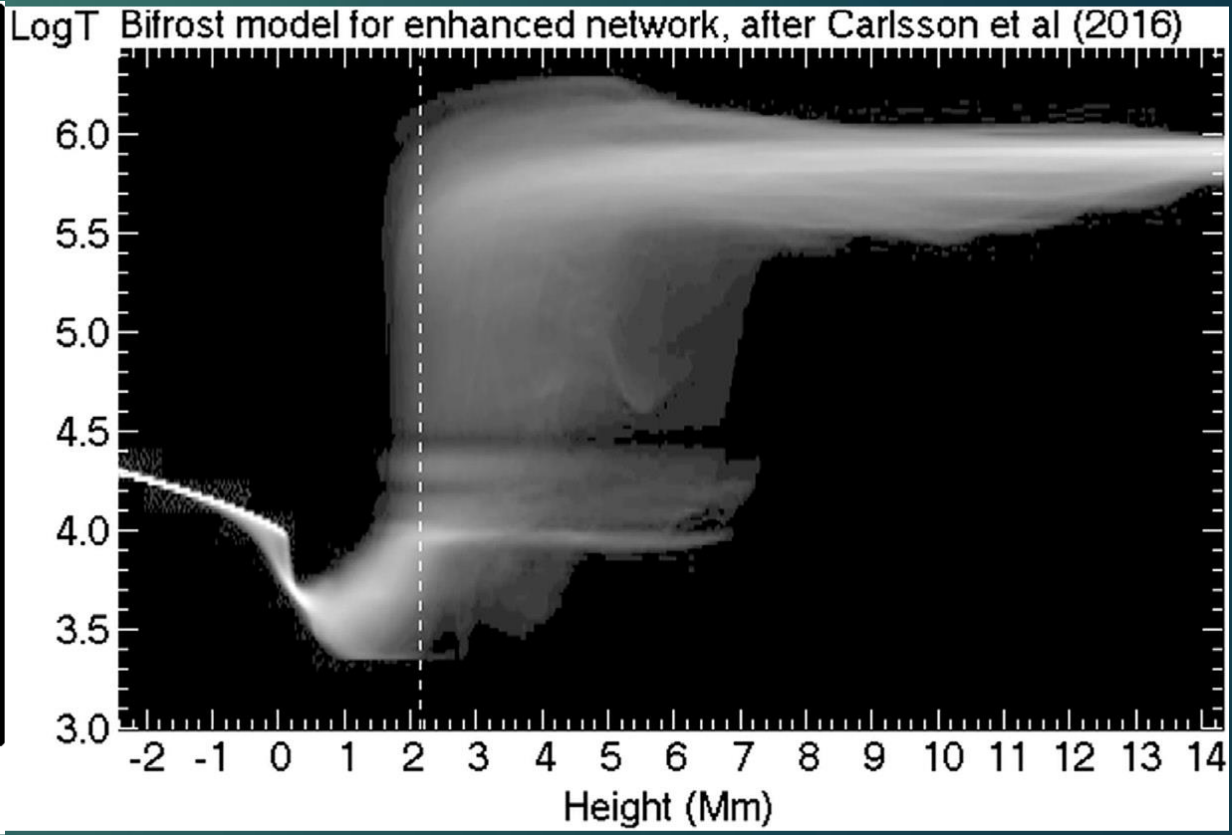
Why are the sun's layers that different ?

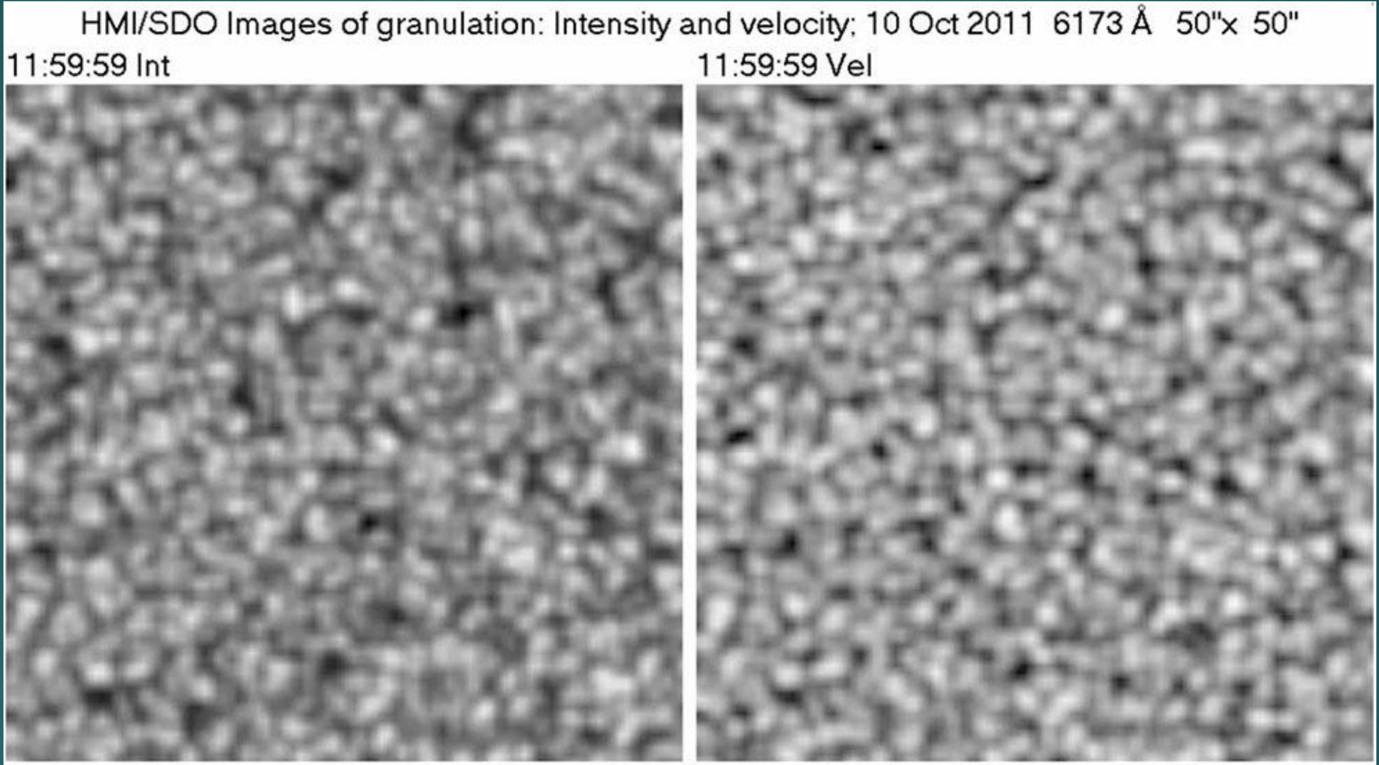
a. The temperature varies with height





b. The magnetic field is there

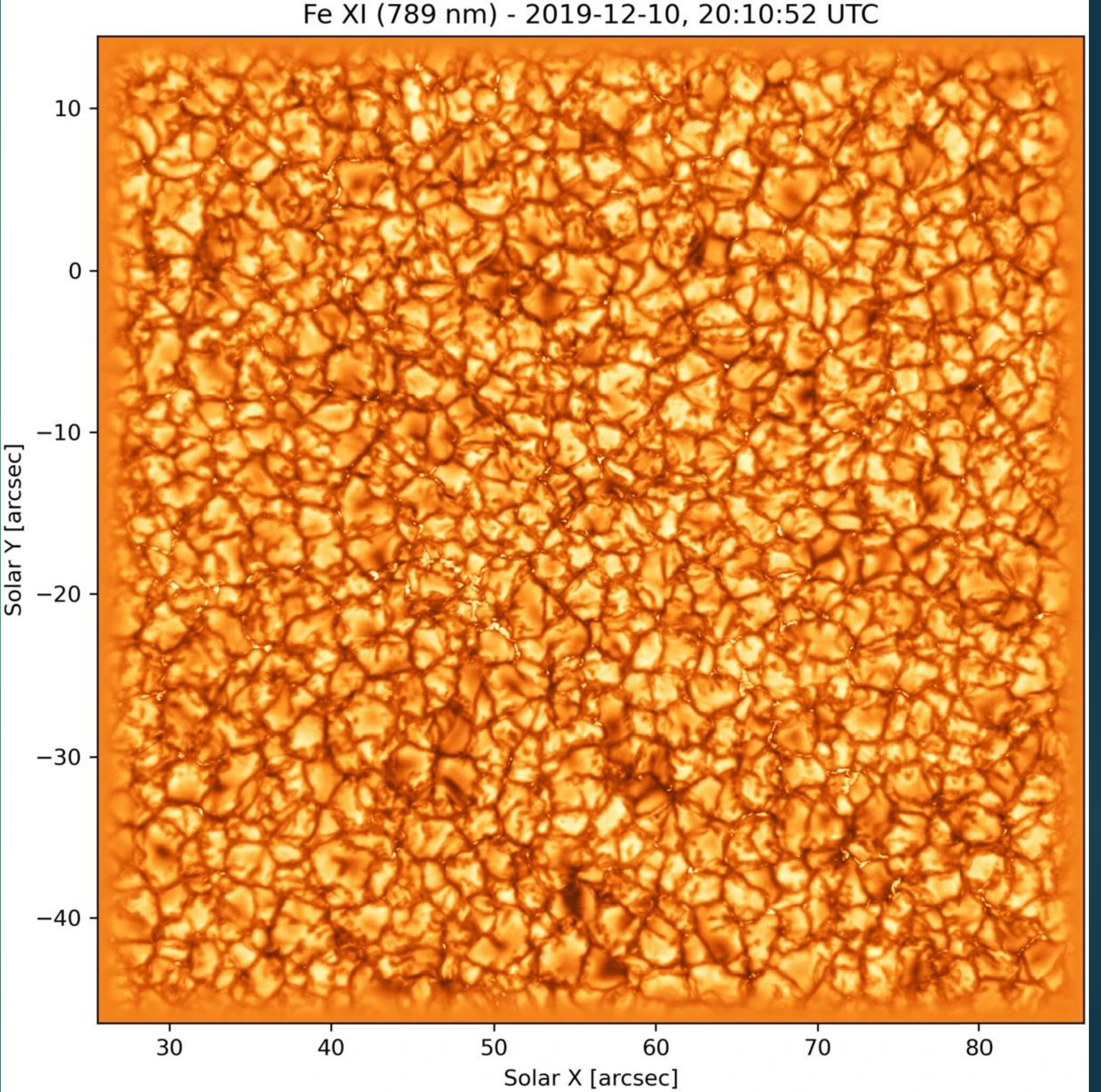
The photosphere is not that homogeneous



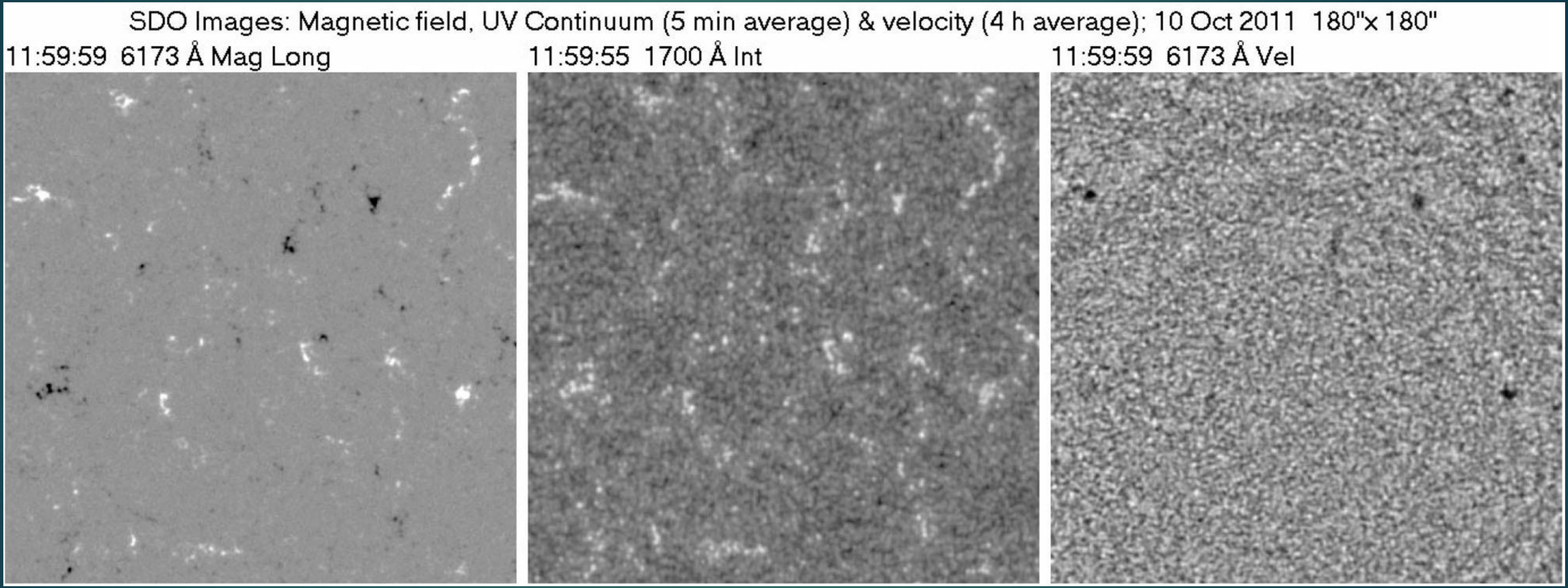
Intensity Line-of-sight velocity

Granulation: convection cells with ascending hot material and descending cool material.
Convection is the principal mechanism of energy transport in the upper part of the solar interior

Tiny bright points at granular borders: magnetic flux tubes compressed by the convective motions



Let's check the magnetic field and go a bit higher

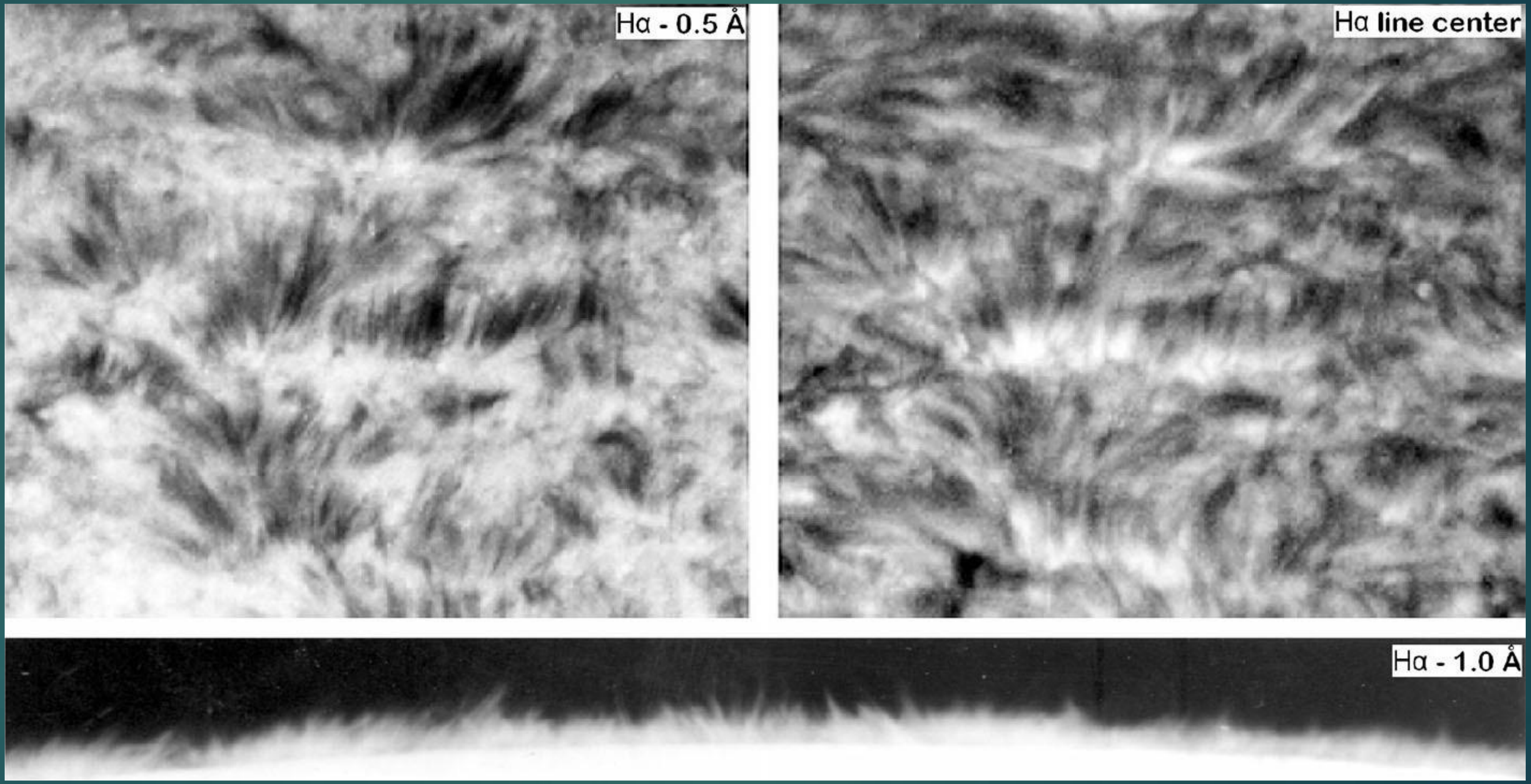


Larger scale convection cells (supergranulation) => chromospheric network

Let's go to the chromosphere

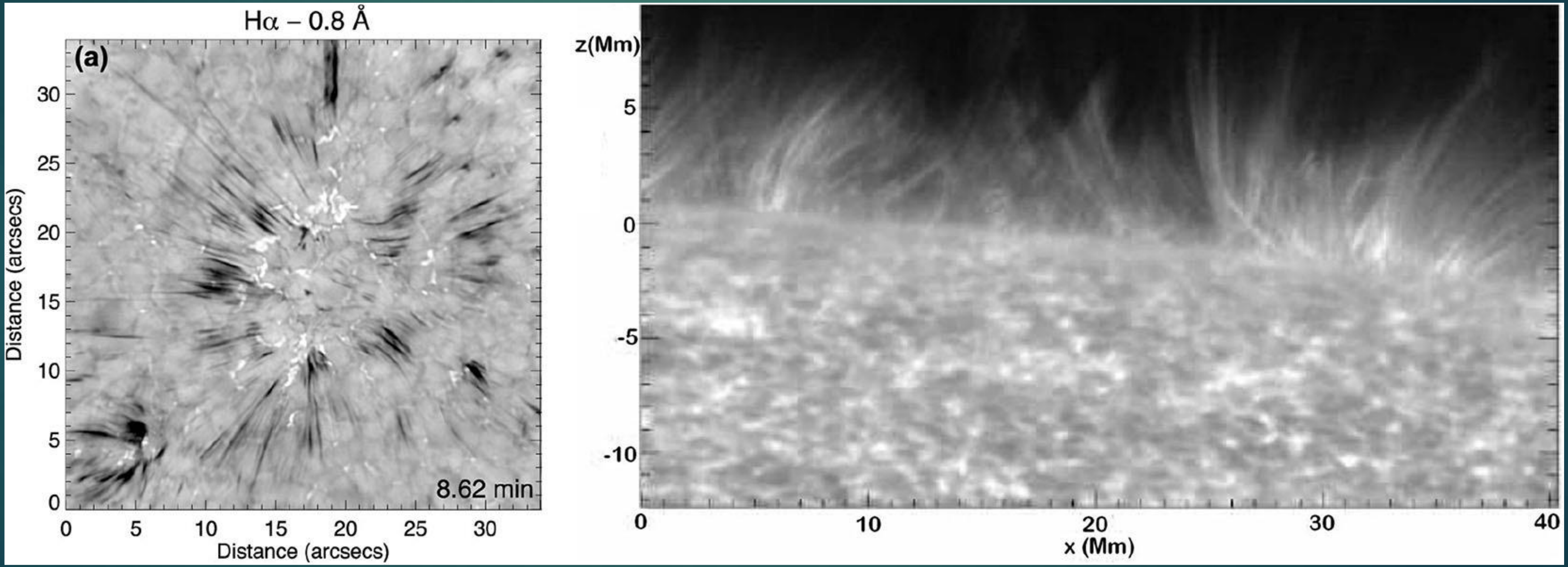
On the solar disk

At the limb



Very different from the photosphere: elongated structures (spicules)

Better seen here, (modern instruments, improved resolution)



Why do photospheric & chromospheric structures differ that much ?

MHD has the answer through the induction equation: $\frac{\partial \boldsymbol{B}}{\partial t} = \frac{c^2}{4\pi\sigma}\nabla^2 \boldsymbol{B} + \nabla \times (\boldsymbol{V} \times \boldsymbol{B})$

If the magnetic Reynolds number is << 1, the first term in the right hand side dominates, and we get a diffusion equation: $\frac{\partial \boldsymbol{B}}{\partial t} = \frac{c^2}{4\pi\sigma}\nabla^2 \boldsymbol{B}$
Magnetic energy is converted to heat (Joule heating).

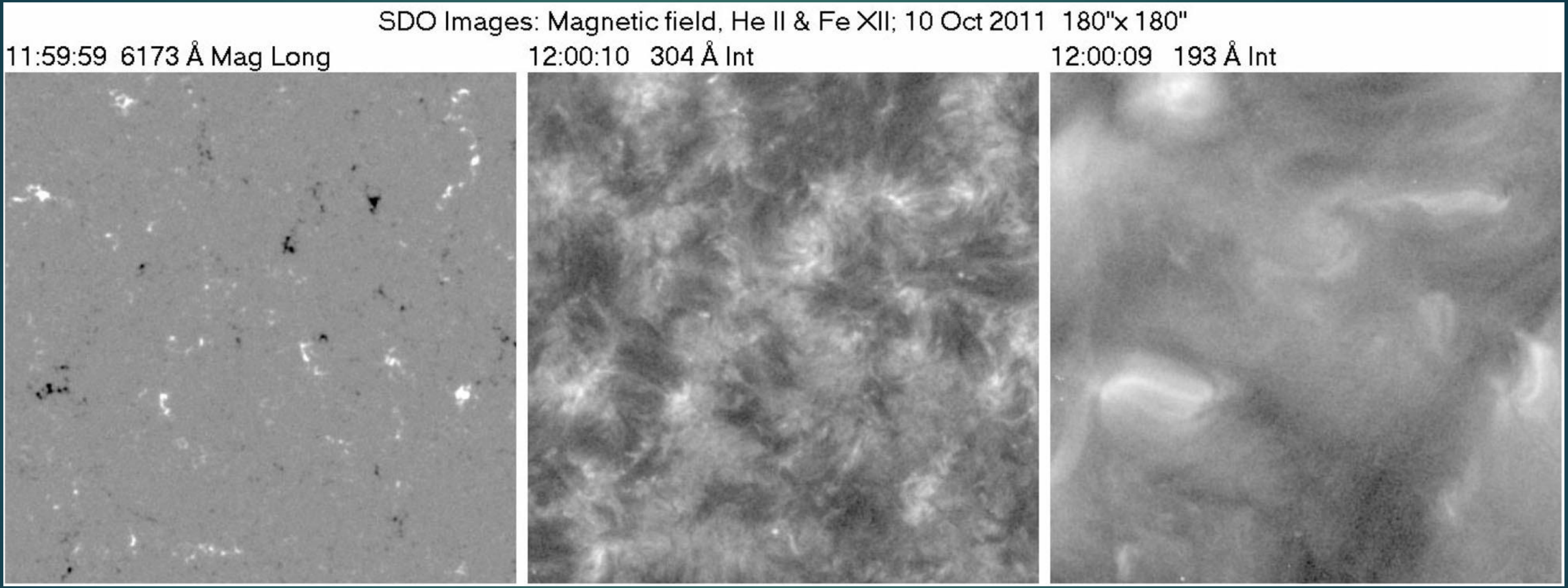
In the opposite case, we have $\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{V} \times \boldsymbol{B})$, which means that the magnetic field is frozen in the plasma (cannot move across the field lines of force) .

Consequences of frozen-in magnetic field

Almost everywhere in the solar atmosphere the magnetic Reynolds number is much larger than unity. Thus, the behavior of the plasma and the magnetic field depends upon their relative energy density

- If the energy density (thermal plus kinetic) of the plasma is much smaller than that of the magnetic field or, equivalently, if the sum of the gas pressure and the dynamic pressure is much smaller than the magnetic pressure, then the magnetic field dominates and the plasma flows along the field lines. This is the case in the chromosphere, the corona and in sunspots.
- In the opposite case the plasma dominates and will drag and deform the field. This happens in the photosphere (outside sunspots) and in the solar wind.

The network is not visible in the corona !

