Introduction to the Solar Atmosphere

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STFC Introductory Course in Solar and Solar-Terrestrial Physics

PROBA2/SWAP image stack 2012-08-06: https://proba2.sidc.be/

Talk Outline

- Observing the solar atmosphere
- Why is the Sun's atmosphere so hot?
- Role of magnetic field in heating and structuring the atmosphere
- Features/phenomena observed in the solar atmosphere:
  - Sunspots/active regions
  - Prominences/filaments
  - Spicules
  - Waves/oscillations and coronal seismology
  - Extended corona

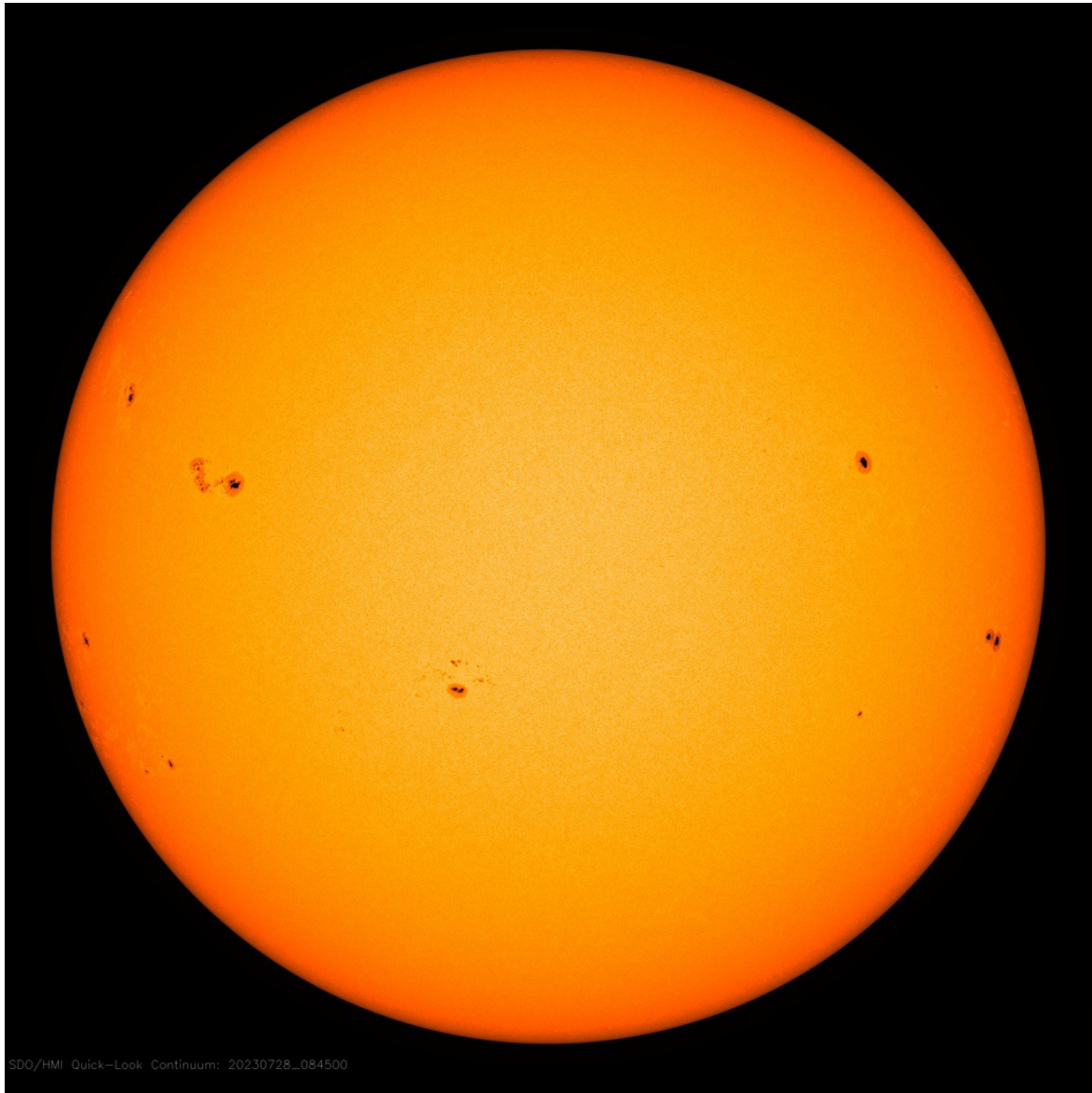
Photosphere: Visible Light

Solar Atmosphere: "the part of the Sun from which photons can escape directly into space." (Priest, 2014)