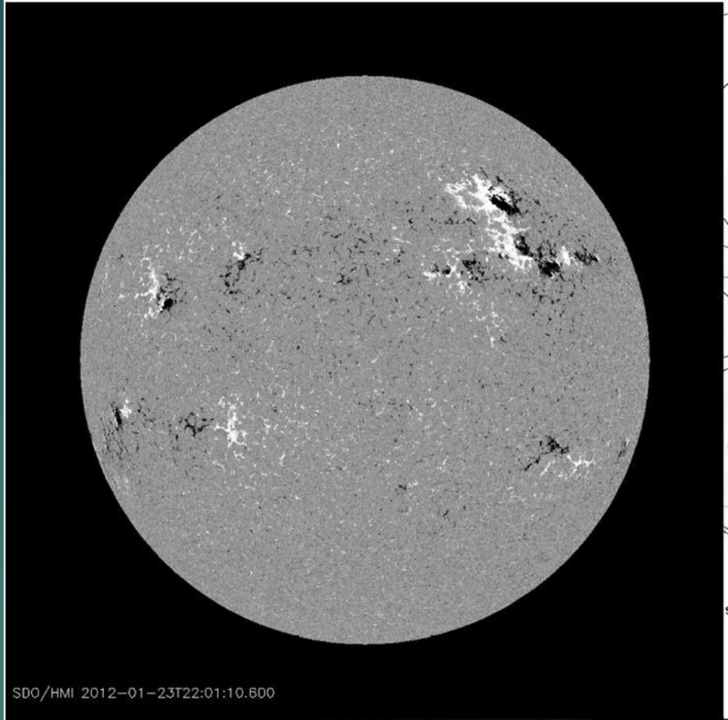


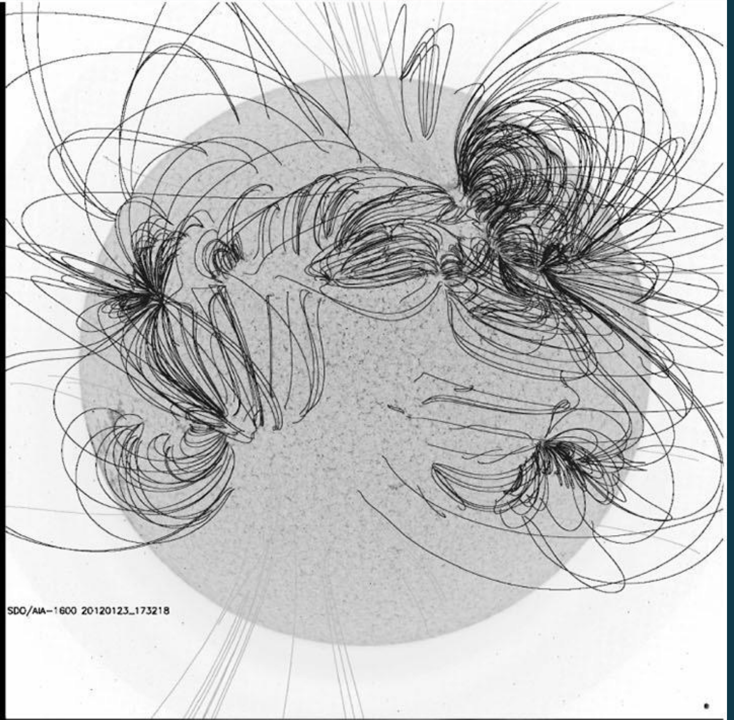
The associated lines of force close at lower heights

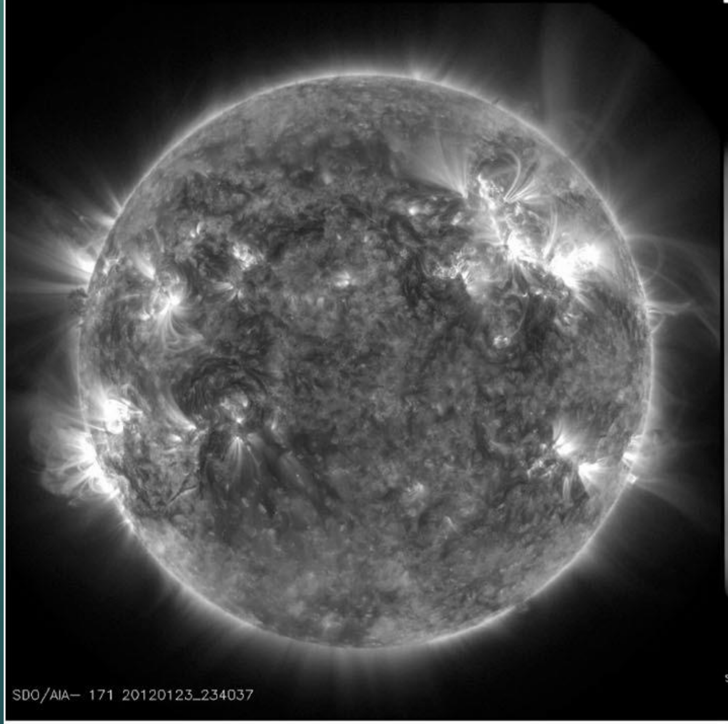
This does not mean that there is no magnetic field in the corona!

The corona is dominated by larger scale fields

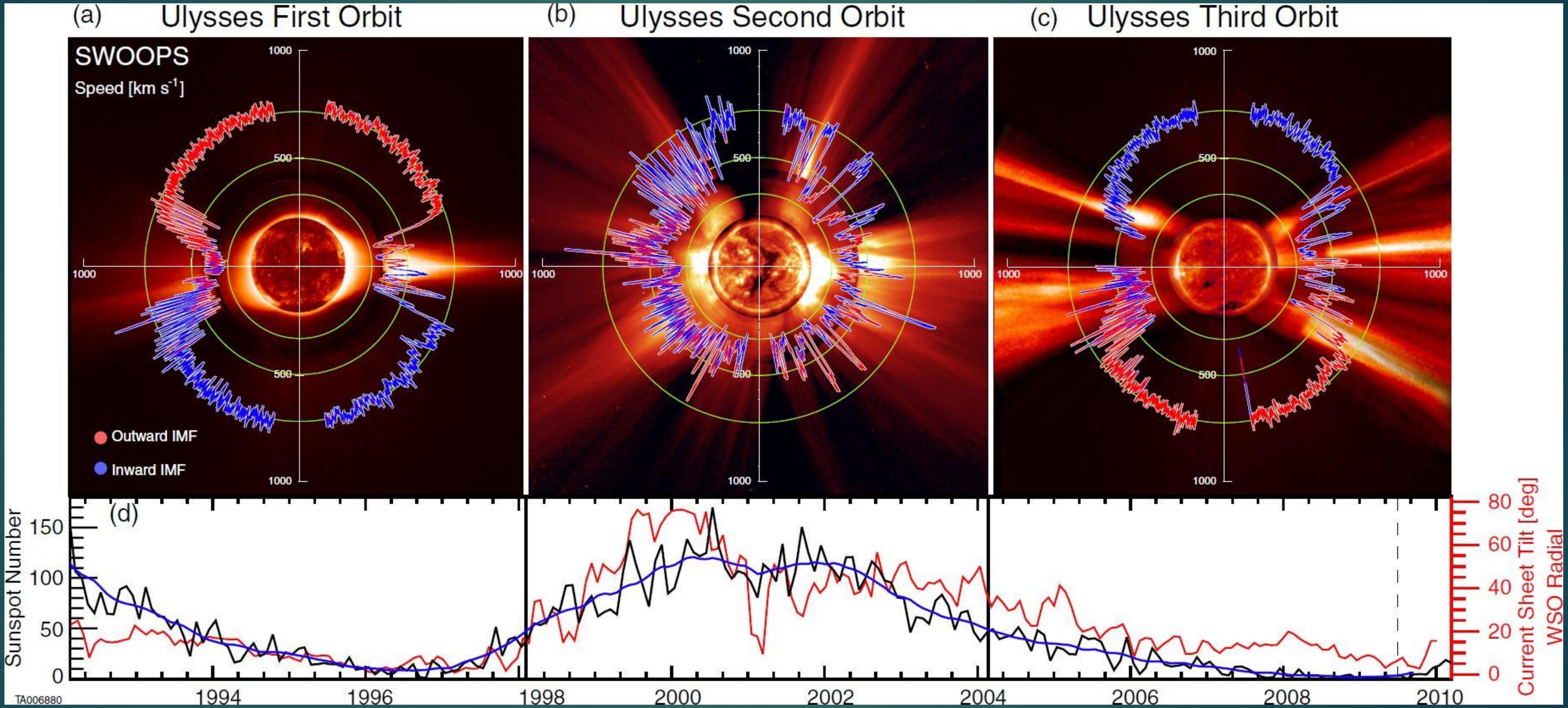
- Closed magnetic field lines
- Open magnetic field regions (coronal holes), from which the fast solar wind originates.





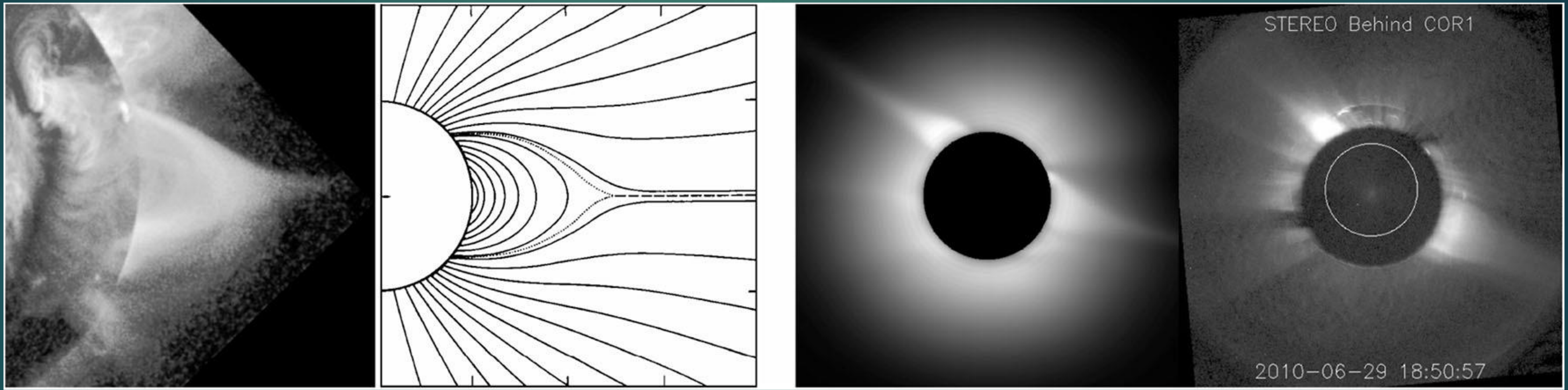


Speaking of the solar wind, here are some measurements of its speed



Polar diagrams of the solar wind speed from Ulysses: Near solar activity minimum, near maximum and near the next minimum. The blue/red colors denote the magnetic field polarity. The bottom panel gives solar activity indices.

Streamers have a peculiar magnetic field morphology



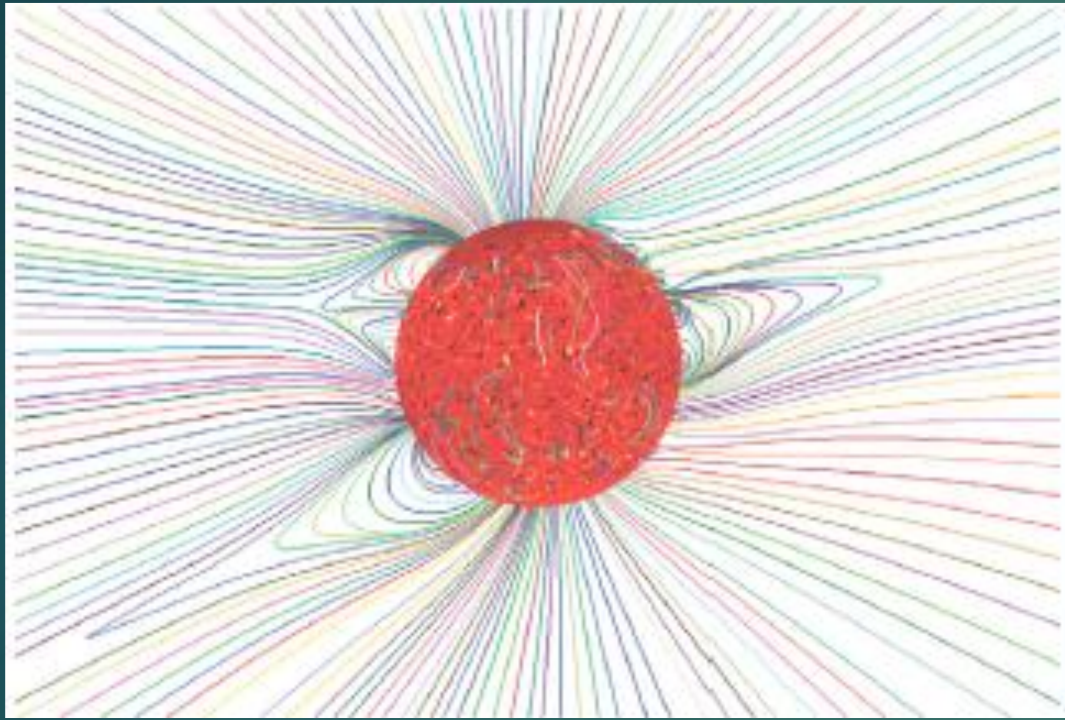
Observed

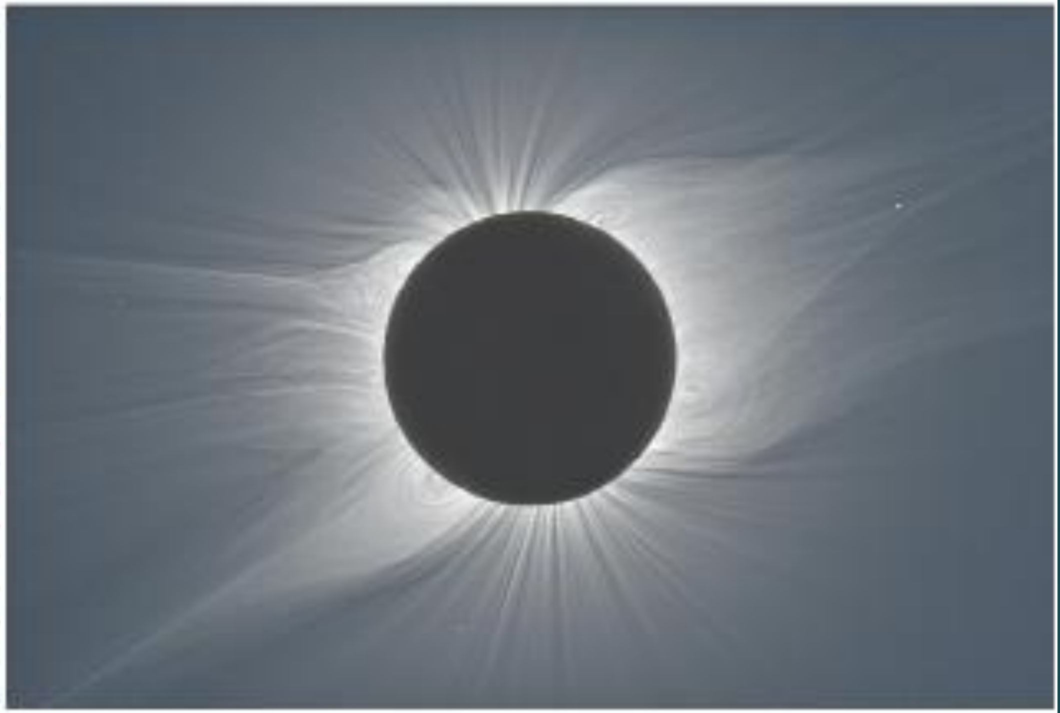
Schematic

Intensity from MHD model

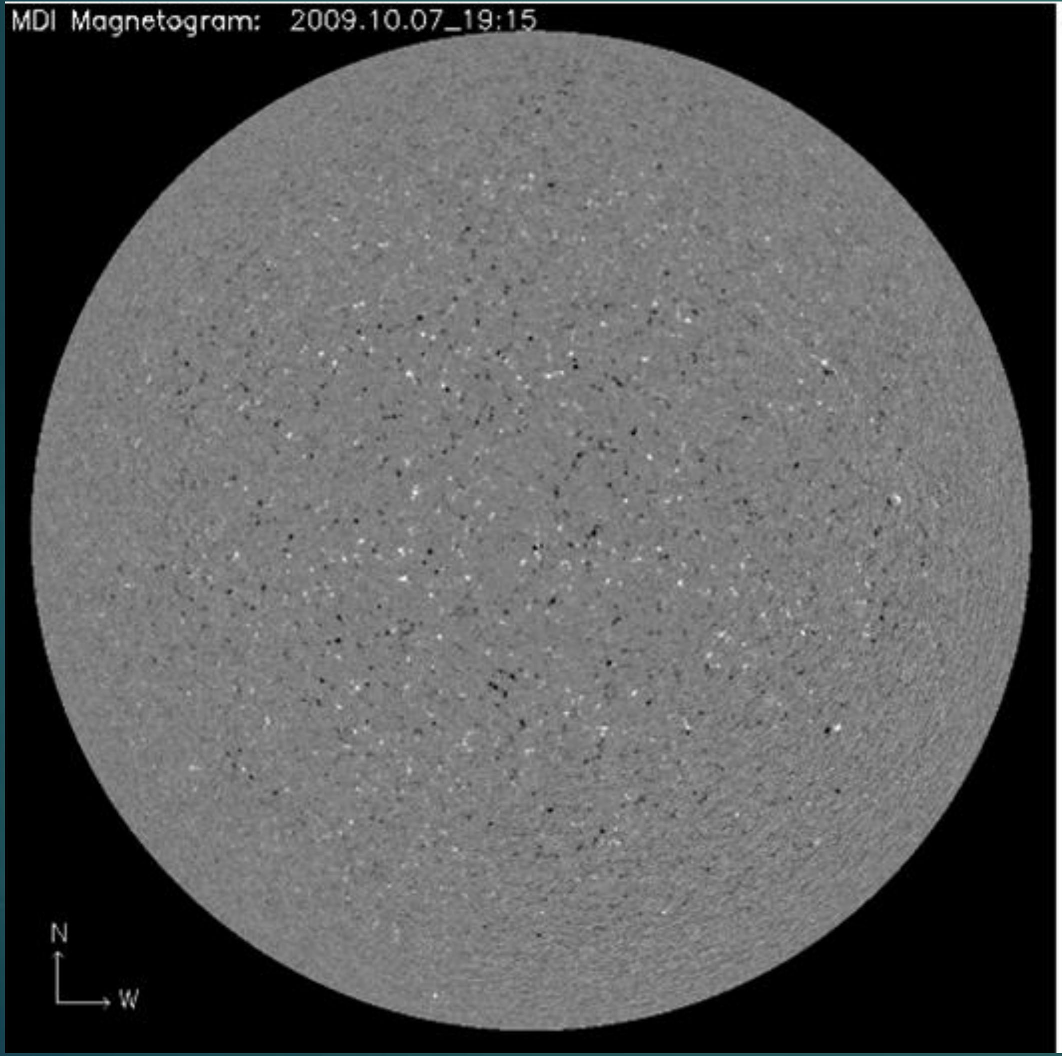
Observed

Magnetic field extrapolation & eclipse image

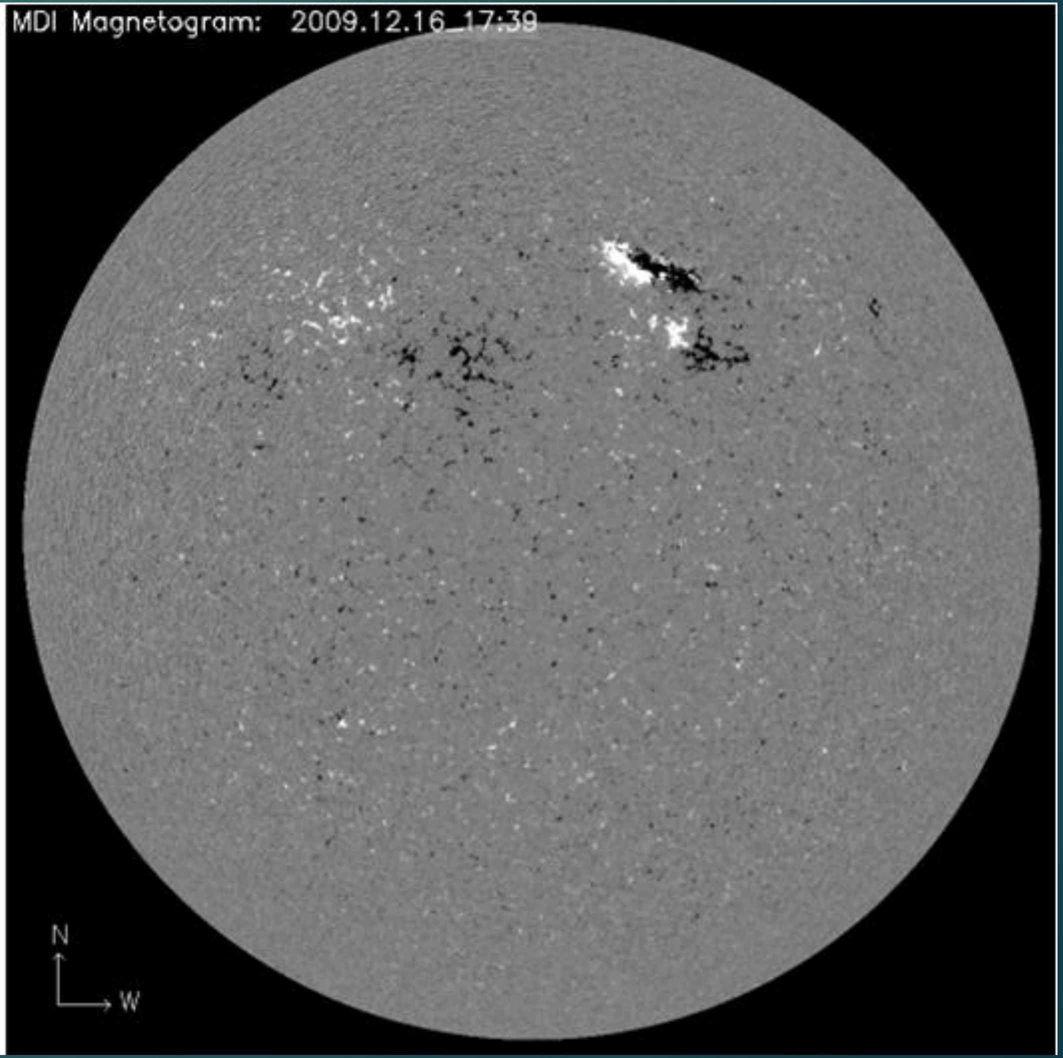




Quiet and active Sun



Quiet

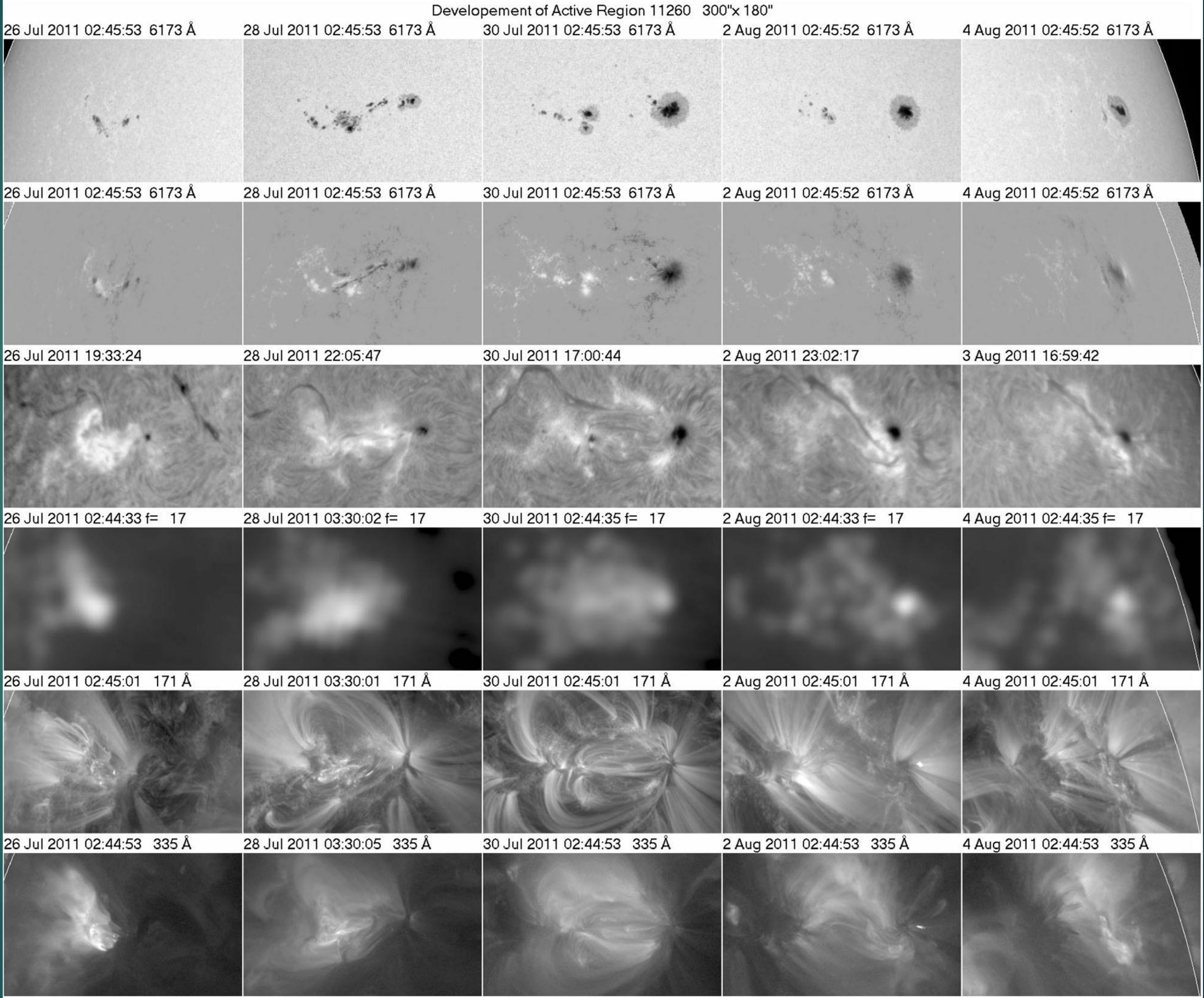


Active

Development of an active region

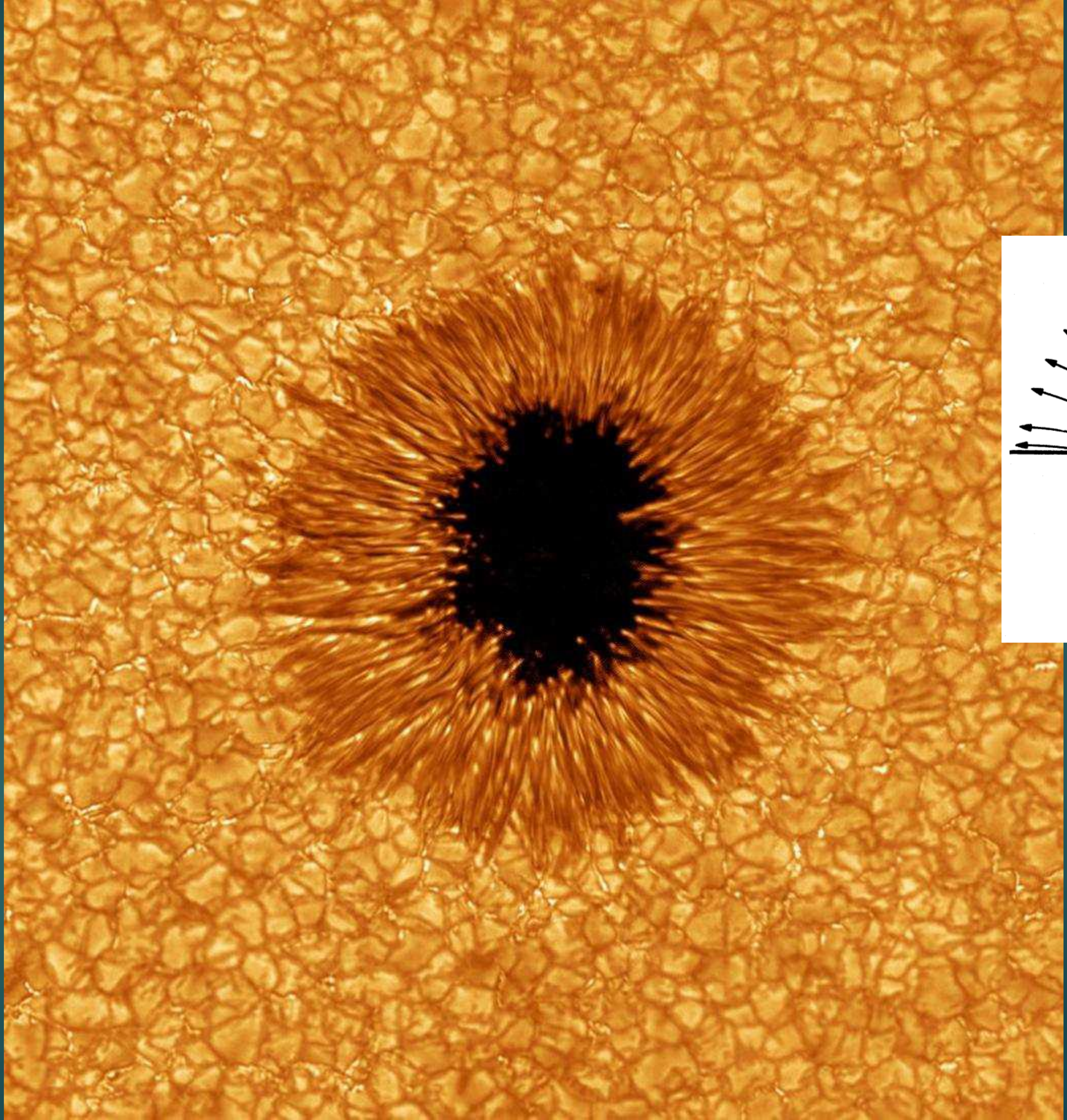
(white light, magnetograms, Ha, radio (17 GHz), EUV (171Å & 335Å)

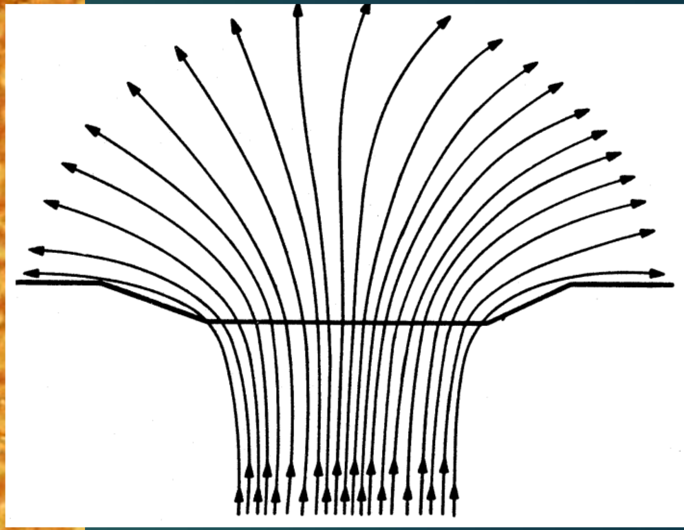
- Flux emergence from sub-photospheric layers
- Dynamo mechanism in which convection and differential solar rotation play crucial roles



Sunspots tell their own story

- Umbra/penumbra
- Magnetic field inhibits energy transport by convection

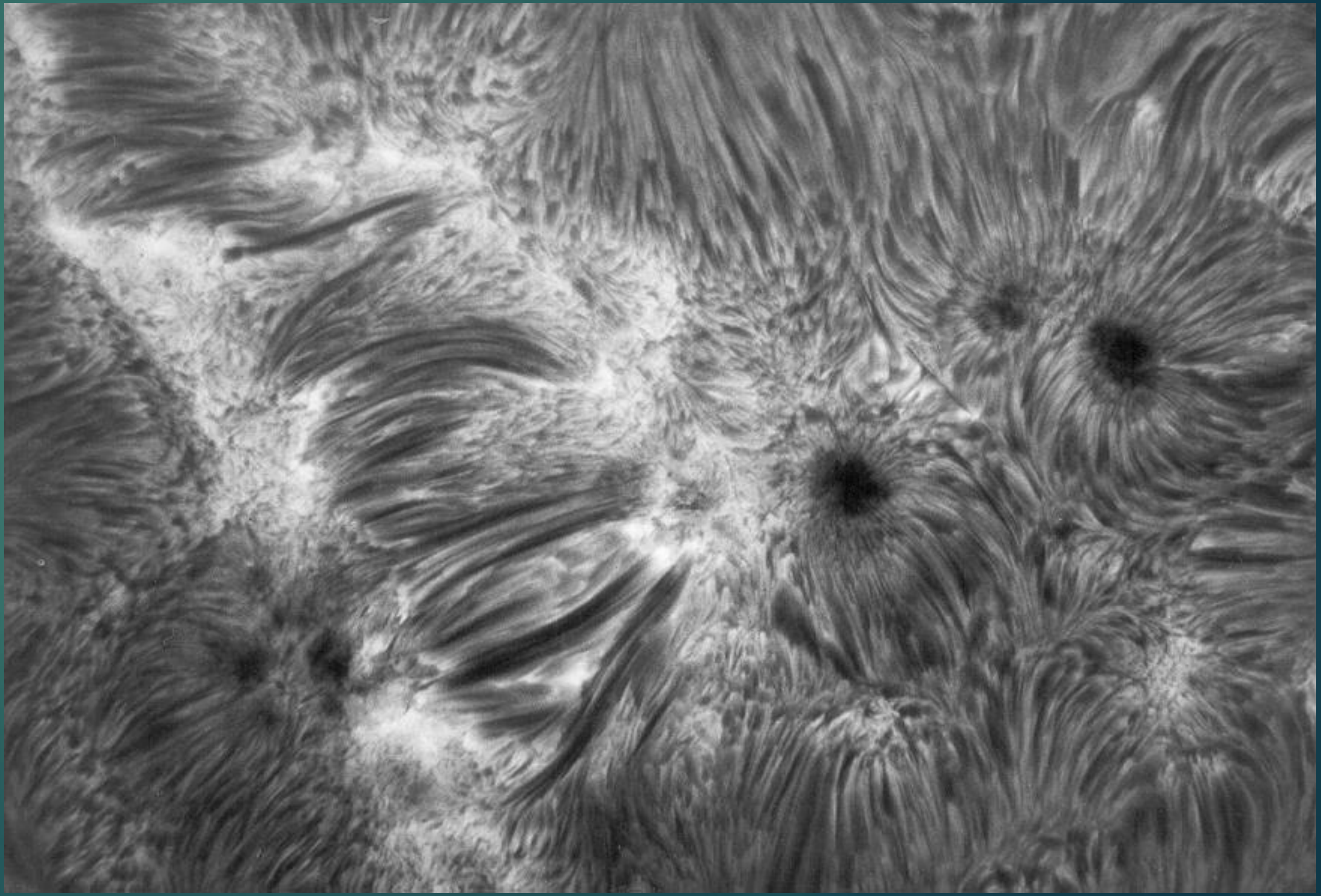




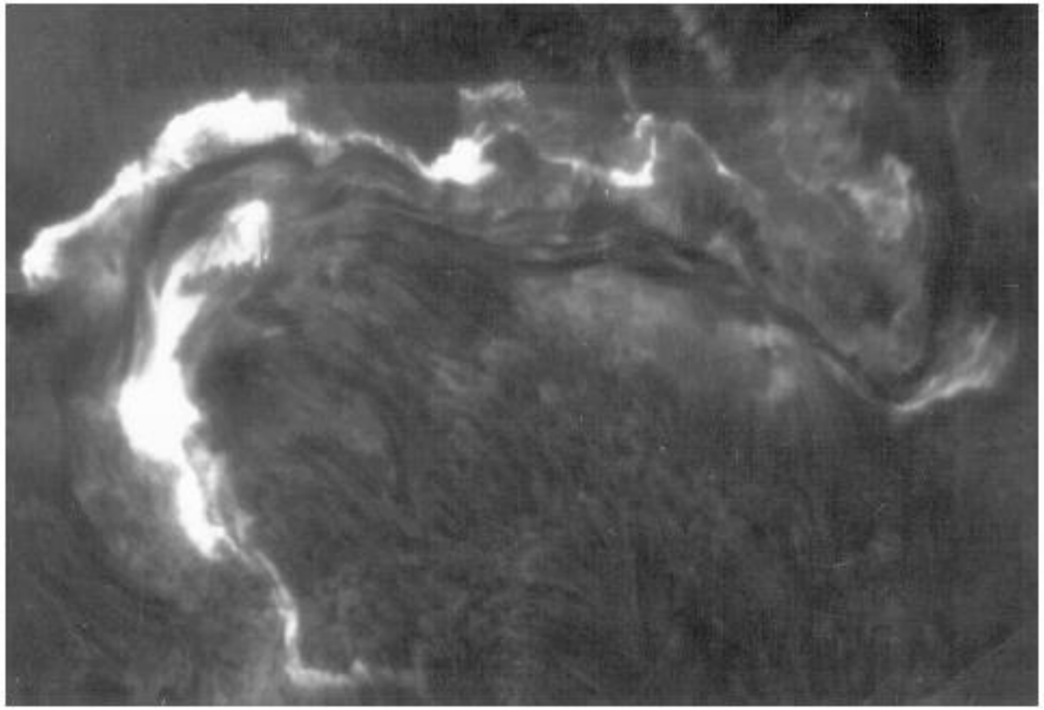
Configuration of the magnetic field

In the active region chromosphere, elongated structures reveal inclined magnetic field

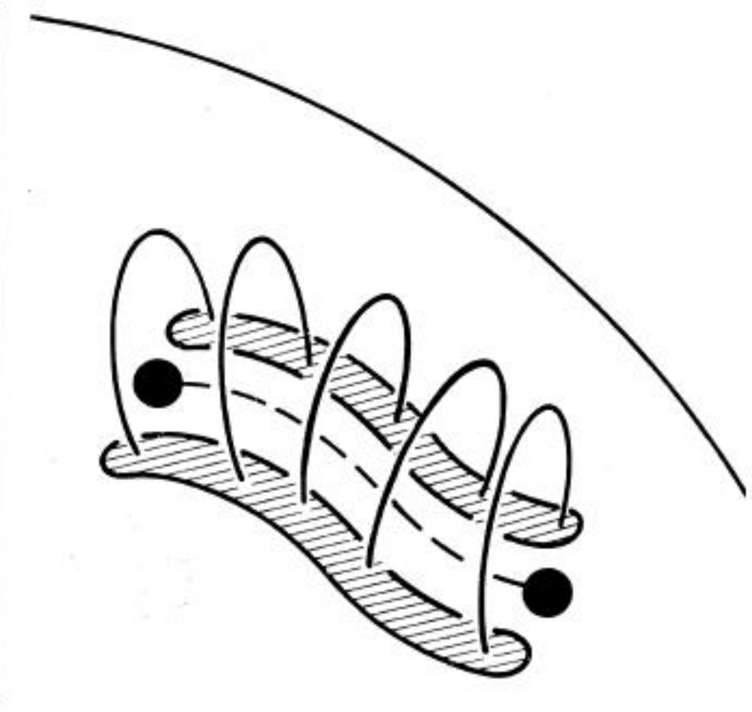
- Sunspots & their *superpenumbra*
- Bright *plage* emission
- Fibrils
- Arch filament systems (emerging magnetic flux) rooted in opposite polarity plage



Active regions host most of the flares (impulsive phenomena of magnetic energy release)

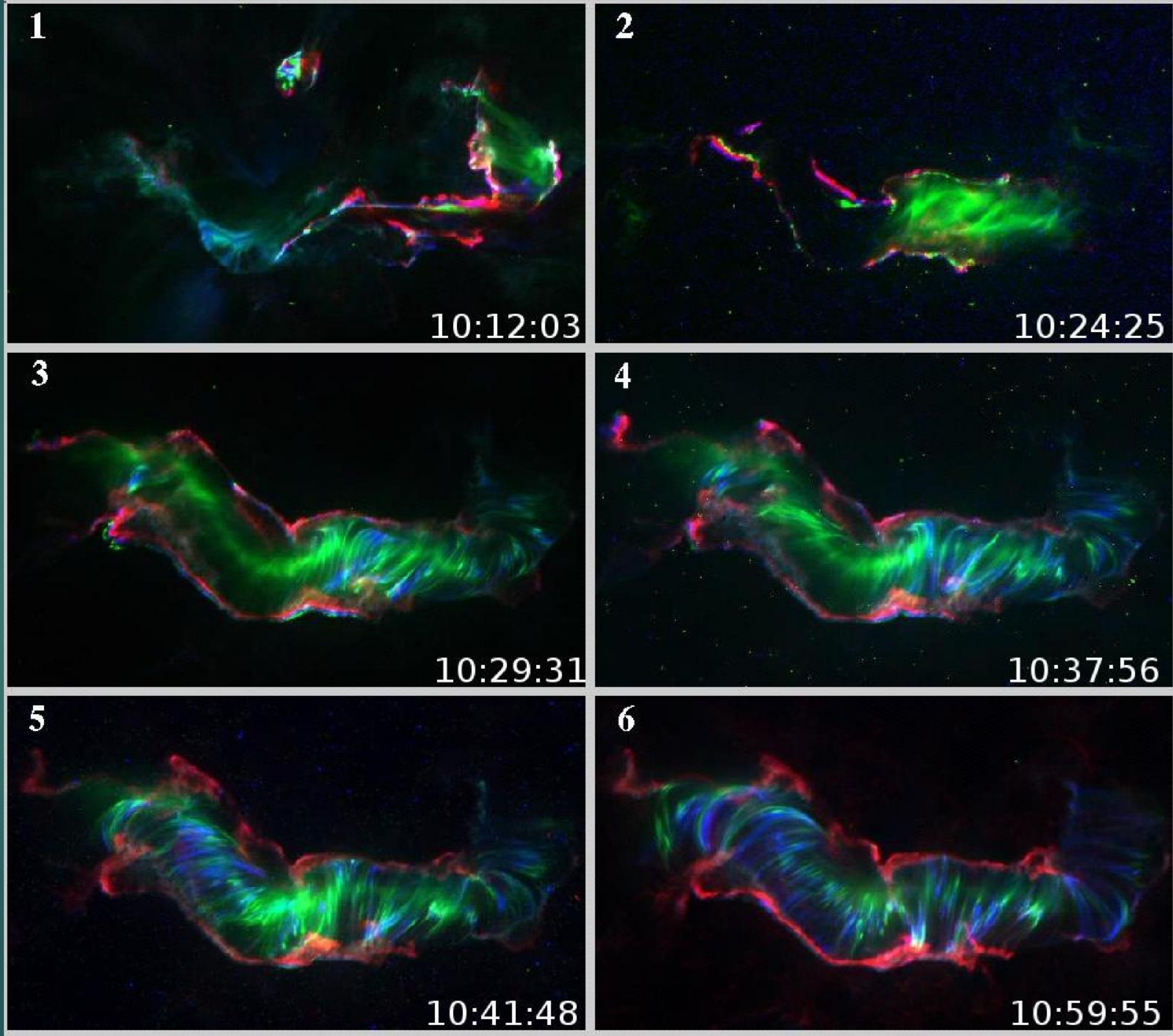


Typical 2-ribbon flare (Ha)

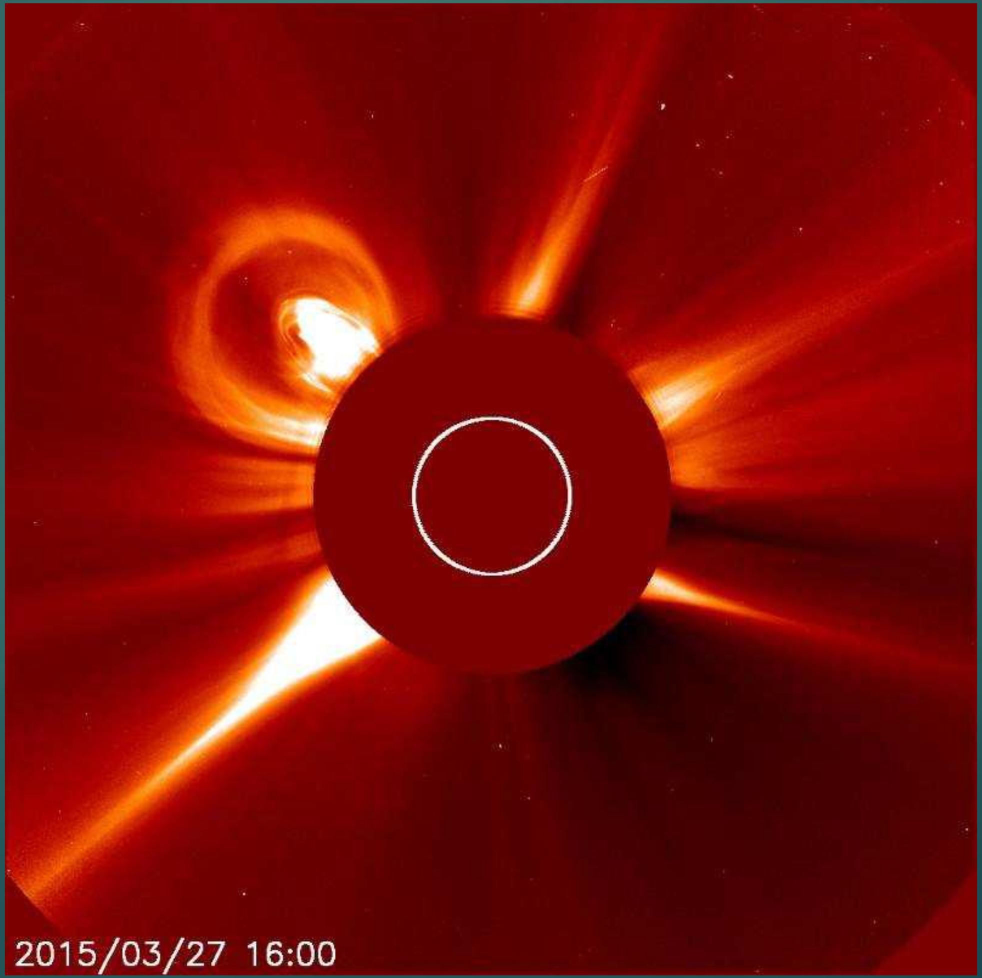


Configuration of the magnetic field

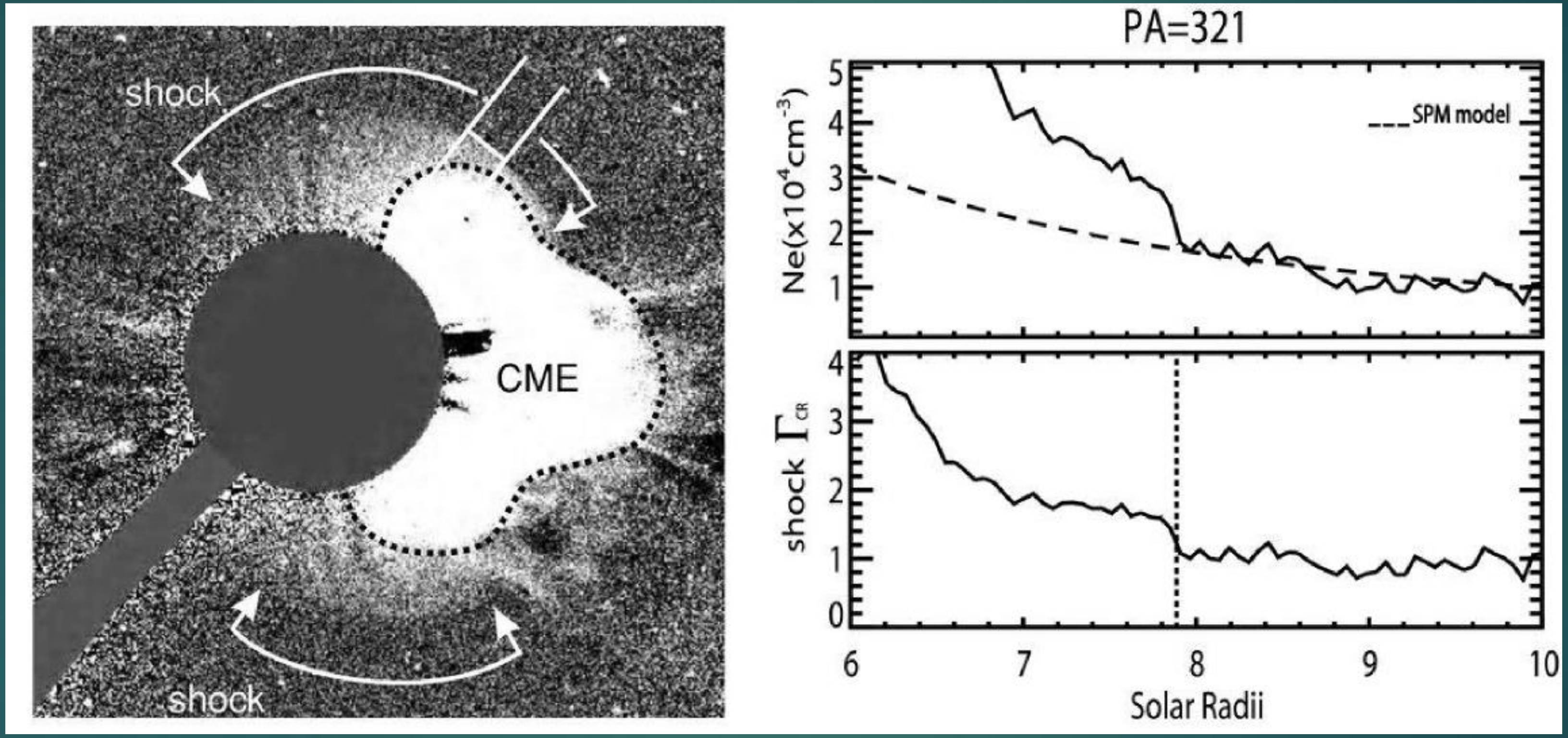
Hot flare loops, with their footpoints in the flare ribbons, are seen in soft X-rays (TRACE)