Photosphere ("surface"):

- Emits most of Sun's visible light.
- Named after Greek word for 'light'.
- $\mathrm{T} \approx 6{,}600\ \mathrm{K}$
- Density ≈ few $\times 10^{-4}\ \mathrm{kg\ m^{-3}}$

(air density in this room $\approx 1.2\ \mathrm{kg\ m^{-3}}$)



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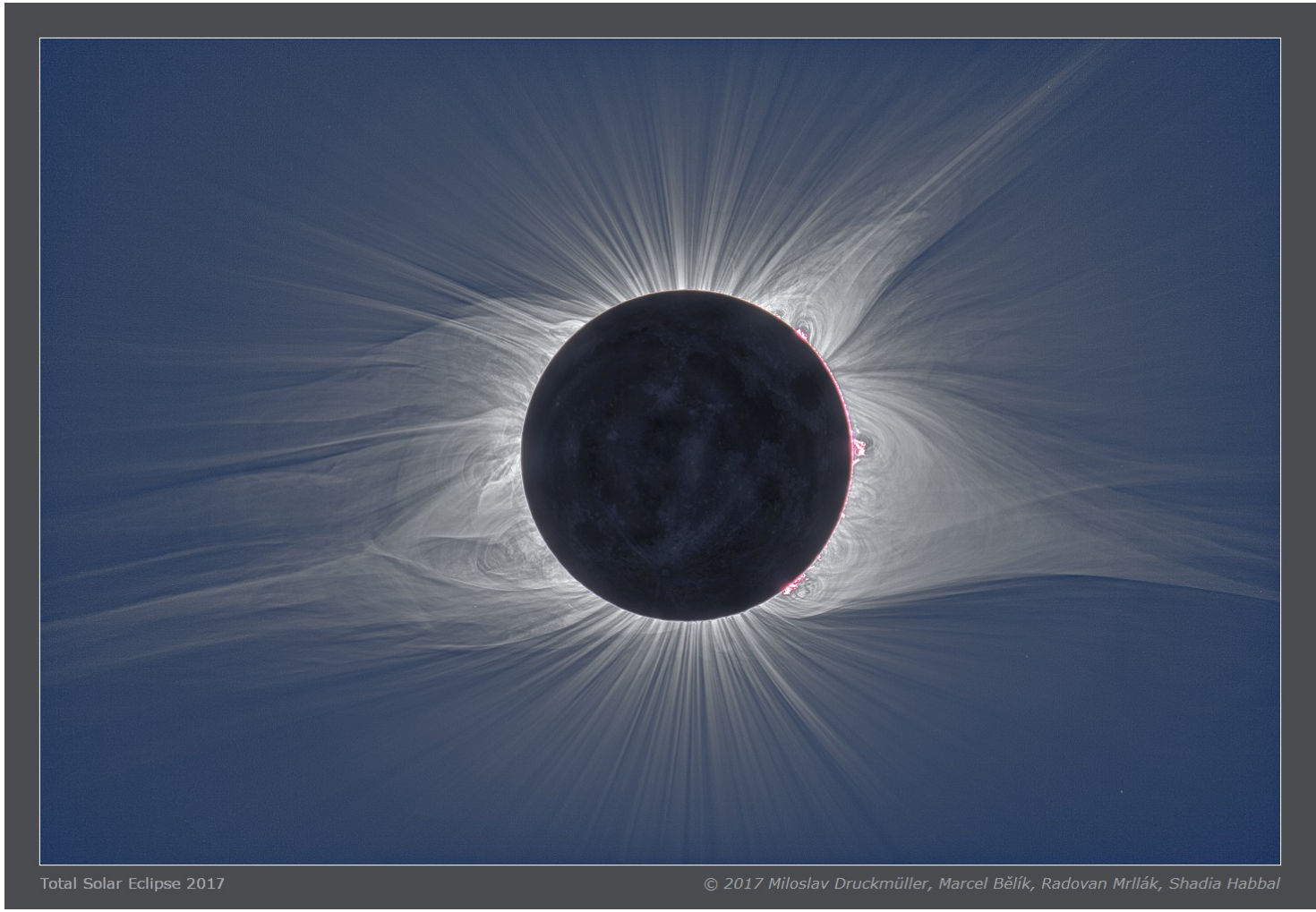
Observing the Solar Atmosphere

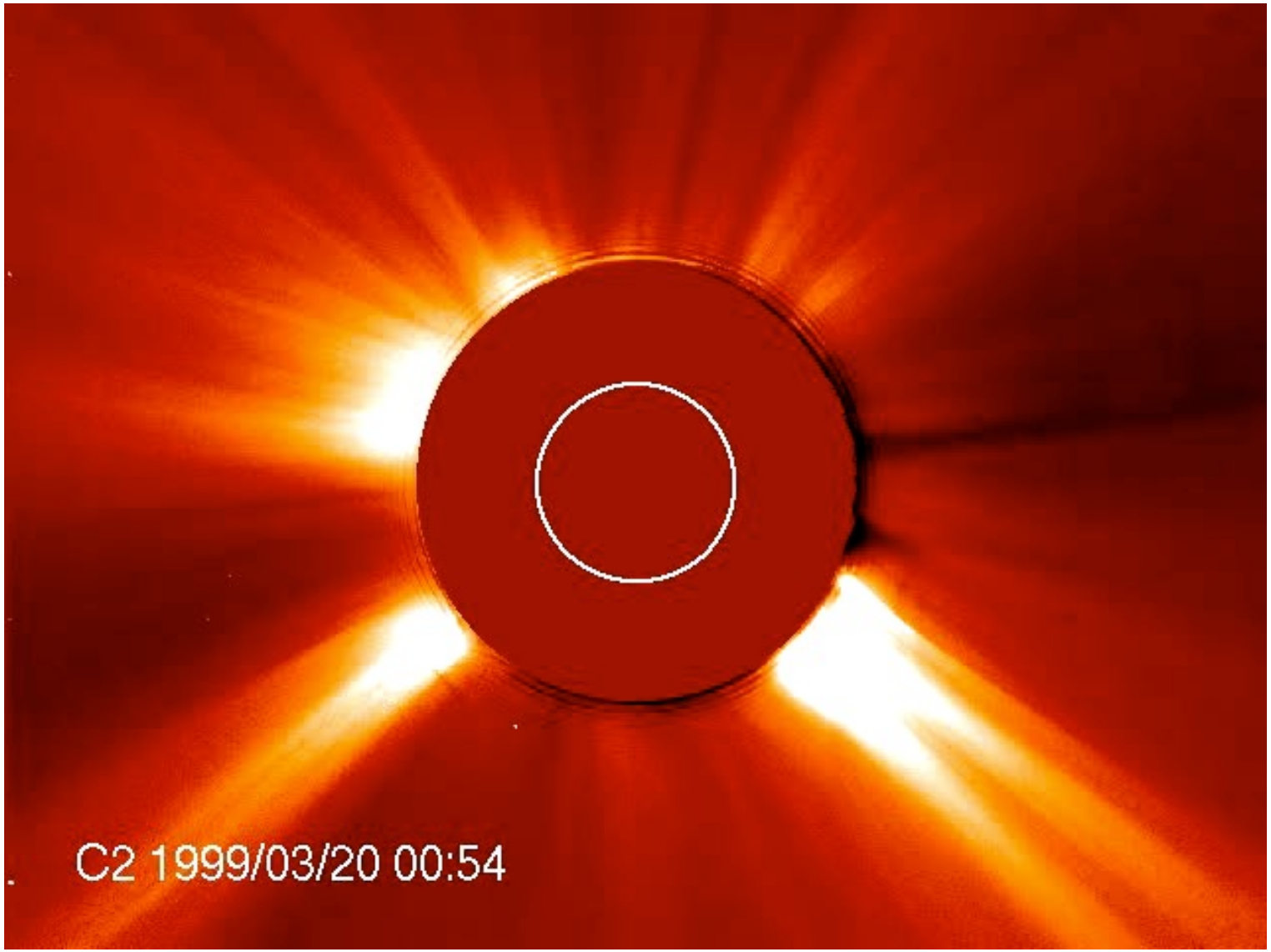
- The corona can be seen in white light during a total solar eclipse.
- In 1868, Secchi detected the emission line of a new element during an eclipse – helium (after Greek Sun god Helios).
- Prominences in red – cooler and denser than coronal plasma.