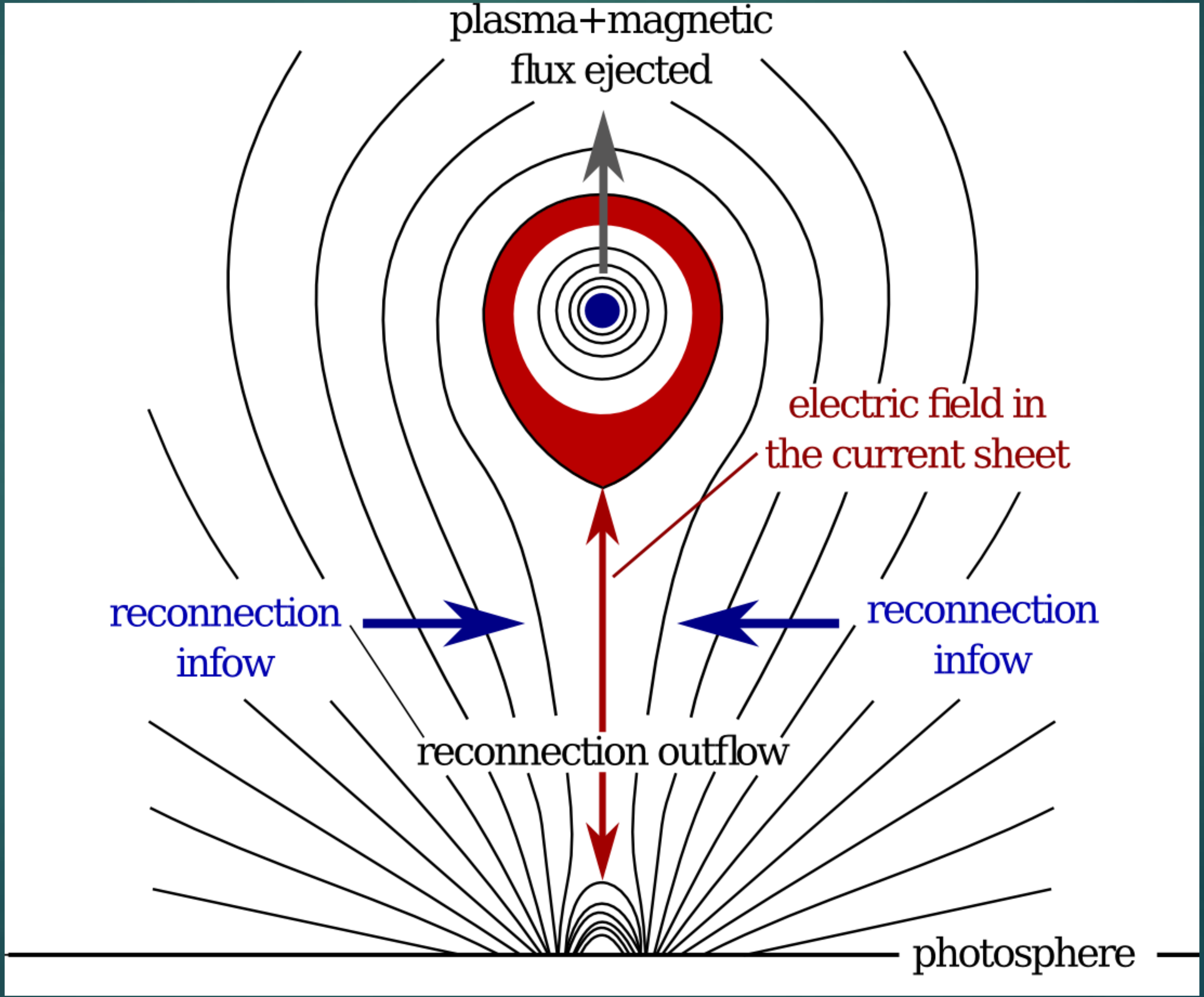
Flares are often associated with Coronal Mass Ejections (CMEs)



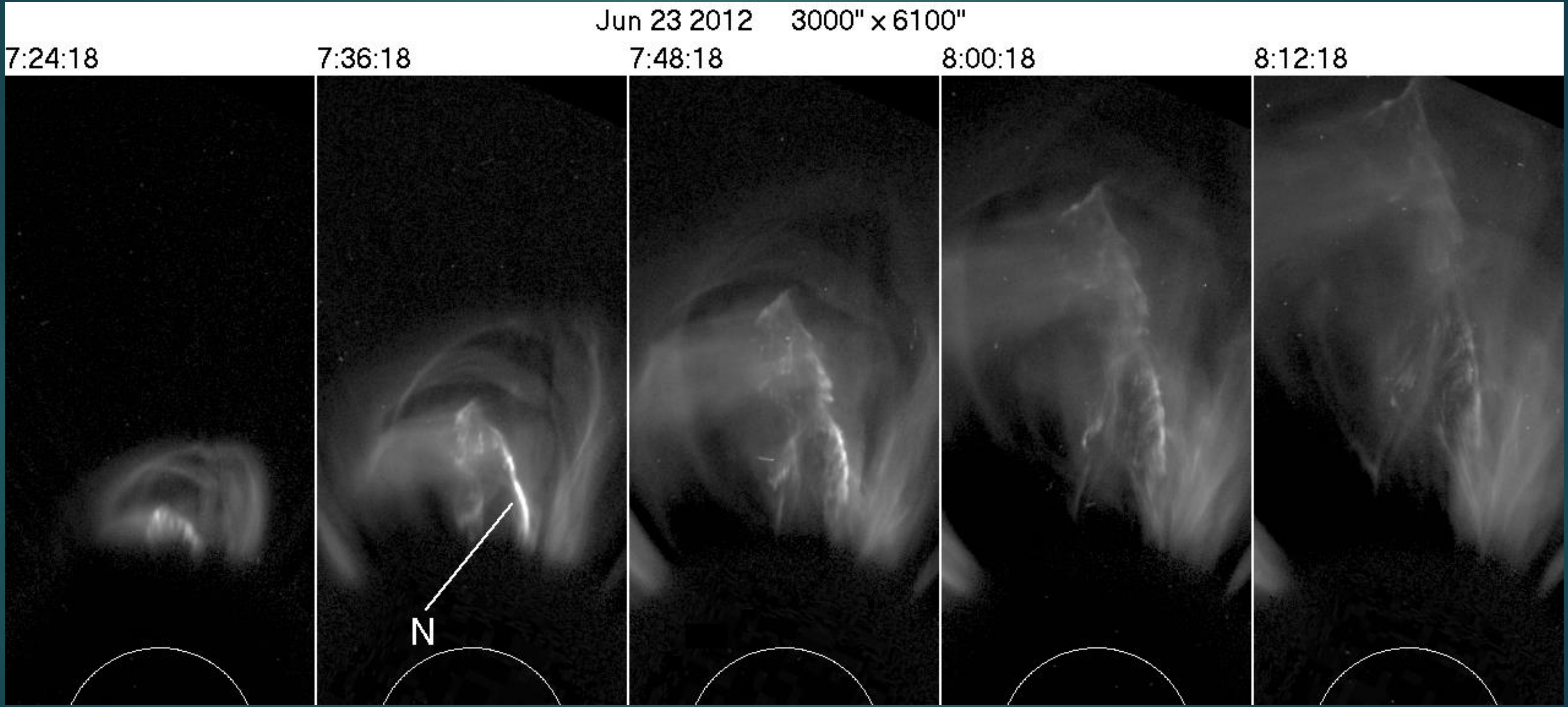
Shock wave in front of a CME



This is (probably) what is going on

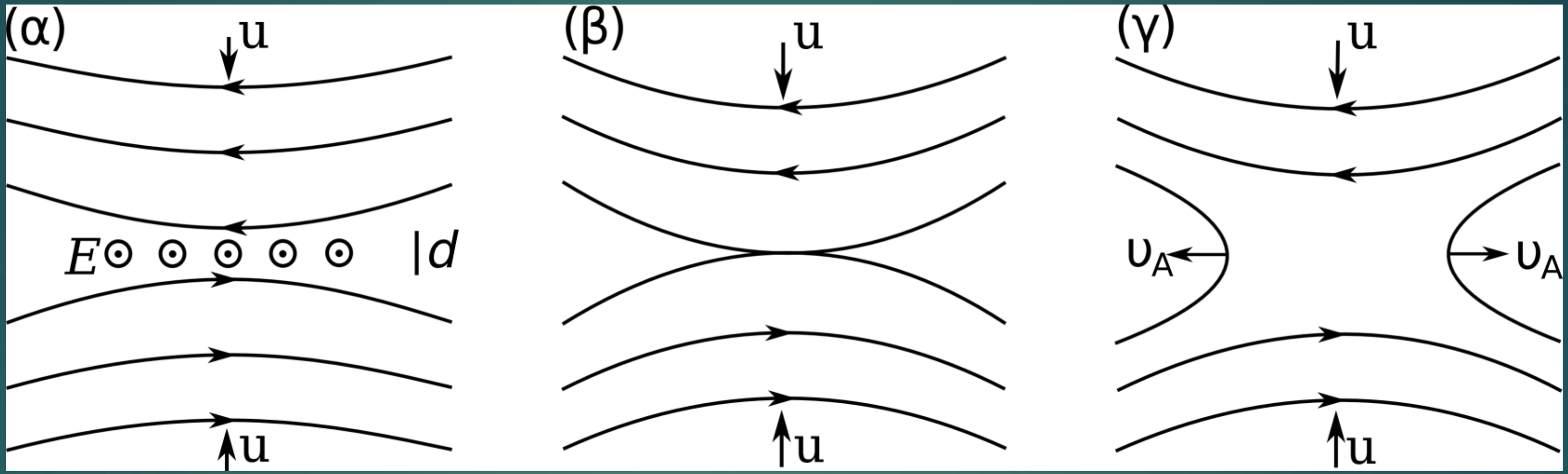


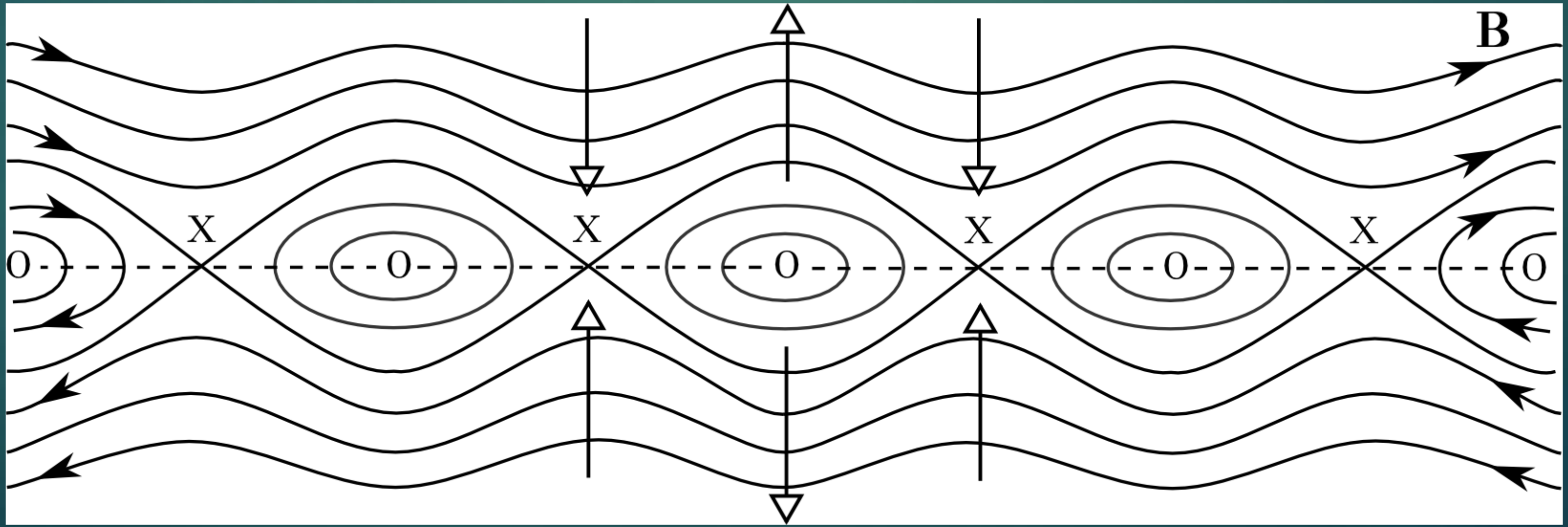
Another example of a CME and its evolution



N marks the exploding filament

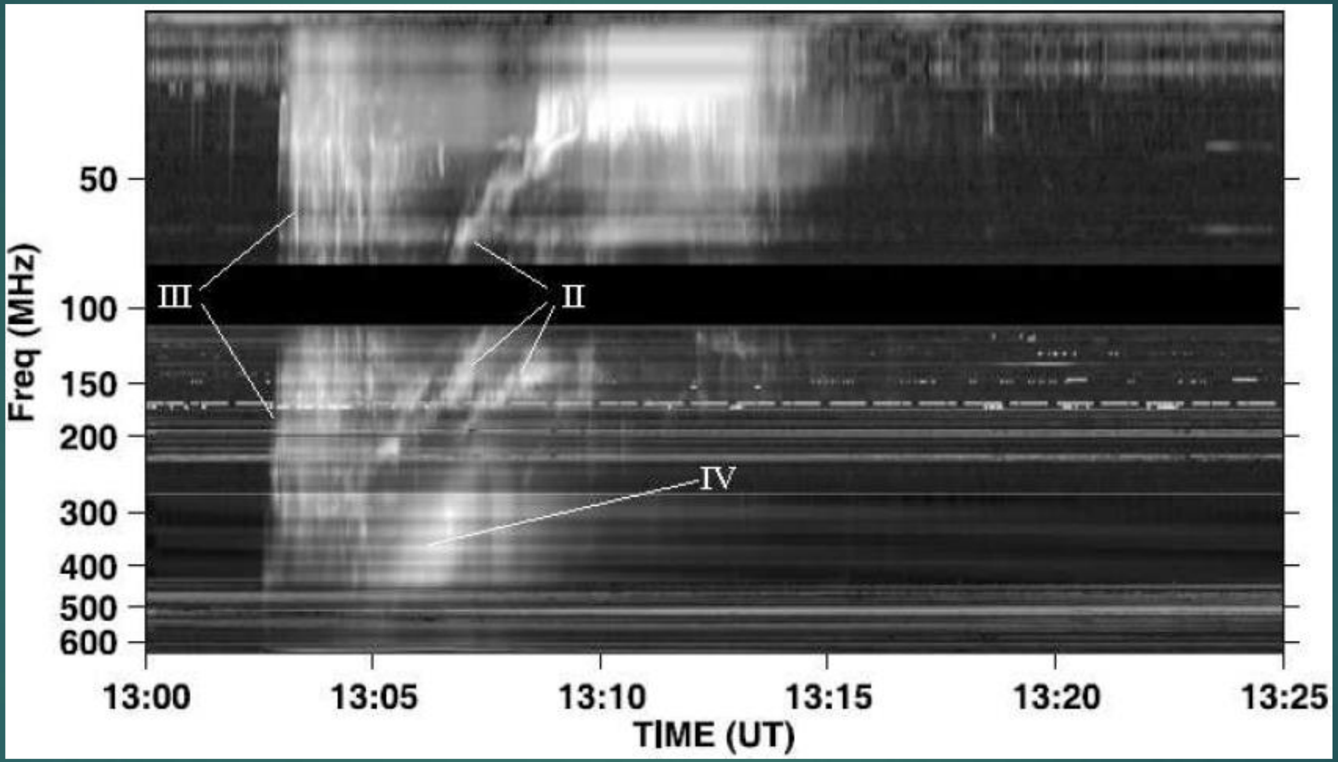
Magnetic reconnection? What is this?





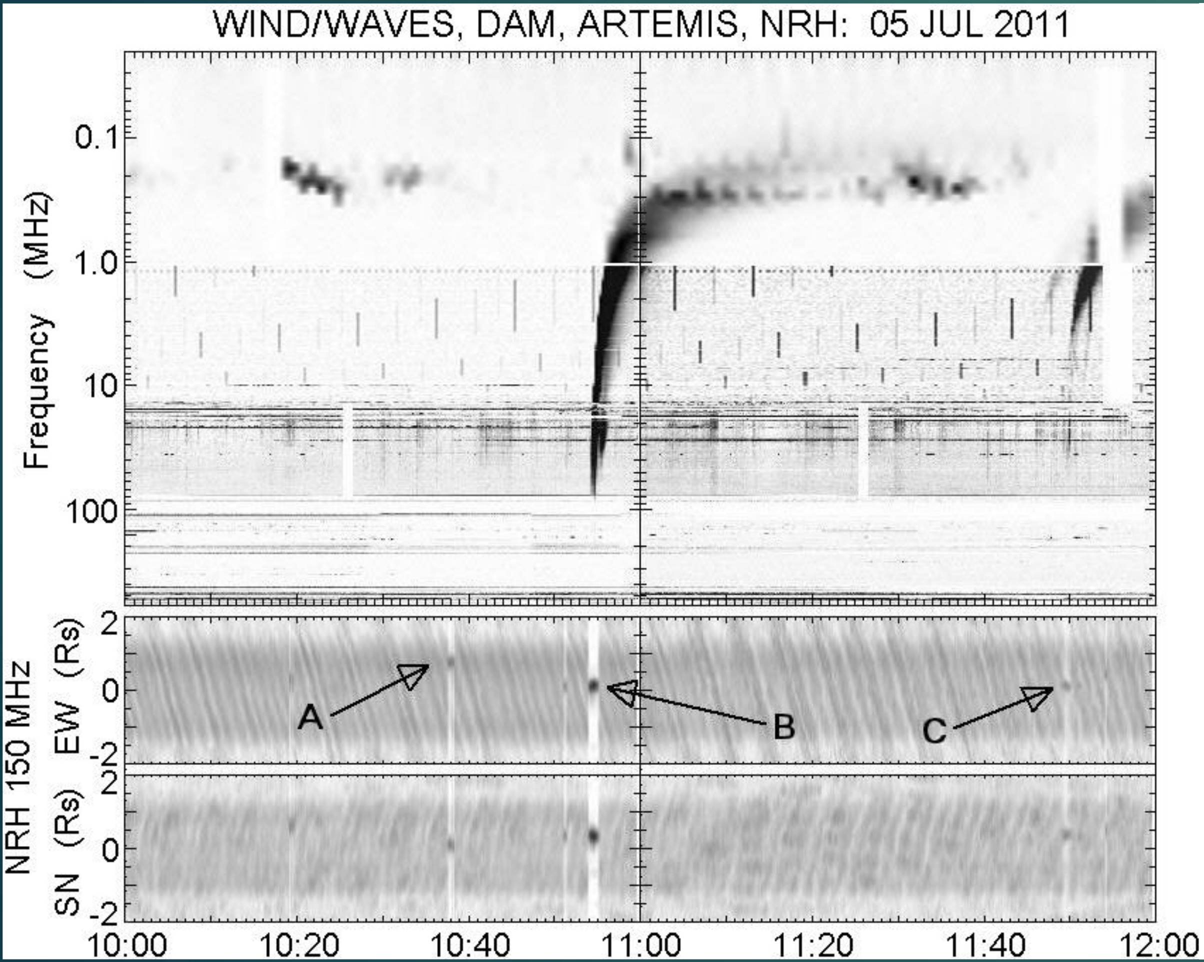
Things that we see in metric radio waves

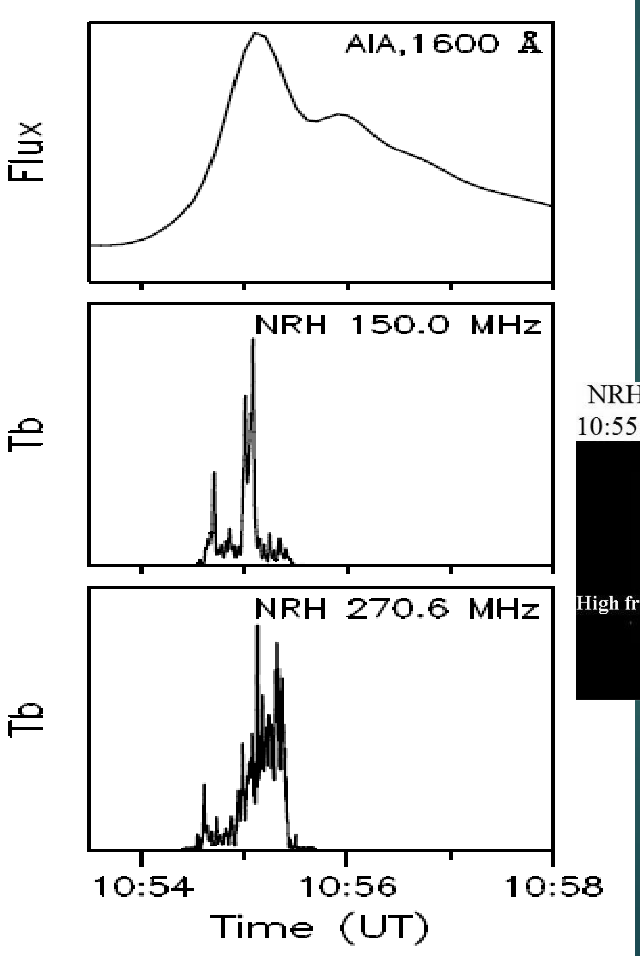
(Dynamic spectrum from our ARTEMIS-JLS radio spectrograph at Thermopylae)

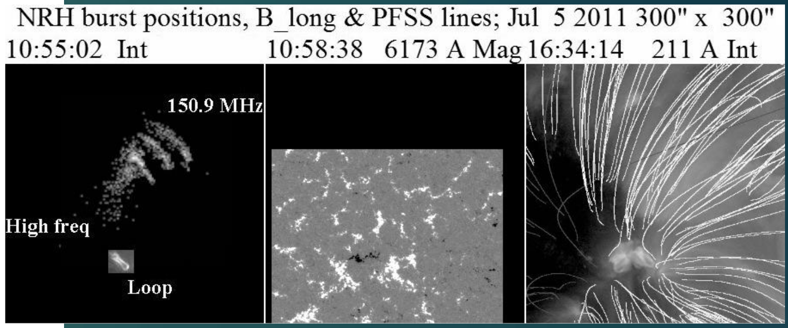


- Type II: shock wave associated emission
- Type III: high energy electron beams traveling up, along open field lines (2-stream instability)
- Type IV: radiation from trapped electrons

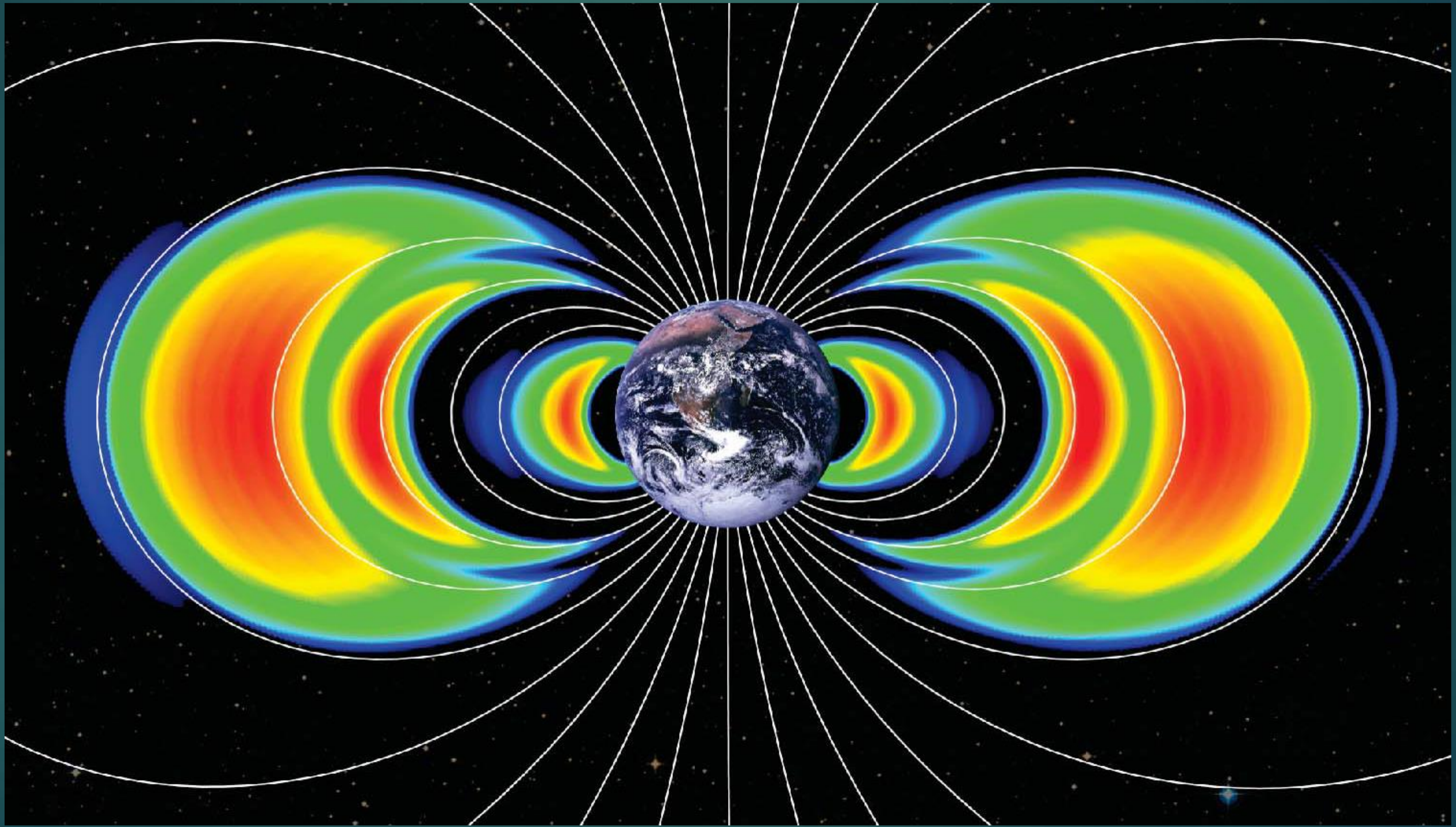
An interplanetary type III from a tiny loop