Composition of 28 eclipse images: www.zam.fme.vutbr.cz/~druck/eclipse/

Artificial Eclipse: Coronagraph

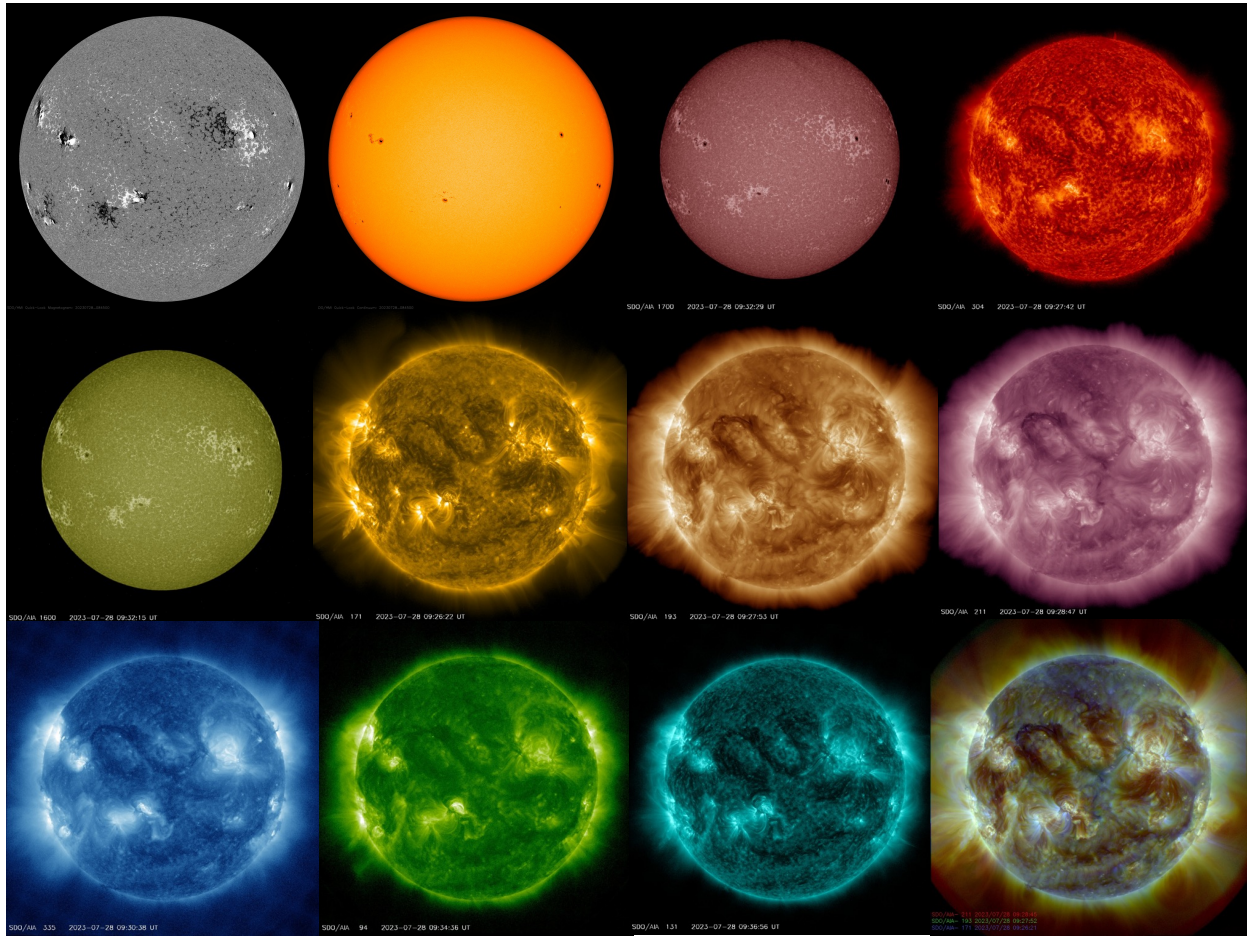
- LASCO C2 instrument on board SOHO (Solar and Heliospheric Observatory).
- Occulter disk: artificial eclipse.
- Solar Wind: material continually flowing outward from Sun (see Stawarz talk next).



Observations from SOHO/LASCO: soho.nascom.nasa.gov/

Observing the Solar Atmosphere

- The Solar Dynamics Observatory (SDO, launched 2010) images the Sun in many wavelengths.
- When heated, gas emits photons in wavelengths characteristic to the elements in the gas.
- Different wavelengths ~different temperatures/layers of solar atmosphere.



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SDO: HMI and AIA Spectral Bands

Band	Primary role, ion(s)	Region of the Sun's atmosphere	Typical Temperature (as log T[K])
6173 Å	HMI scans Fe i 6173	Intensity, velocity, and magnetic field of photosphere	3.7
4500 Å	Continuum	Photosphere	3.7
1700 Å	Continuum	Temperature minimum, photosphere	3.7
304 Å	He ii	Chromosphere, transition region	4.7
1600 Å	C iv, continuum	Transition region, upper photosphere	5
171 Å	Fe ix	Quiet corona, upper transition region	5.8
193 Å	Fe xii, xxiv	Corona and hot flare plasma	6.1, 7.3
211 Å	Fe xiv	Active region corona	6.3
335 Å	Fe xvi	Active region corona	6.4
94 Å	Fe xviii	Flaring regions	6.8
131 Å	Fe xx, xxiii	Flaring regions	7.0, 7.2

HMI: Helioseismic and Magnetic Imager
AIA: Atmospheric Imaging Assembly

sdo.gsfc.nasa.gov/data/channels.php

Photosphere
($T \approx 6{,}600$ K)

↓

Chromosphere
($T \approx 10{,}000$ K)