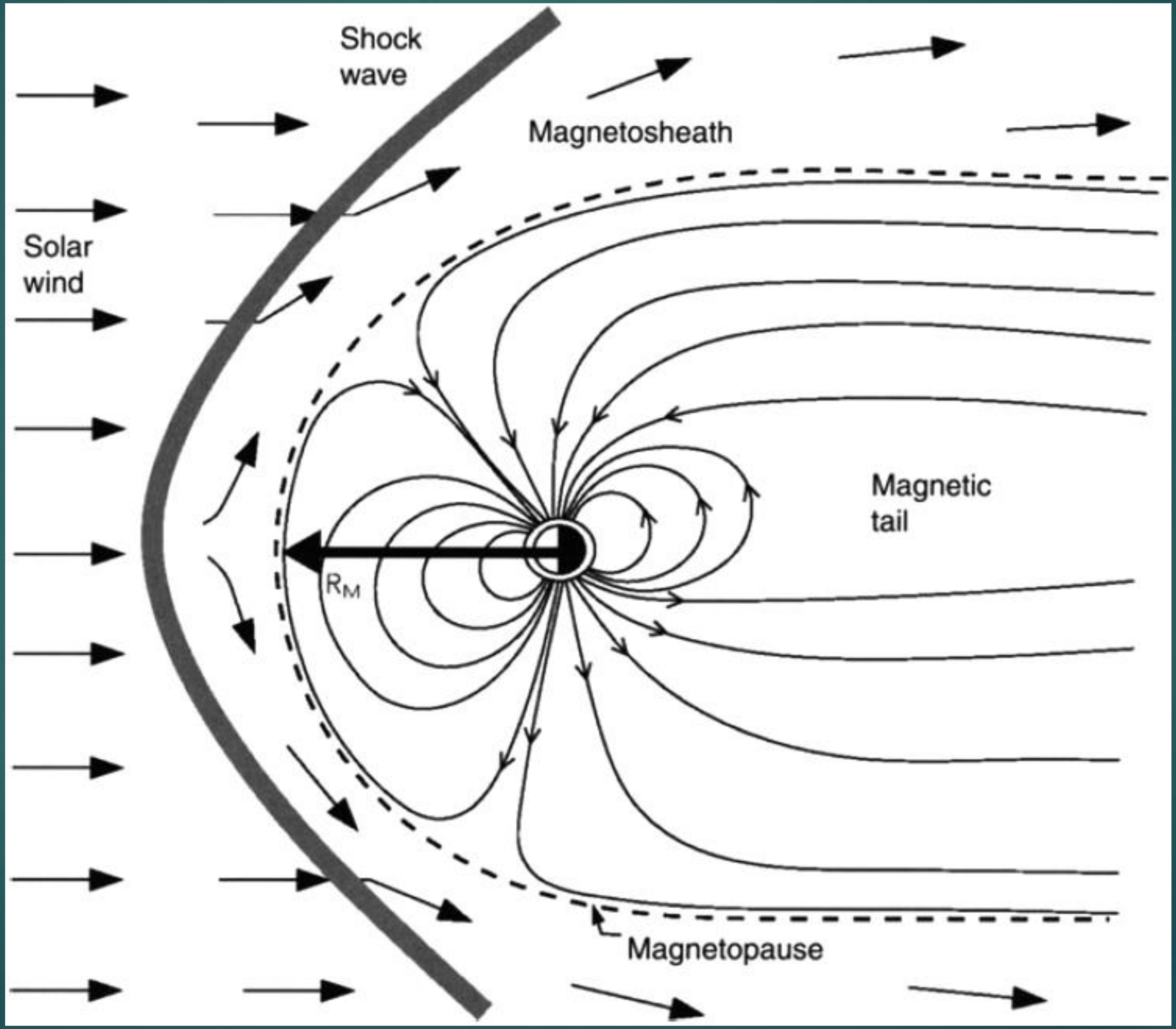


Let’s go down to Earth (almost)



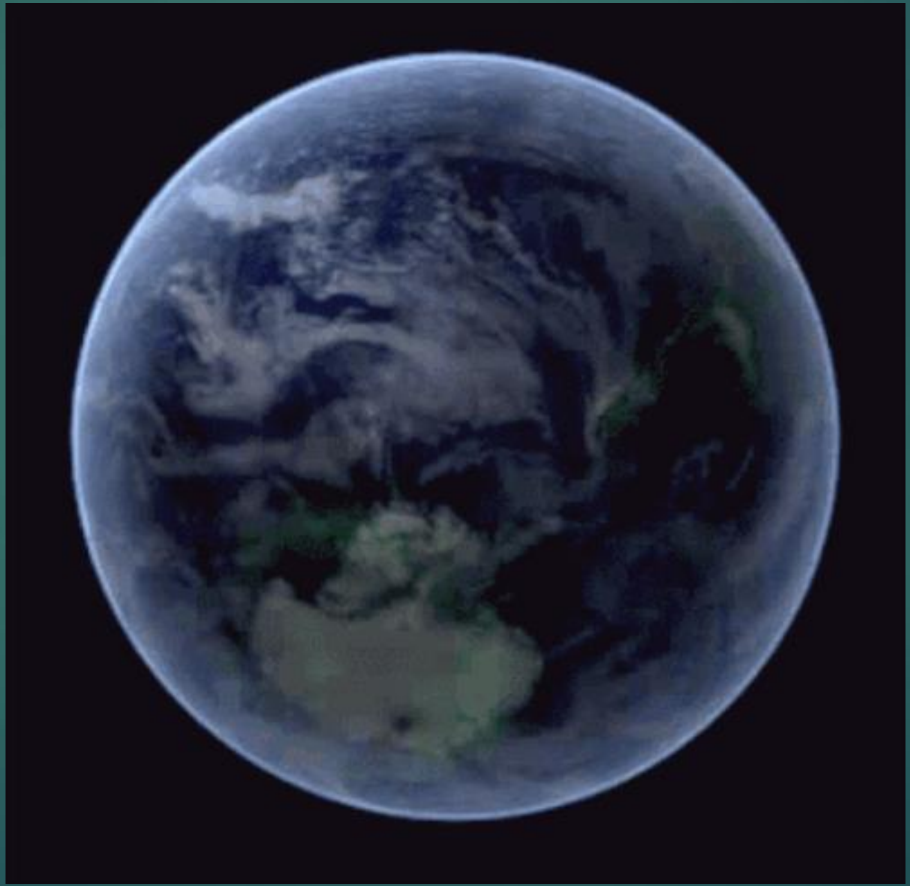
Particles trapped in radiation belts

Earth’s magnetosphere

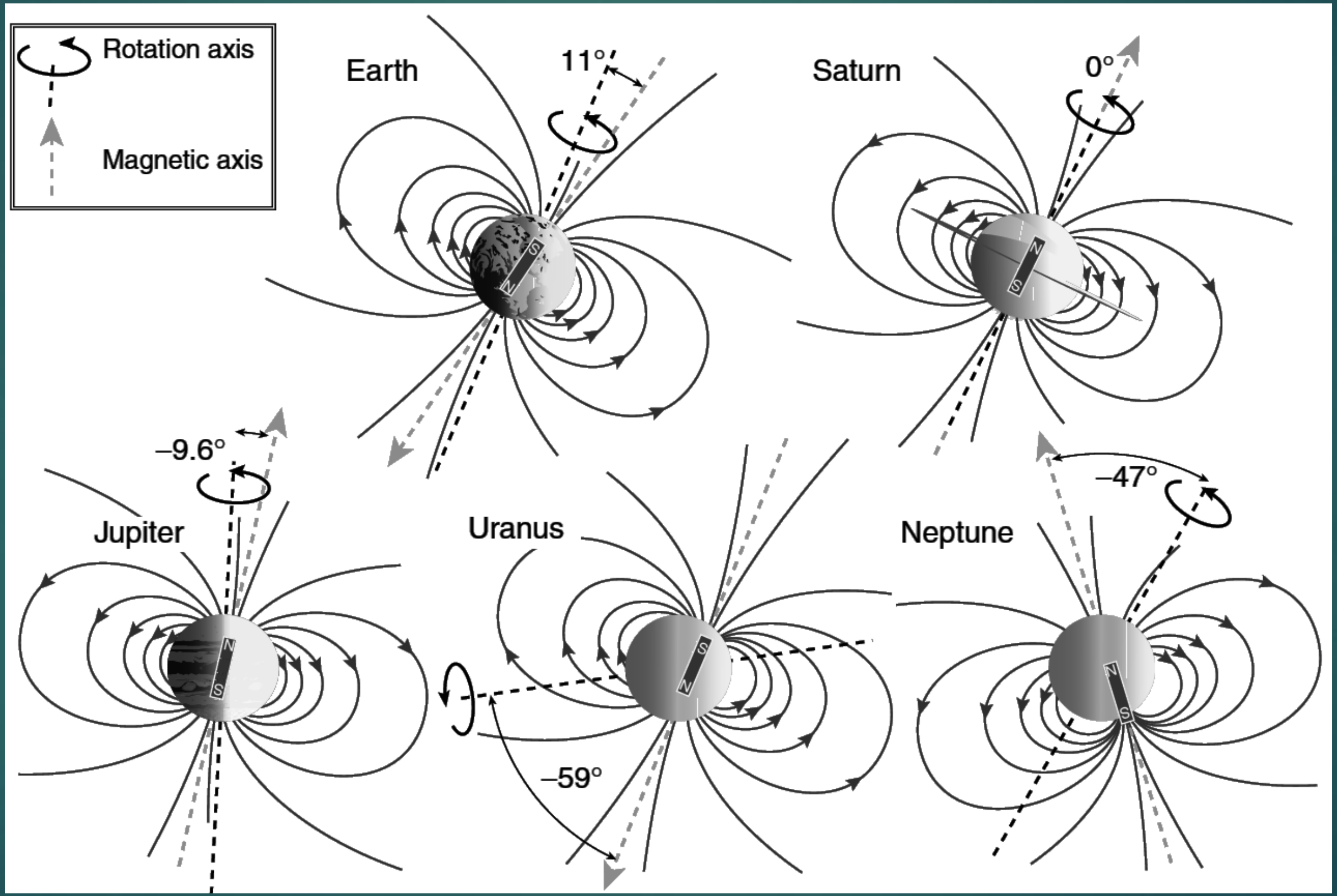


Spectacular from the ground!

Spectacular from space!

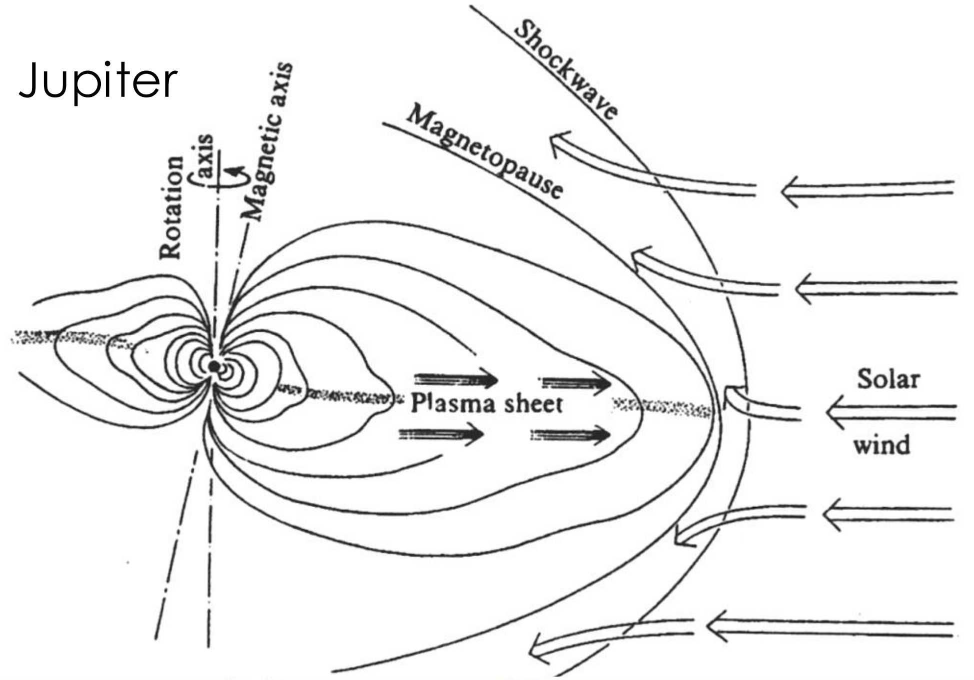


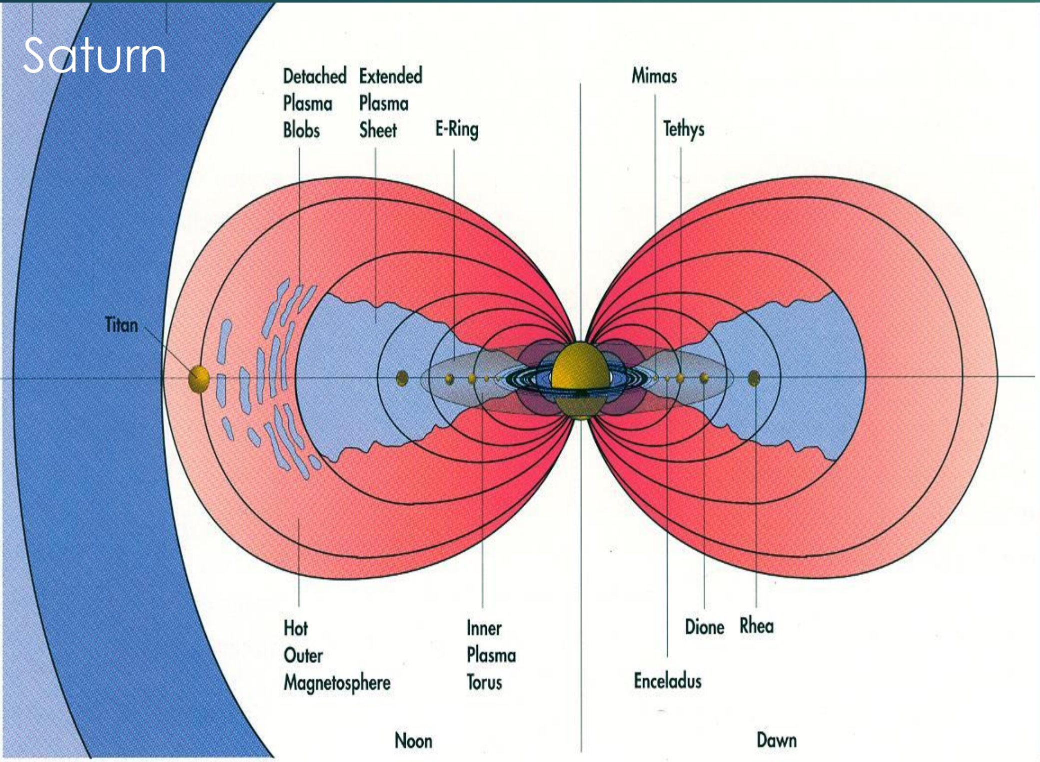
Other planets have magnetic field as well,

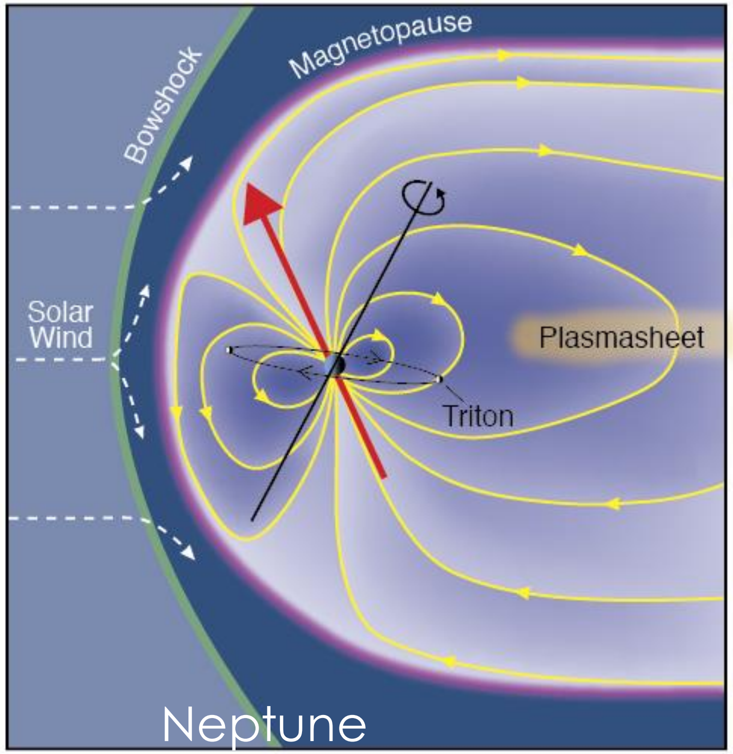


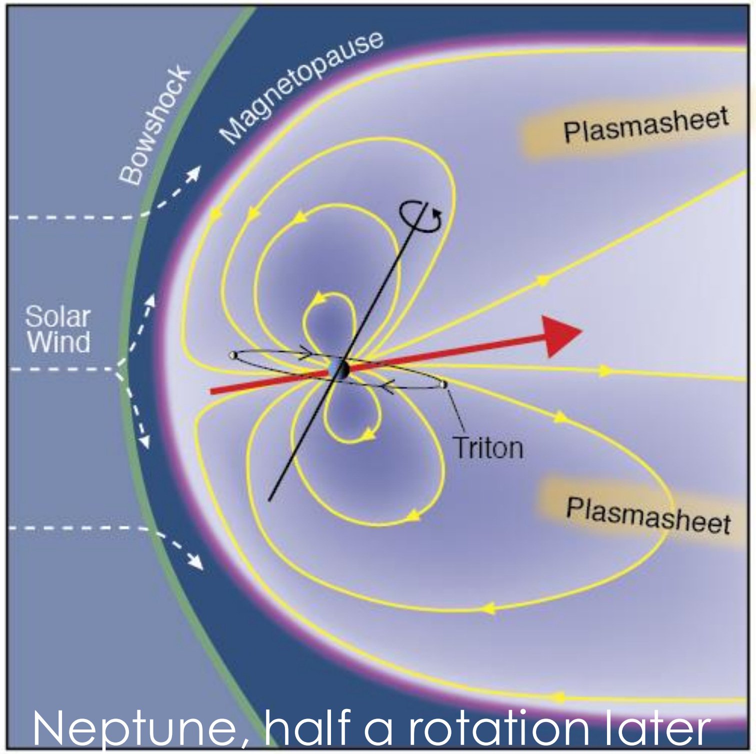
… and magnetospheres,

Note the high inclination of the dipole axis with respect to the rotation axis of Neptune

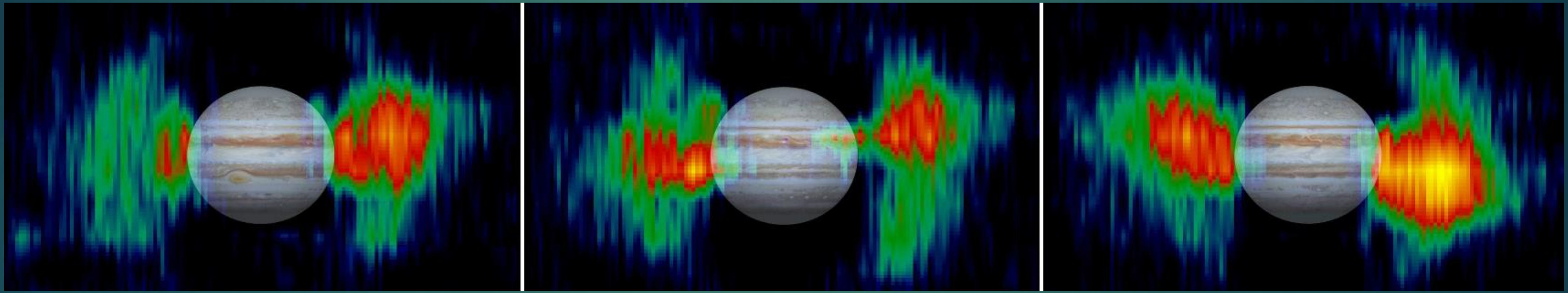






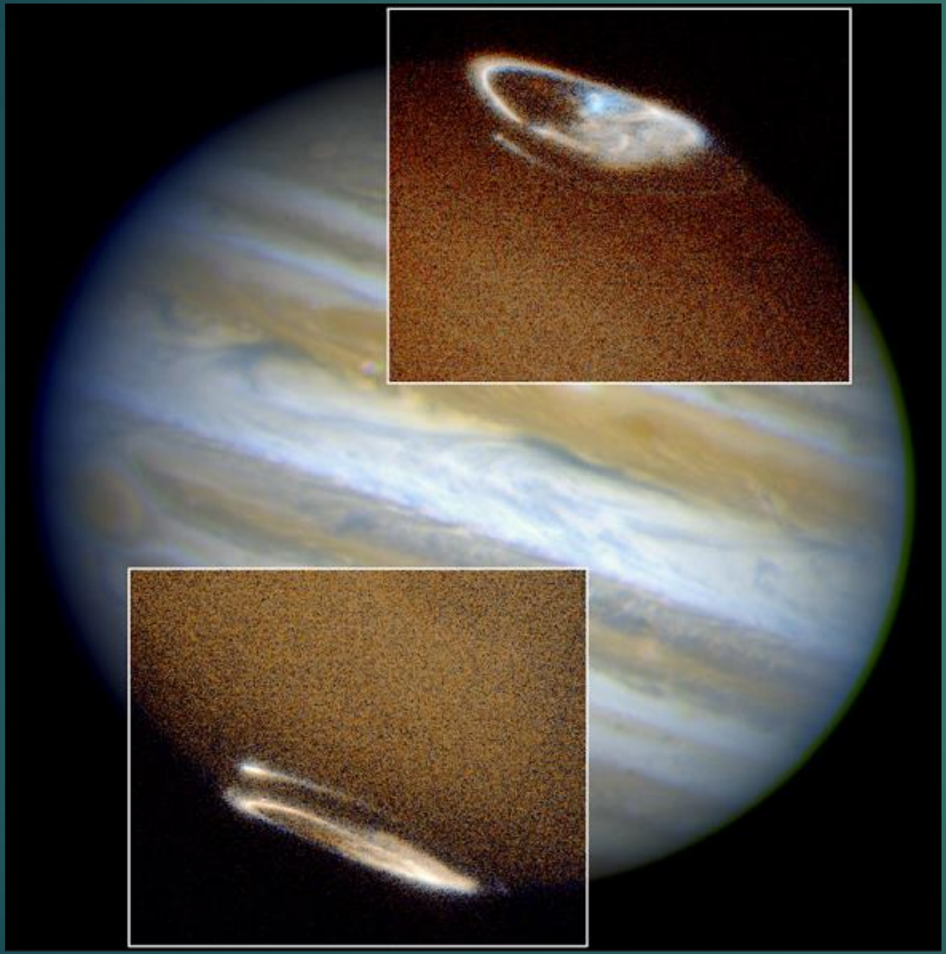


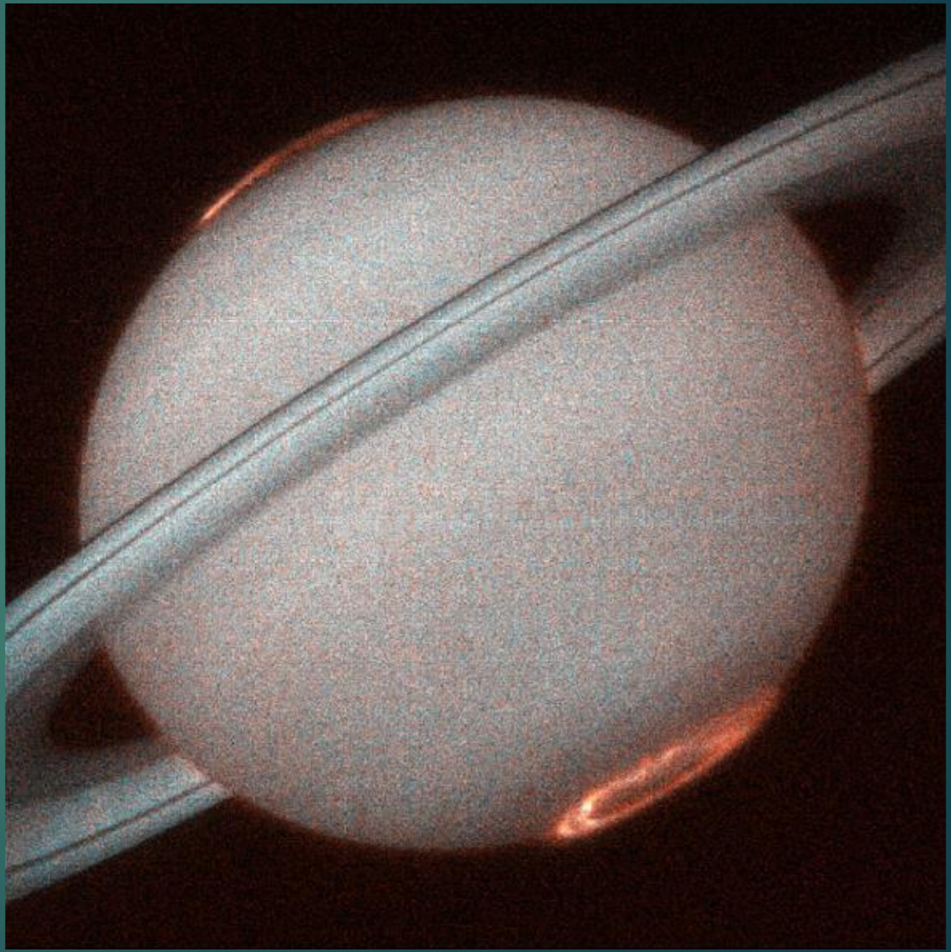
… and radiation belts,



Radio emission from Jupiter's radiation belts at three instances in the course of its rotation (from the New Horizons mission)