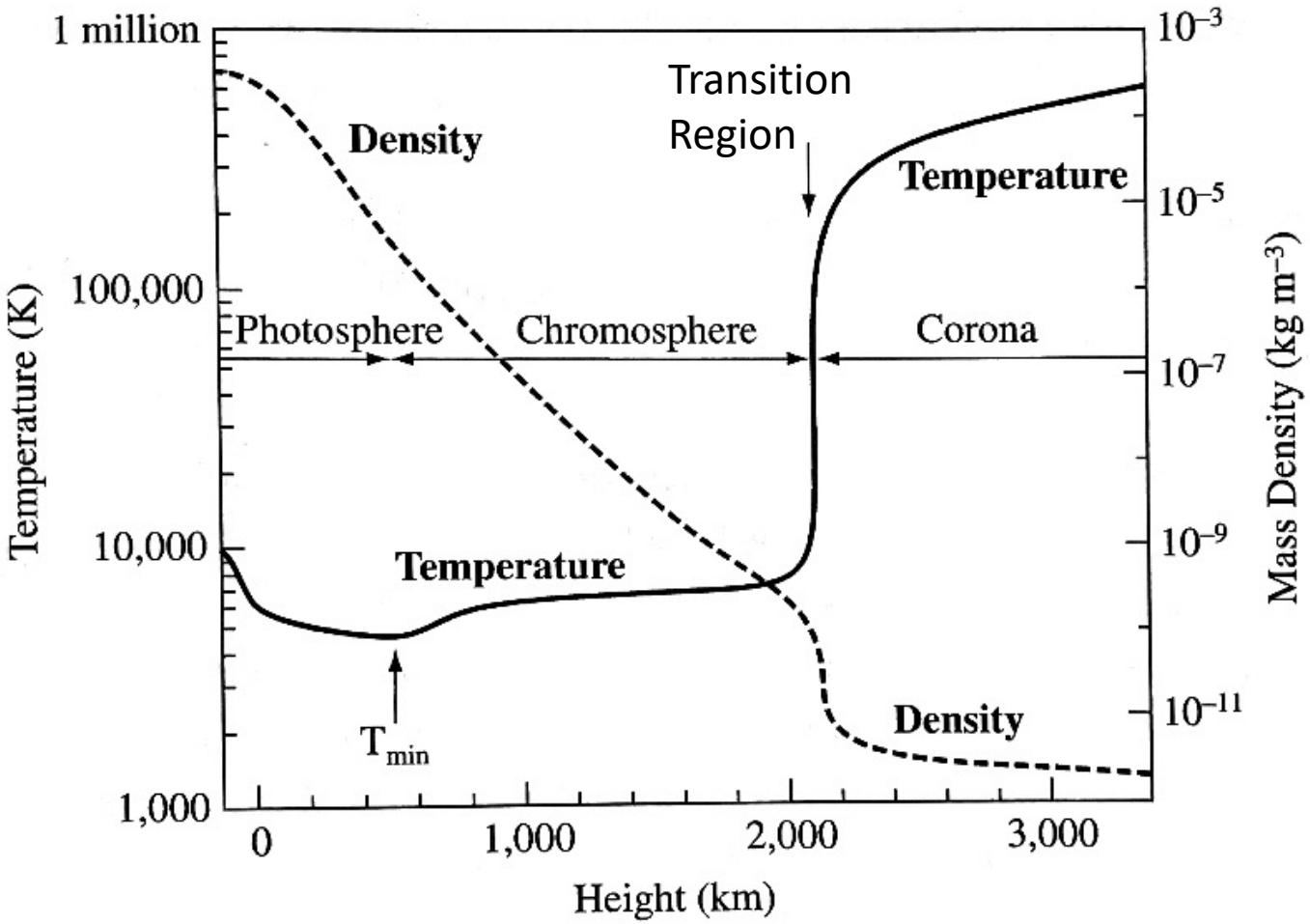
↓

Corona
($T > 1{,}000{,}000$ K)

Observations from SOHO: soho.nascom.nasa.gov/

Mean Variation in Density and Temperature

- Vernazza-Avrett-Loeser (VAL) model of solar atmosphere (1981).
- 1D model, simplification.
- Photosphere ~500 km thick.
- Sharp gradients in temperature and density in narrow transition region (TR) <100 km thick.



Priest (2014), courtesy of G. Avrett

Why is the corona so hot?

- Temperature of corona indicates that it requires some non-thermal energy input.
- Magnetic fields have a key role in heating the corona.
  - Plot: relationship between X-ray spectral radiance and magnetic flux.
- Energy transported upwards from photosphere by magnetic field and dissipated.
- Exact mechanism(s) are still unclear.