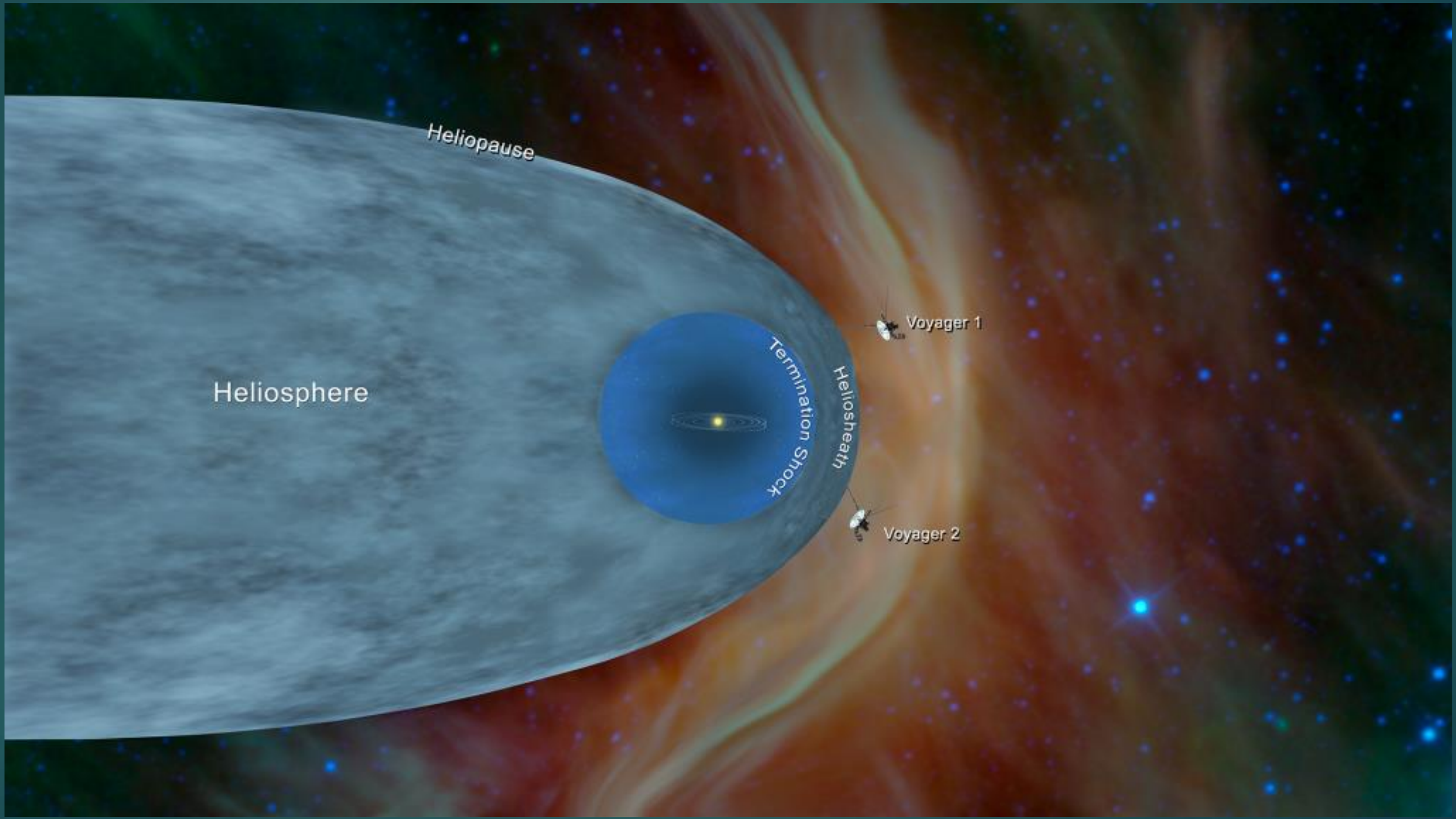
… and aurorae





Reaching the end of the heliosphere

(Voyager 1 & 2 have crossed it !)

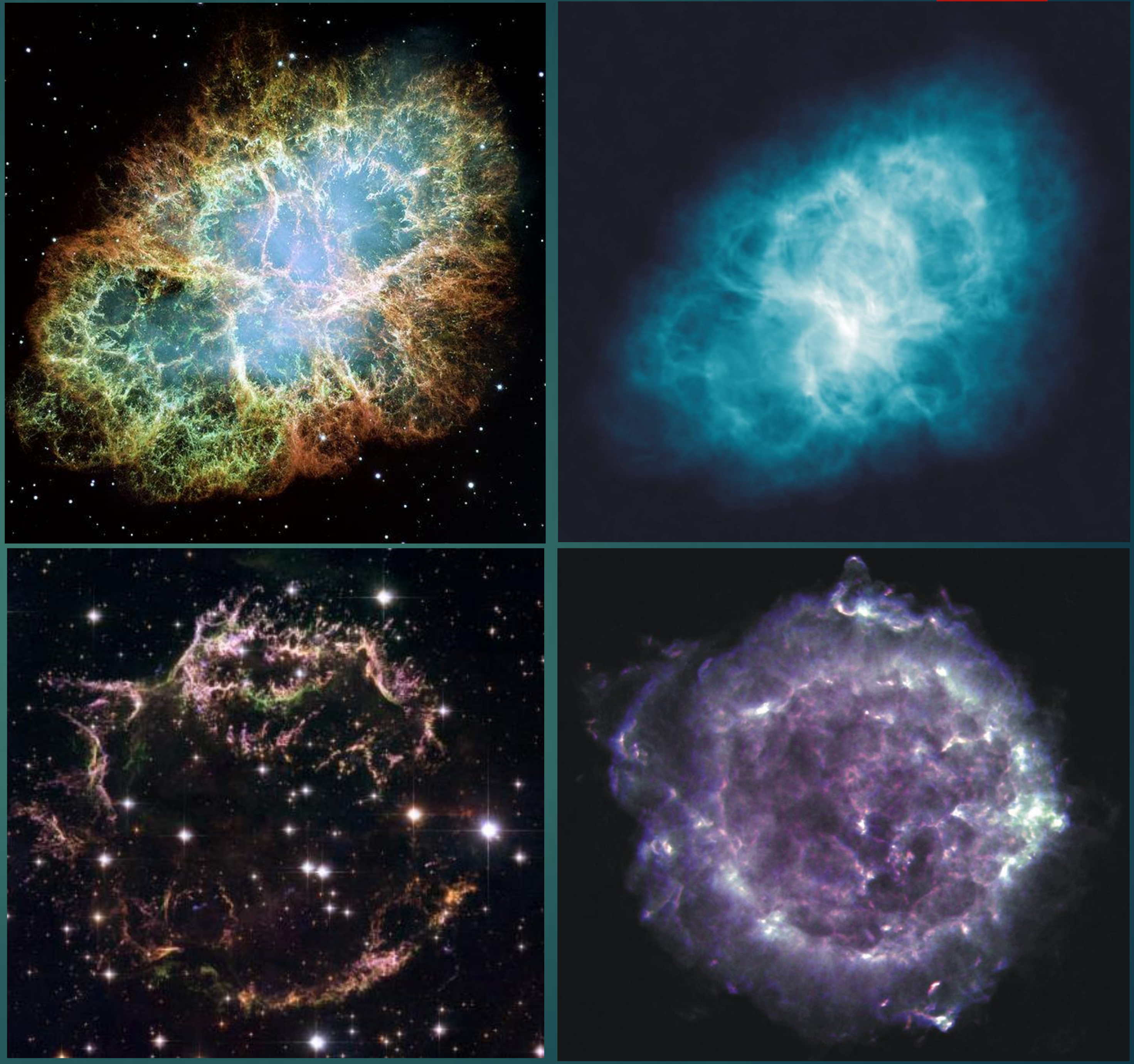


And going to the stars…

Radio emission from supernova remnants (synchrotron) reveals magnetic field

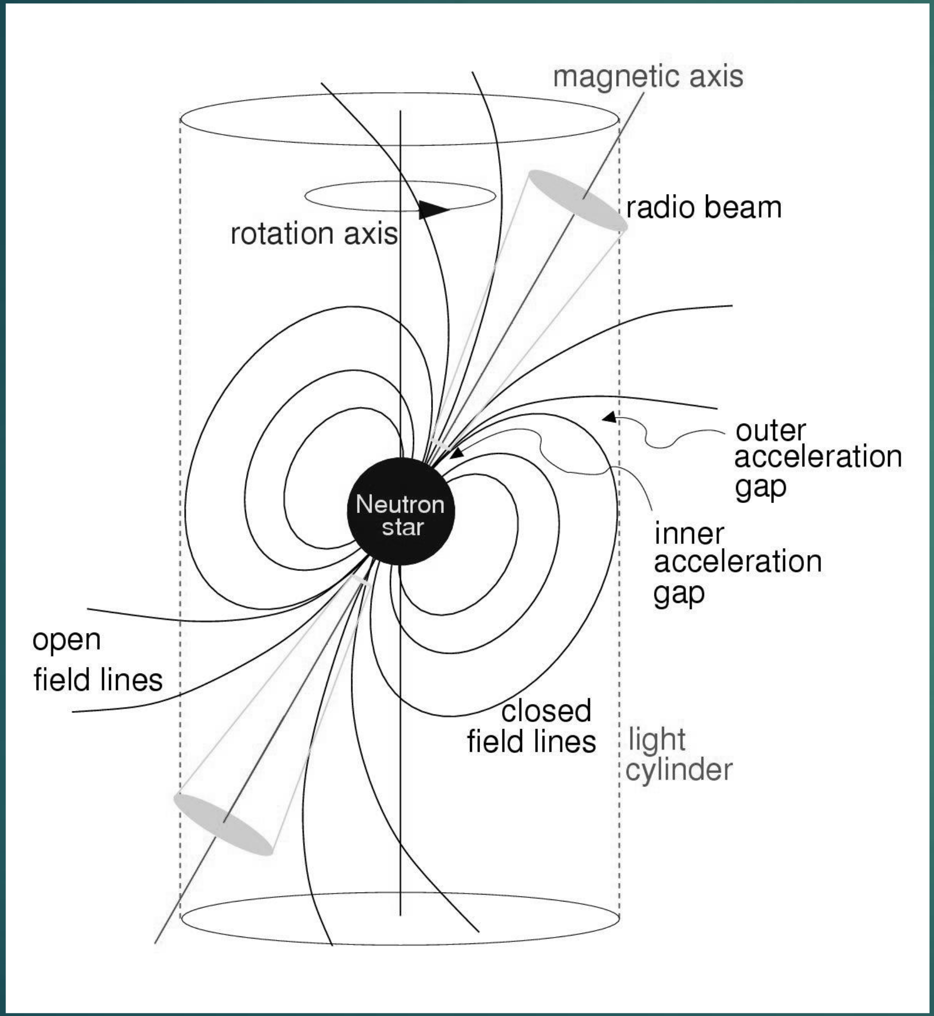
Crab

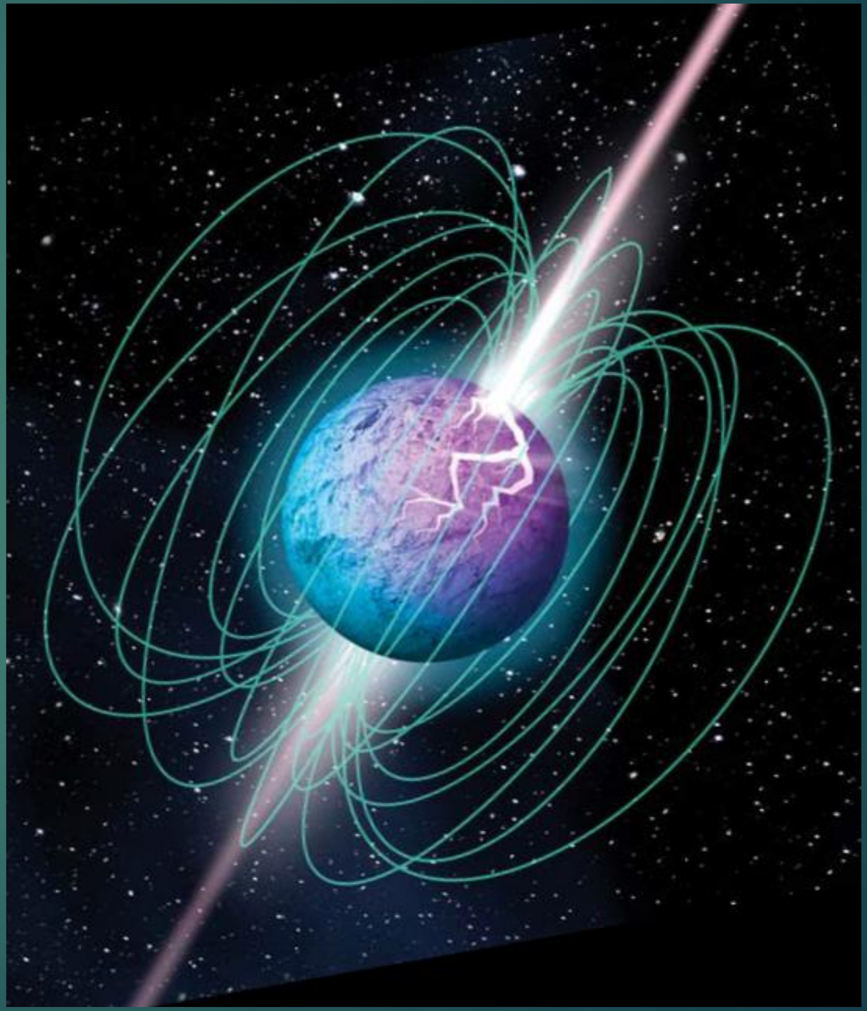
Cas A



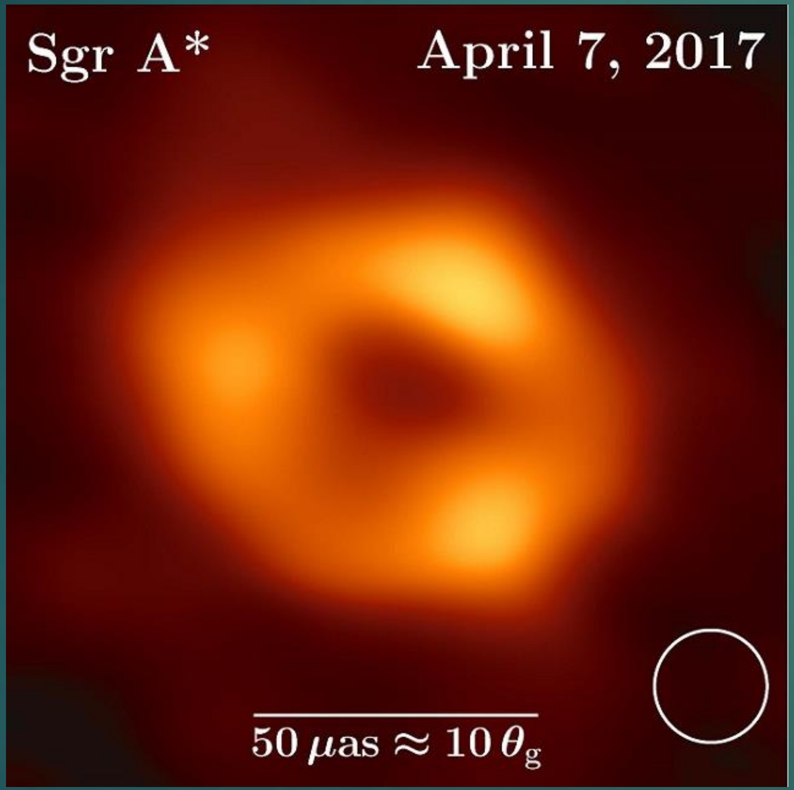
Optical (HST) Radio (NRAO)

Visiting a pulsar and a magnetar,

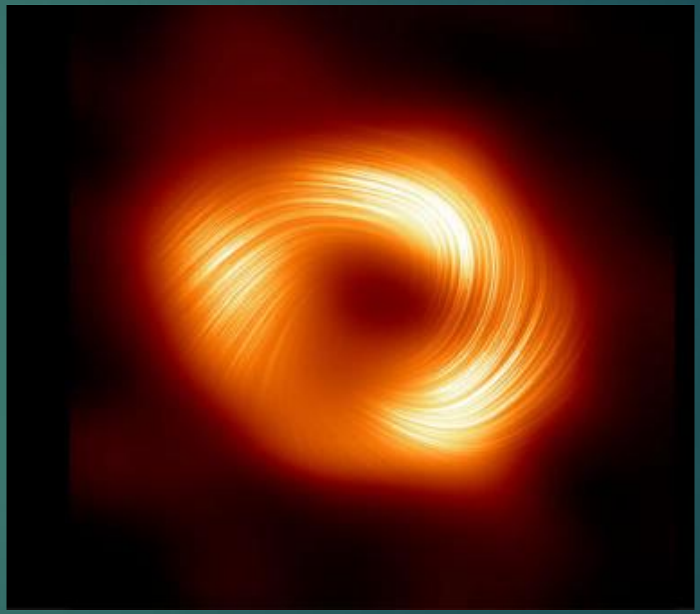




… and the black hole at the center of the Galaxy (EHT)



Intensity



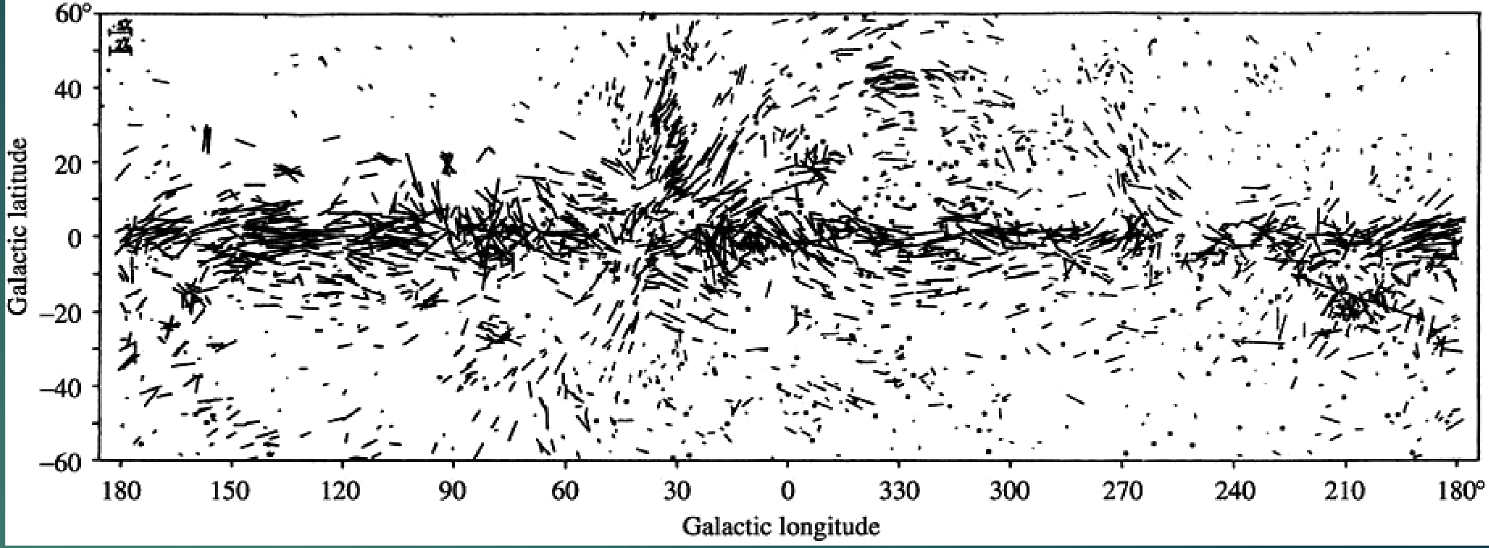
Linear polarization

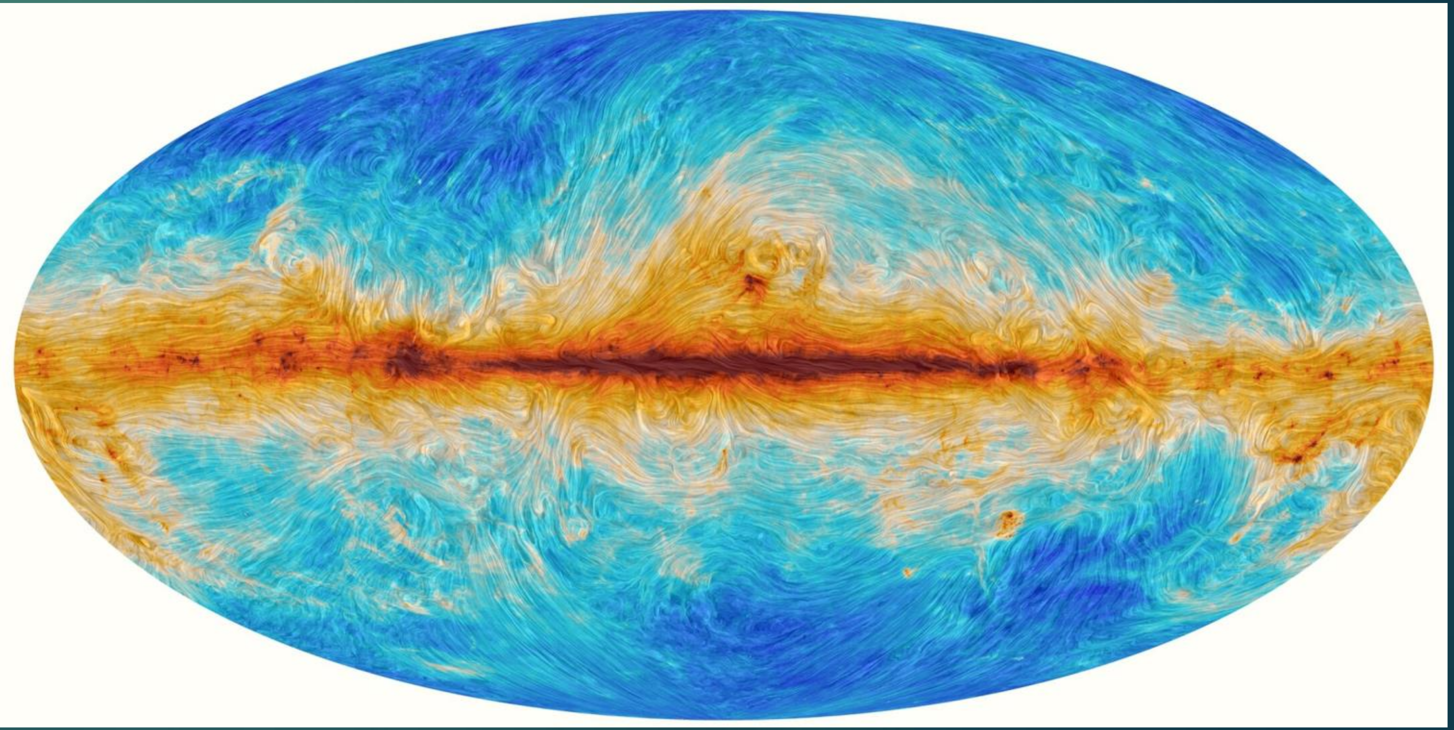
… and interstellar dust

- Polarization of stelar light due to interstellar dust in optical wavelengths

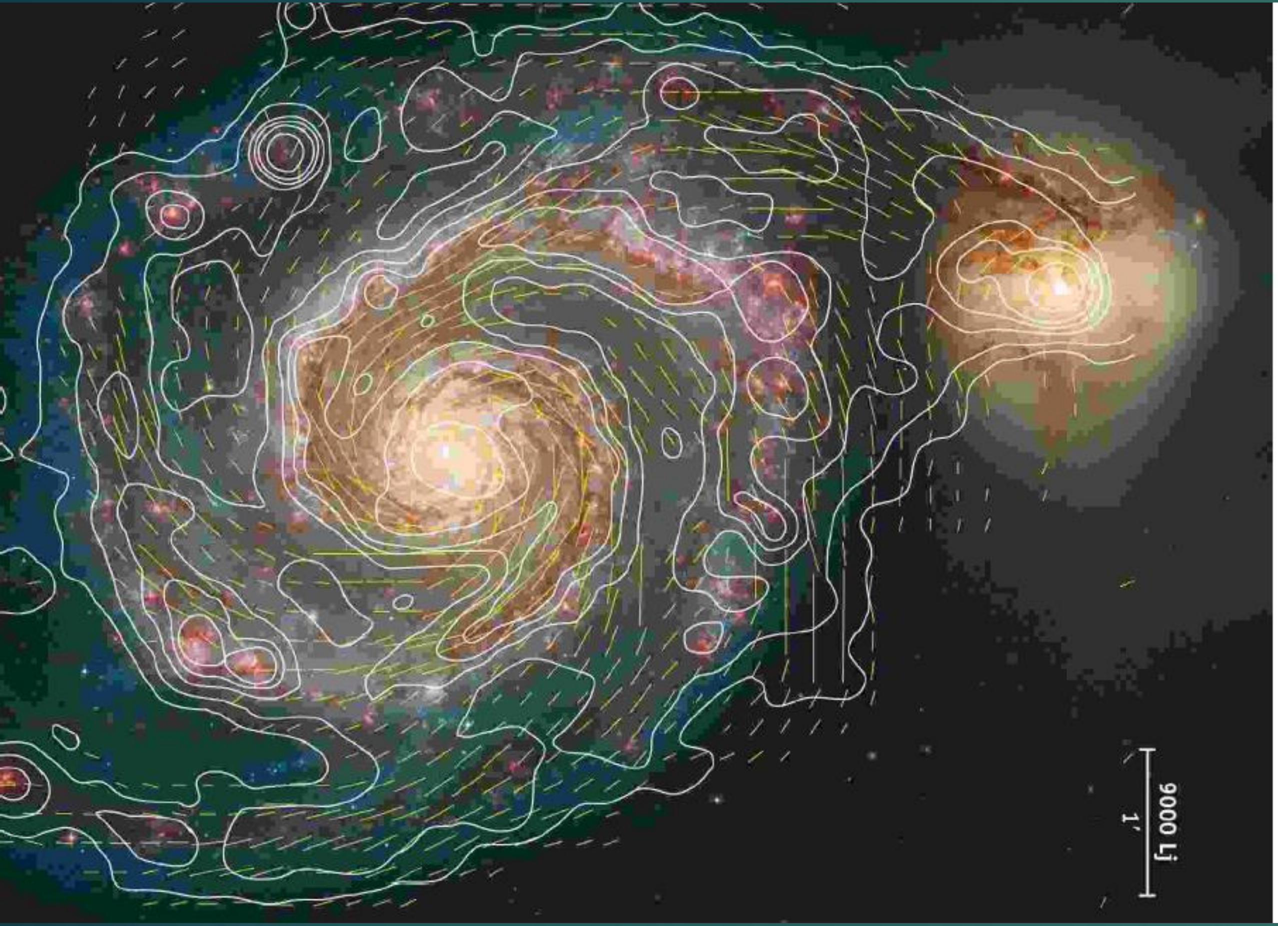
- Polarization of the radio emission of interstellar dust in the sub-mm wavelength range (Planck)

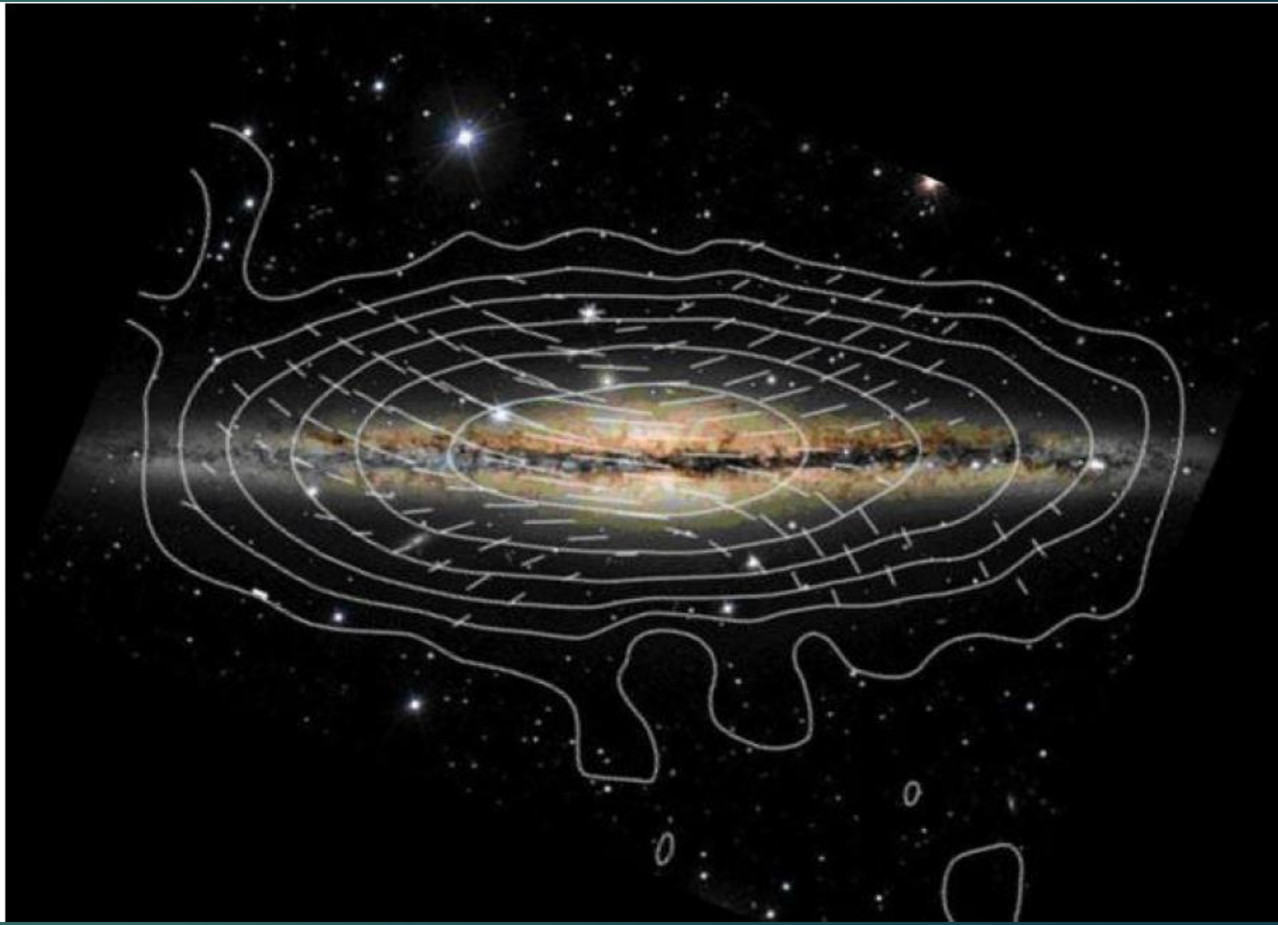
=> Our galaxy possesses a large-scale magnetic field





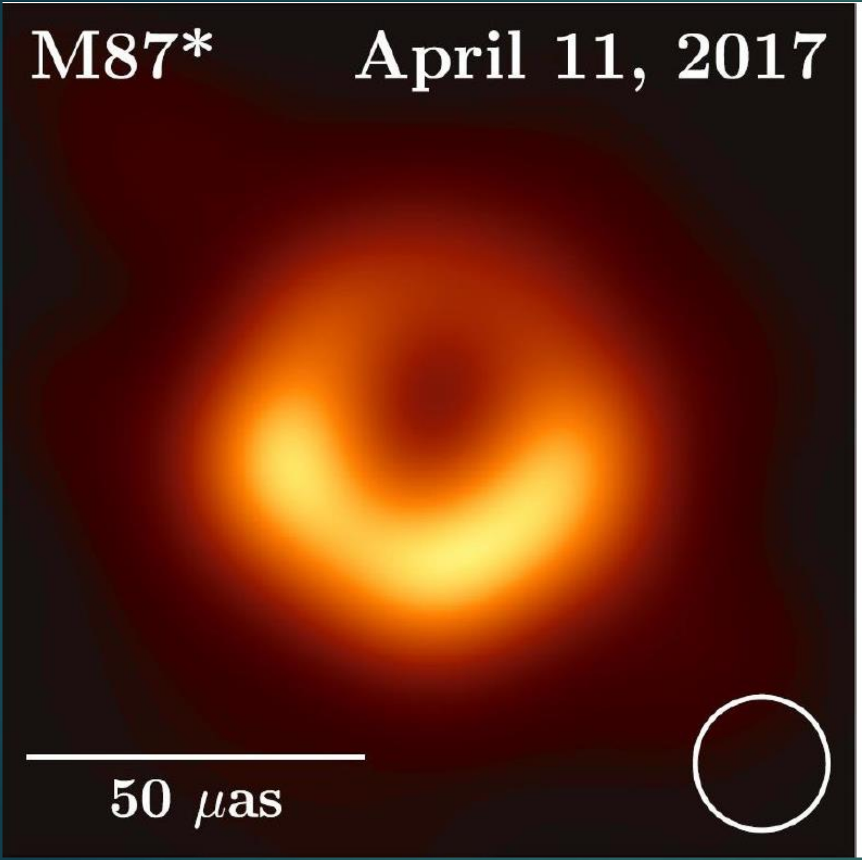
Let’s go to other galaxies…



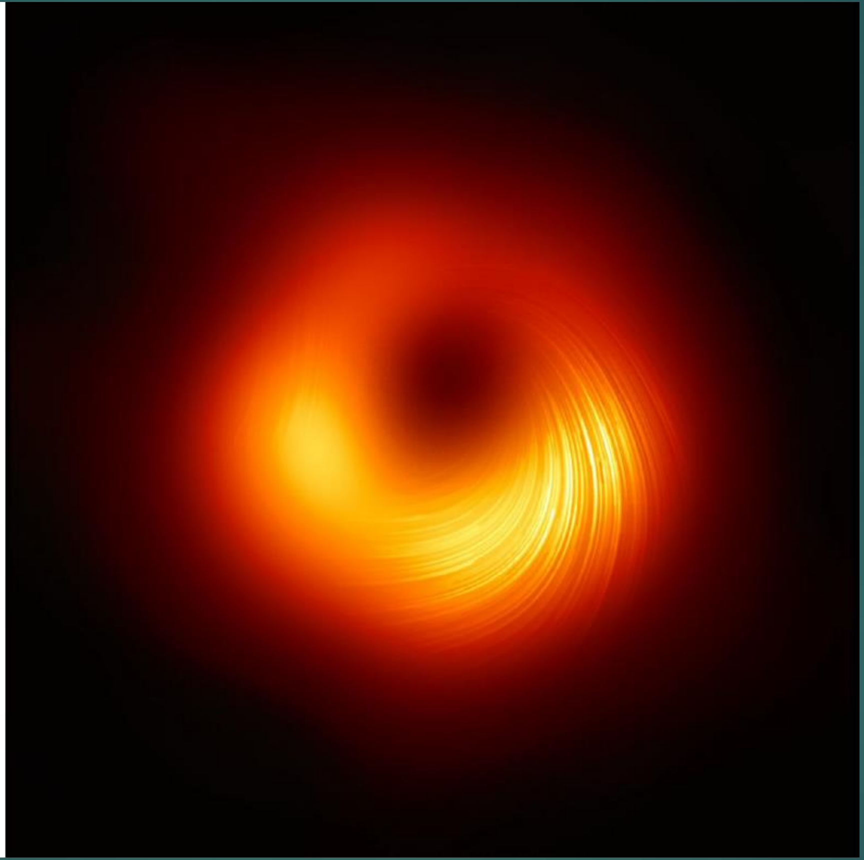


Optical (image), radio (contours) emission & the direction of the magnetic field (line segmens) for M51 (left) and NGC891 (right)

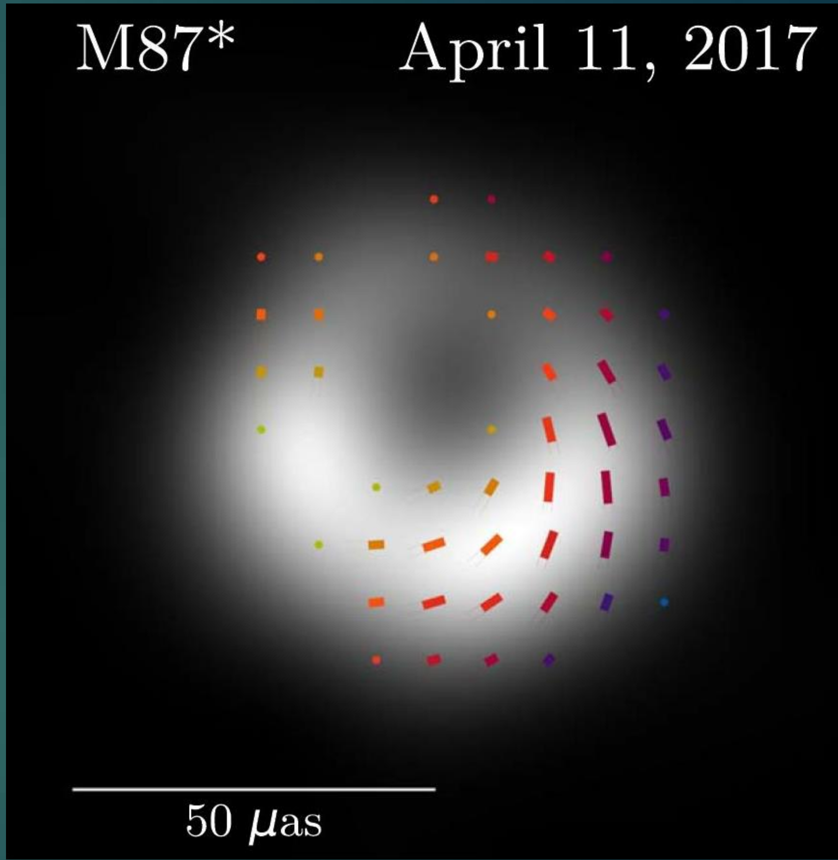
… and another black hole



Intensity

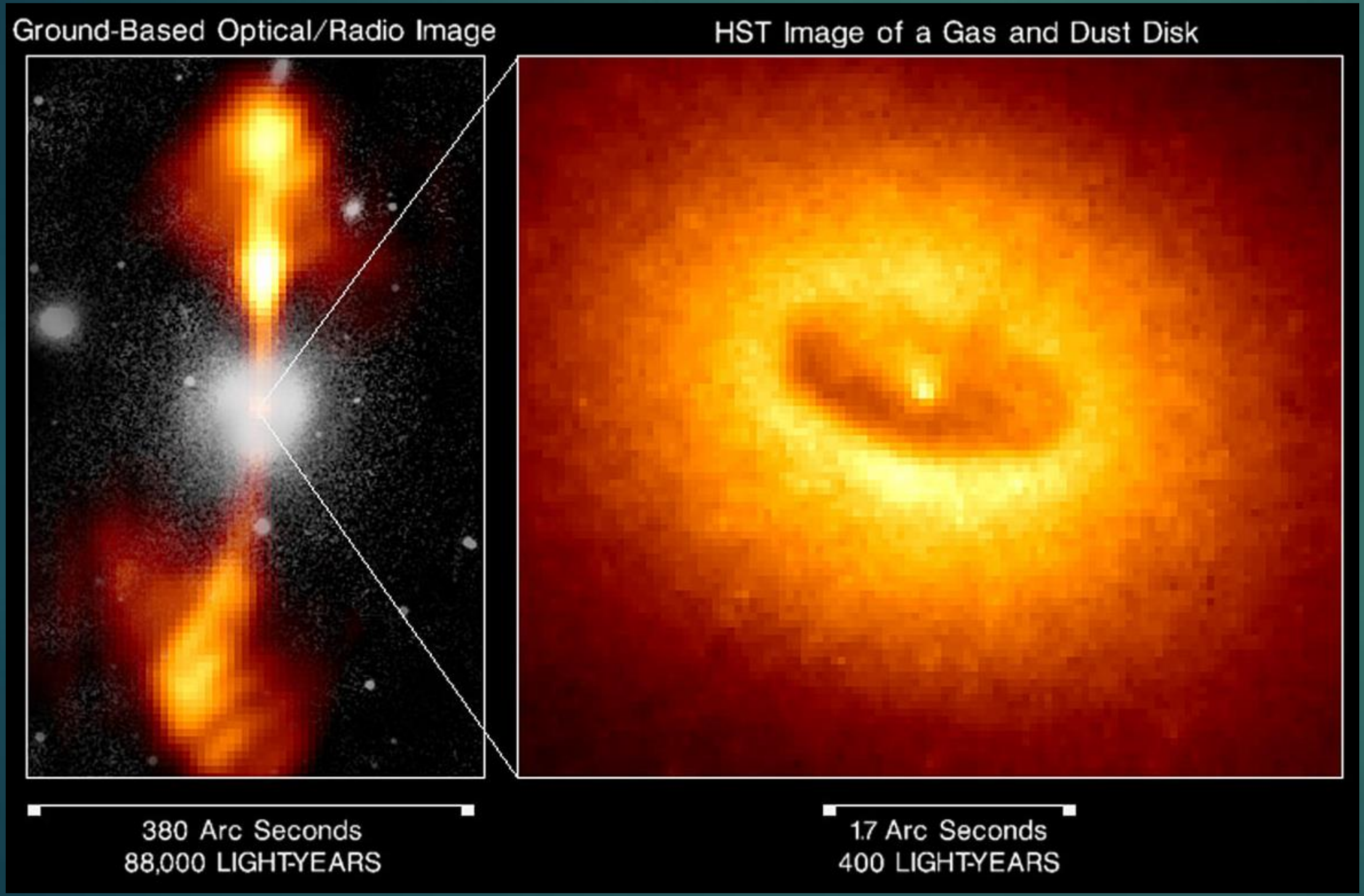


Linear polarization

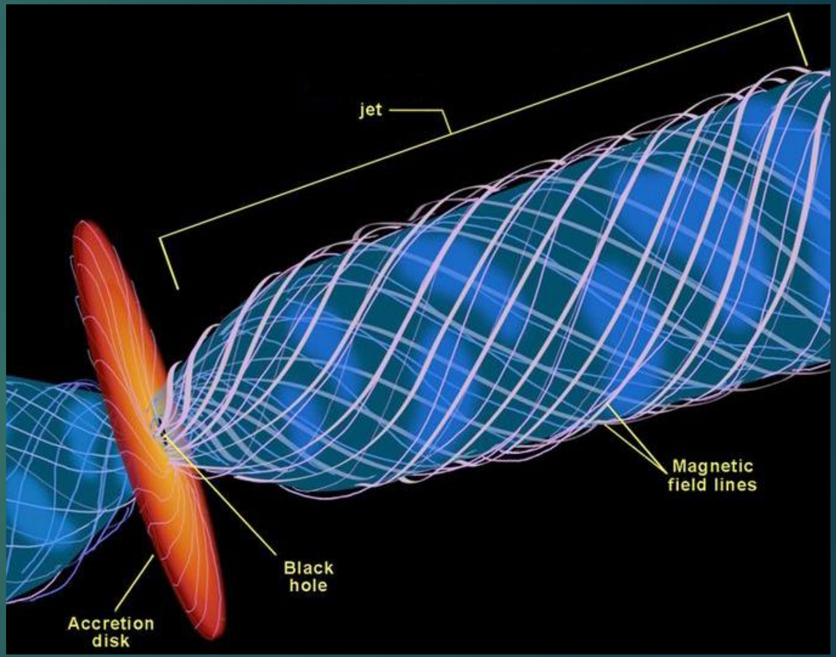


Intensity + polarization

Accretion disks and jets

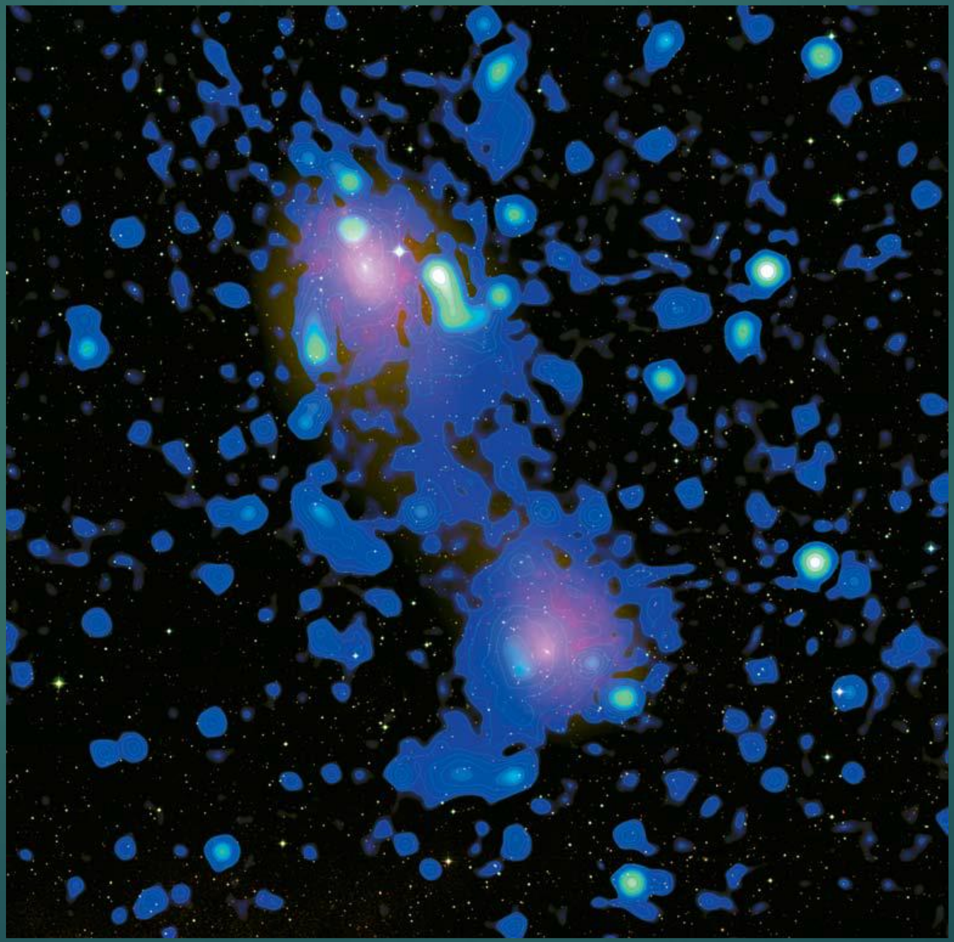


NGC 4261



Artist's concept with magnetic field lines added

Synchrotron emission between 2 merging galaxy clusters

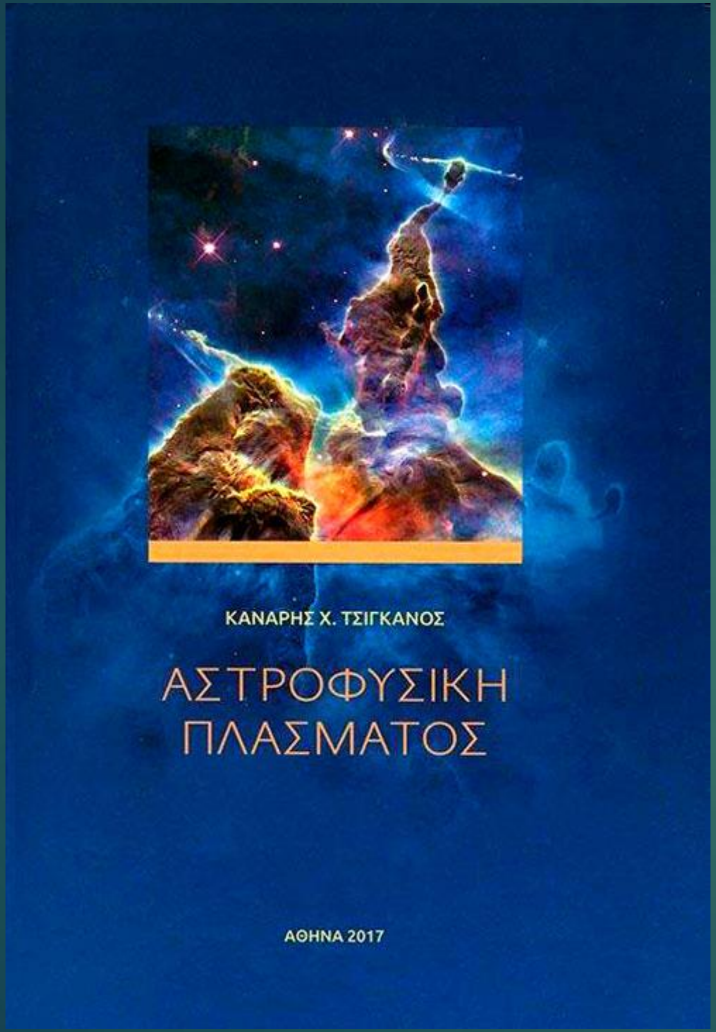


Cannot go any further (yet)

Conclusions

- Plasma is everywhere in the universe
- So is magnetic field
- MHD is a good approximation in many cases, but not always
- It is *sine qua non* to use Plasma Physics in order to understand how the universe works
- => Take the most out of this Summer School

Selected bibliography (1 of 4)



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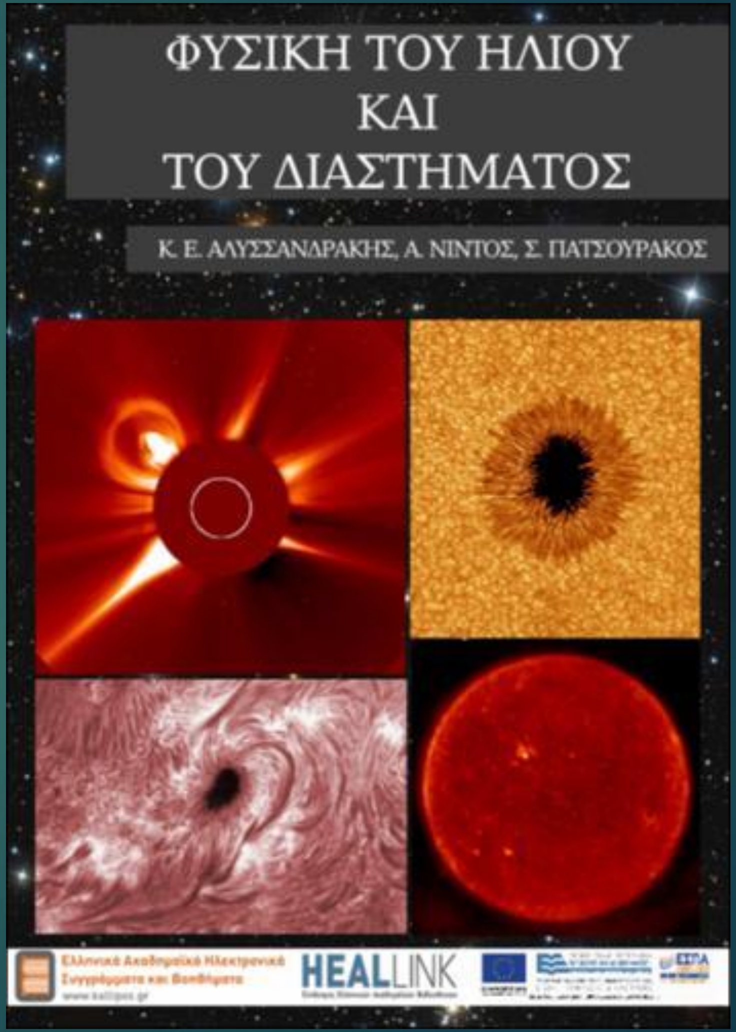
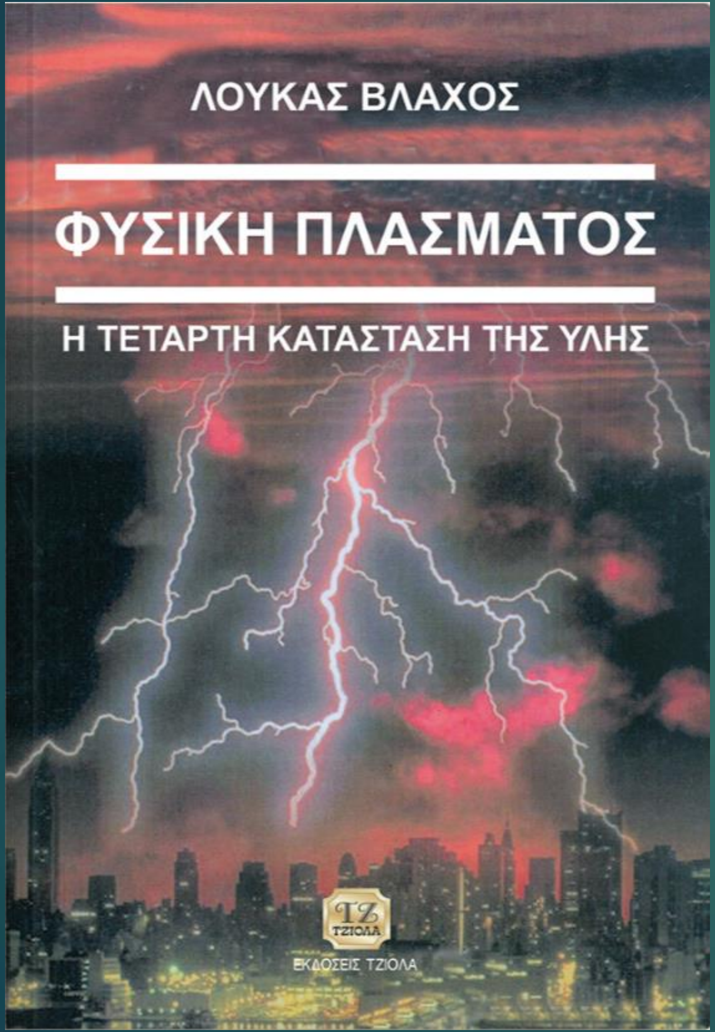


Open access

Selected bibliography (2 of 4)



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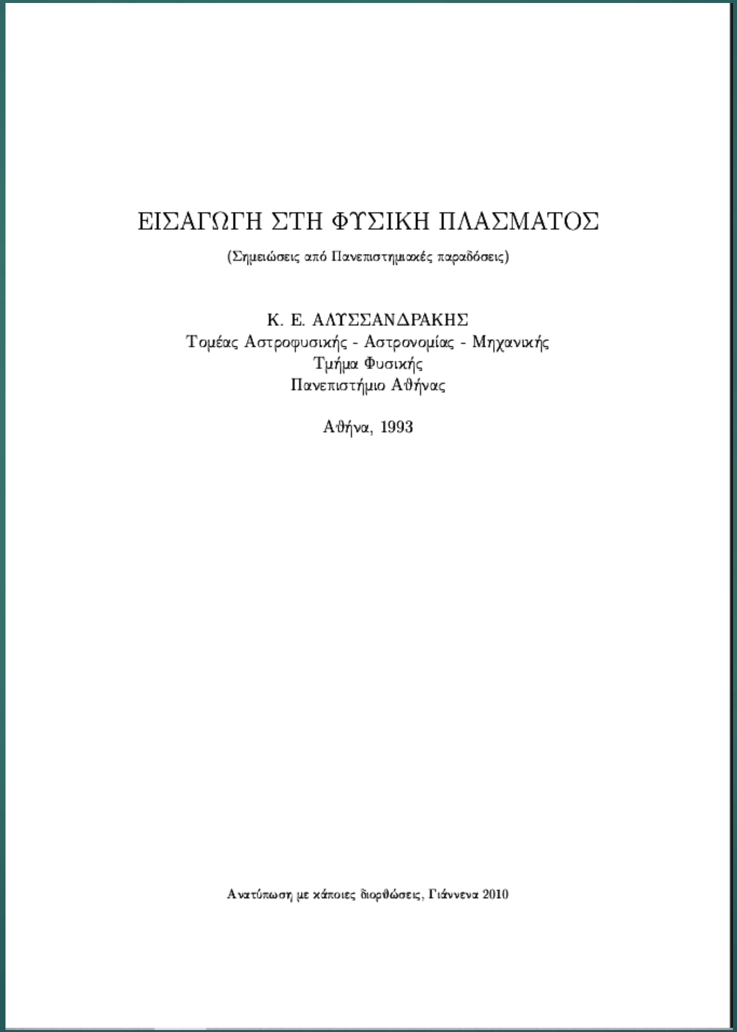
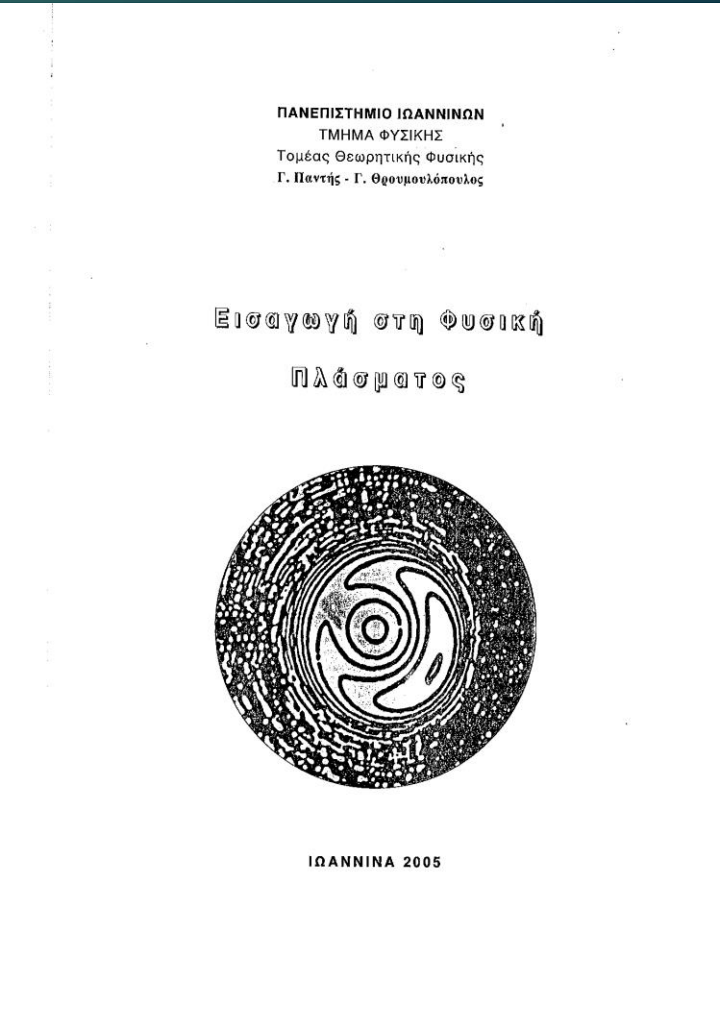

ΕΙΣΑΓΩΓΗ ΣΤΗ ΦΥΣΙΚΗ ΠΛΑΣΜΑΤΟΣ
(Σημειώσεις από Πανεπιστημιακές παραδόσεις)

Κ. Ε. ΑΛΥΣΣΑΝΔΡΑΚΗΣ
Τομέας Αστροφυσικής - Αστρονομίας - Μηχανικής
Τμήμα Φυσικής
Πανεπιστήμιο Αθήνας

Αθήνα, 1993

Ανατύπωση με κάποιες διορθώσεις, Γιάννενα 2010

Link



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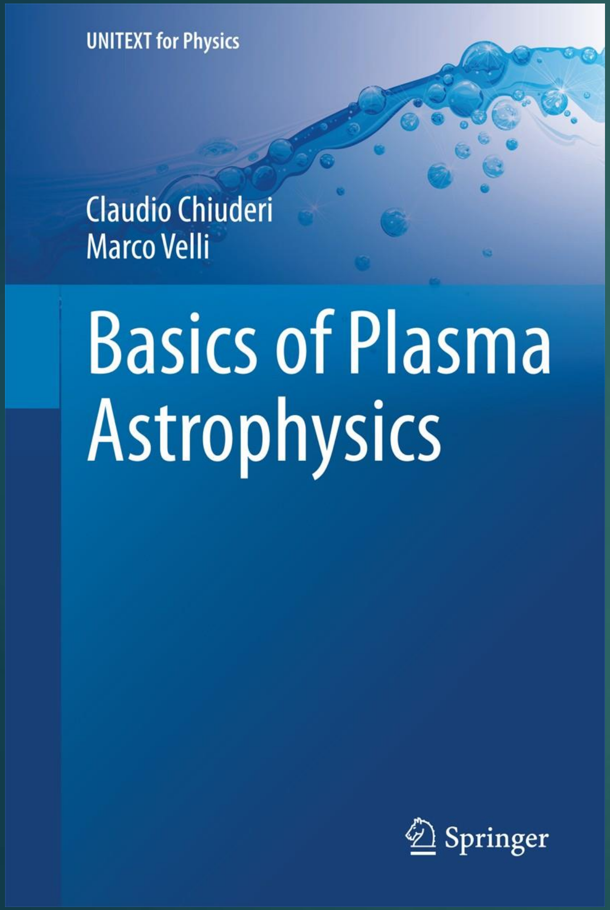
Selected bibliography (3 of 4)



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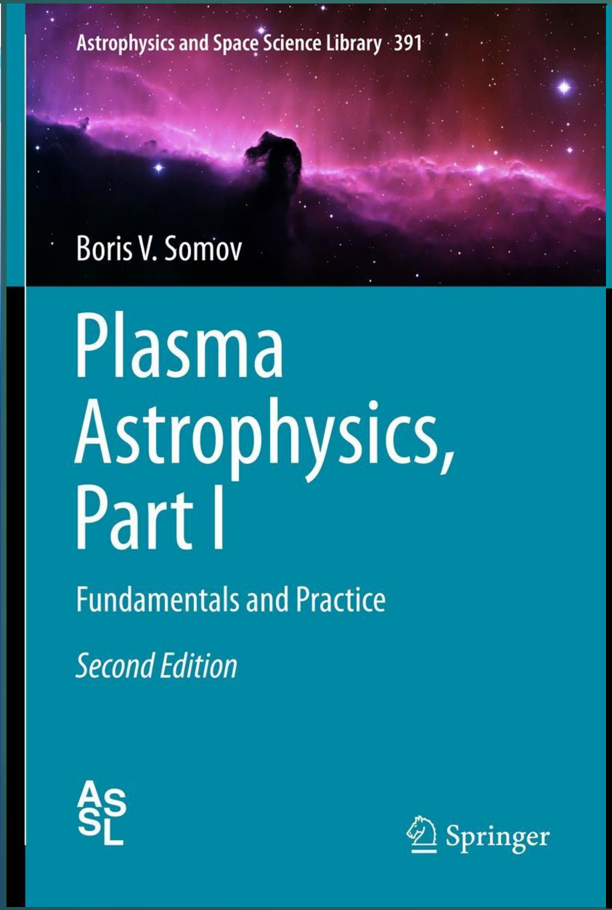

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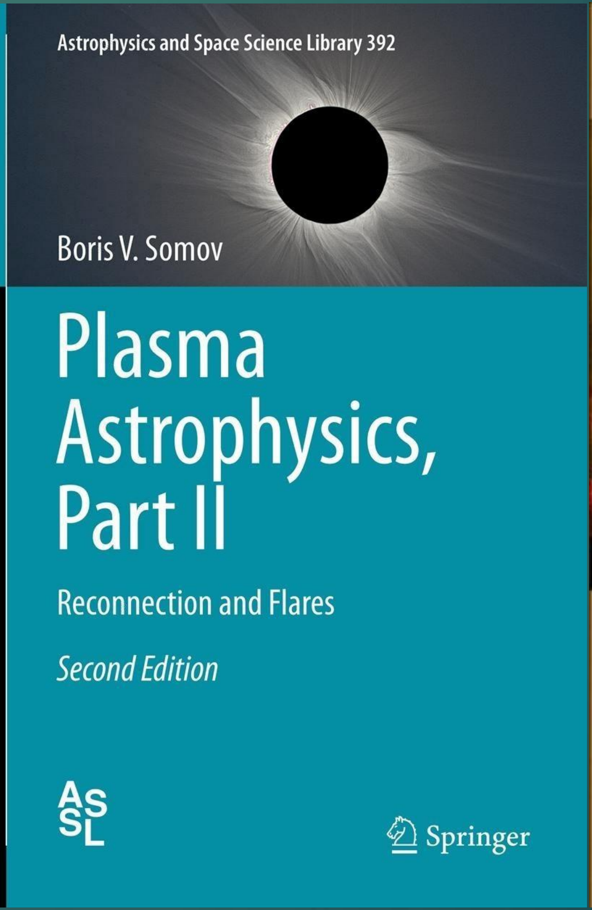

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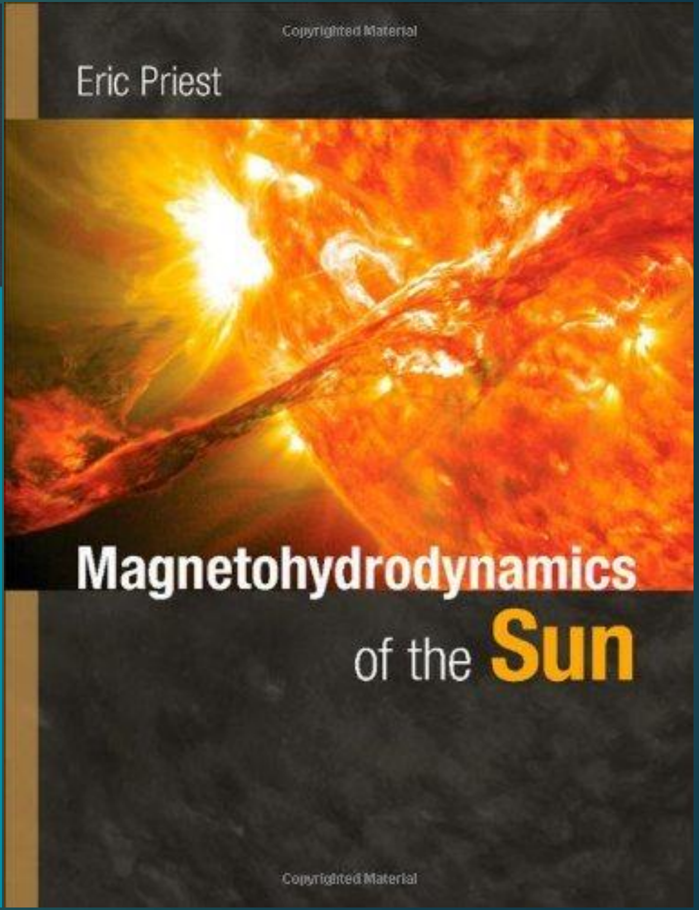

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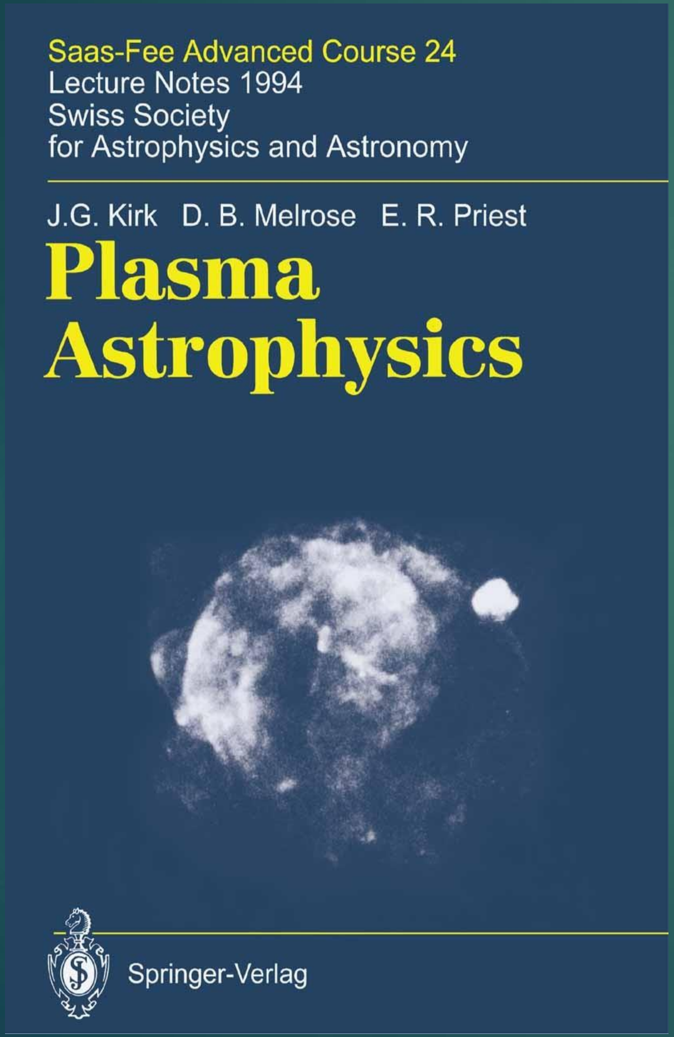

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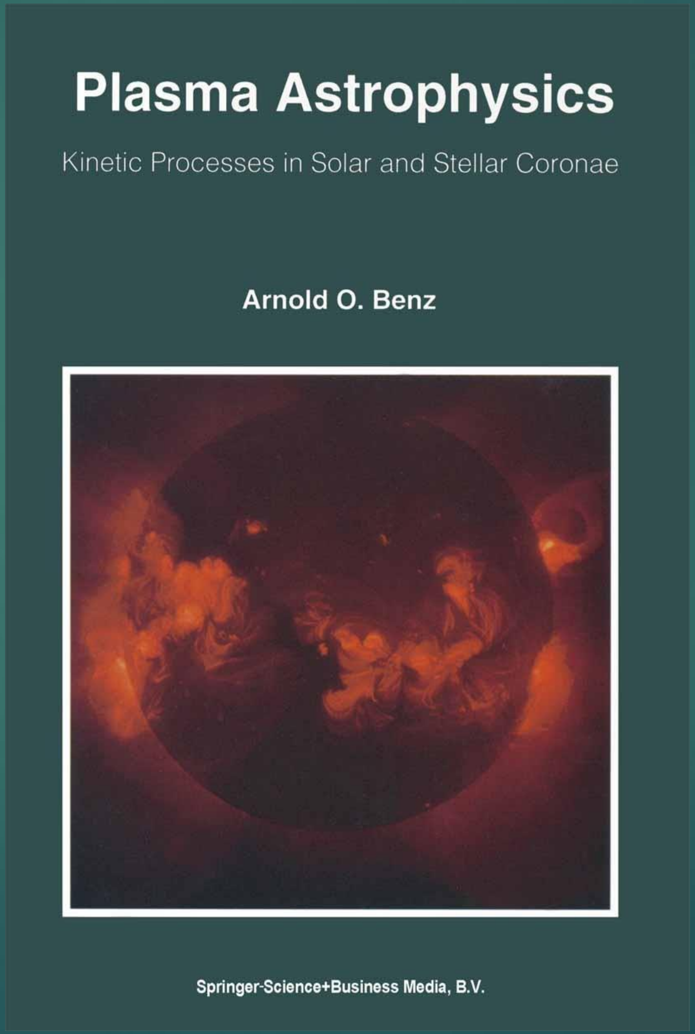

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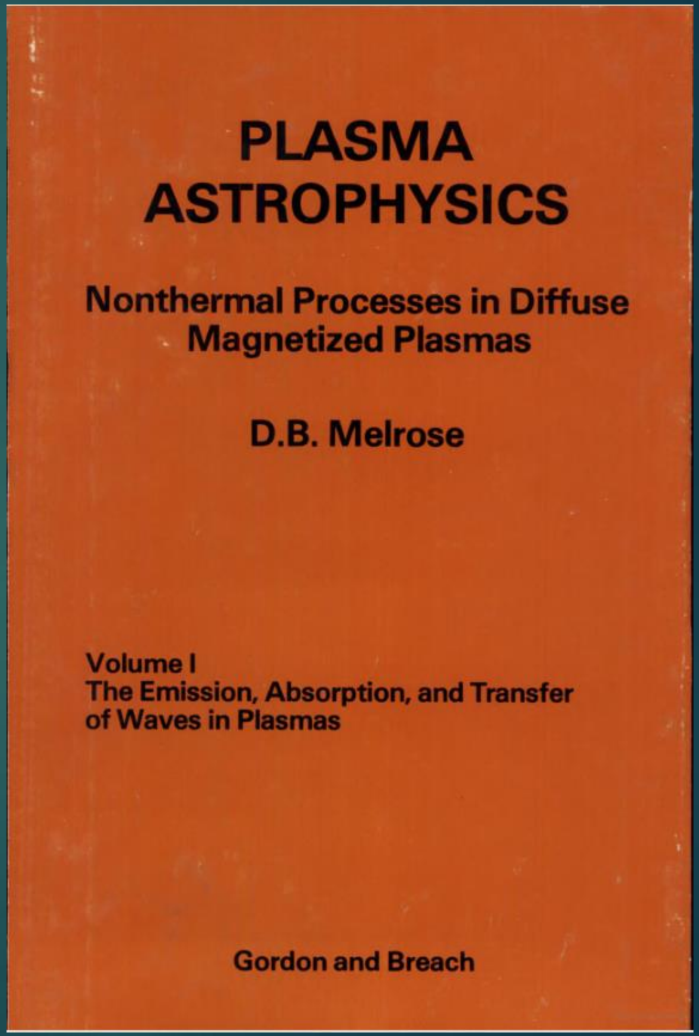

Link


That's all Folks!