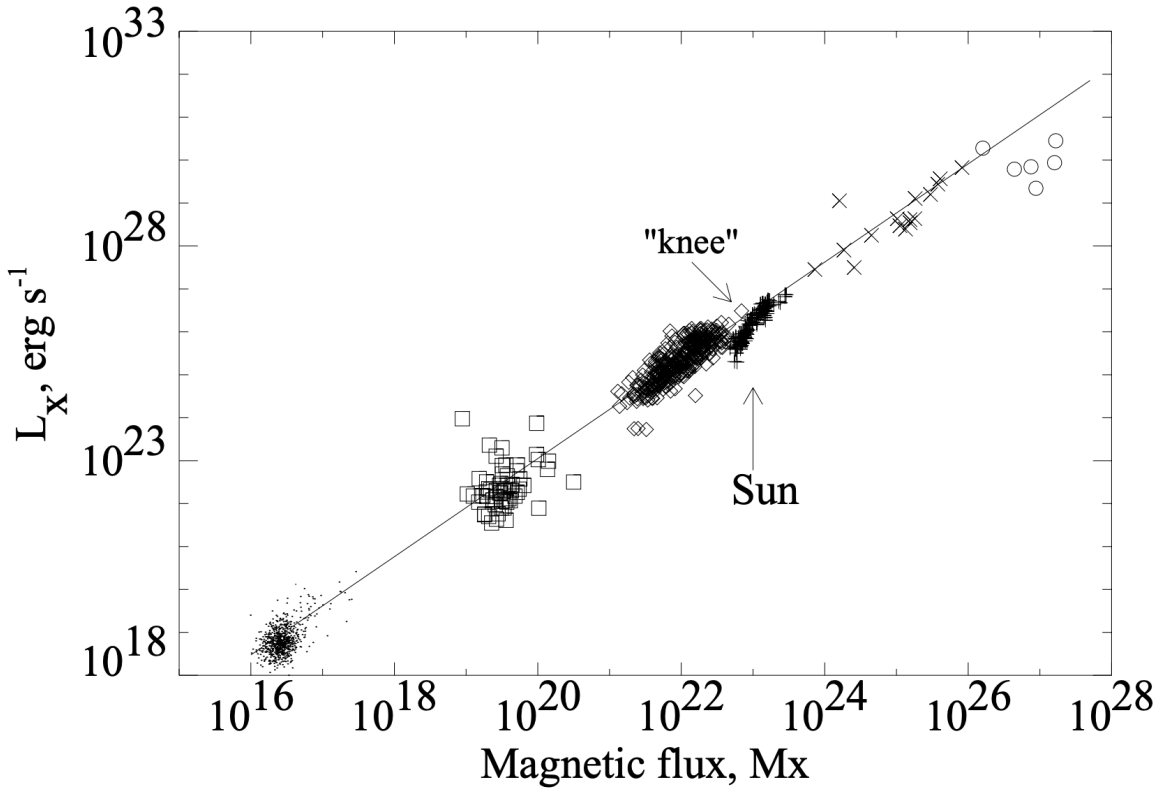


FIG. 1.—X-ray spectral radiance L_X vs. total unsigned magnetic flux for solar and stellar objects. *Dots*: Quiet Sun. *Squares*: X-ray bright points. *Diamonds*: Solar active regions. *Pluses*: Solar disk averages. *Crosses*: G, K, and M dwarfs. *Circles*: T Tauri stars. *Solid line*: Power-law approximation $L_X \propto \Phi^{1.15}$ of combined data set.

Pevtsov et al. (2003): "The relationship between X-ray radiance and magnetic flux"

Energy requirements

Combined radiative and conductive losses ($\mathrm{erg\ cm^{-2}\ s^{-1}}$) in the chromosphere and corona (Withbroe & Noyes, 1977):

	Quiet Sun	Active Region
Chromosphere	4×10^{6}	2×10^{7}
Corona	3×10^{5}	10^{7}

- Chromosphere actually requires more energy to sustain than corona.
- Where does the energy come from?

Energy Injection

Turbulent convective motions move the footpoints of magnetic field lines at the photosphere and:

- quasi-statically stress the field (slow motions, long timescales) – DC heating.
- generate waves (fast motions, short timescales) – AC heating.

It can be shown (see, e.g. Klimchuk (2006), Parnell & De Moortel (2012), Priest (2014)) that these footpoint motions inject more than enough energy to heat the solar atmosphere.

Energy Injection

Energy transported into/out of solar atmosphere by Poynting flux through surface (see Parnell & De Moortel, 2012):

$$S = \frac{1}{\mu_0} \iint_{S_\circ} \mathbf{E} \times \mathbf{B} \cdot \mathbf{dS}$$

- $\mathbf{E}$ electric field
- $\mathbf{B}$ magnetic field
- $S_\circ$ solar surface
- μ_0 magnetic permeability

Assume ideal motions and write $\mathbf{B}$ and $\mathbf{v}$ in terms of components parallel (p) and perpendicular/normal (n) to solar surface. Poynting flux per unit area through solar surface:

$$\frac{1}{\mu_0}(\mathbf{E} \times \mathbf{B}) \cdot \hat{\mathbf{n}} = \underbrace{-\frac{1}{\mu_0}(\mathbf{B}_p \cdot \mathbf{v}_p) B_n}_{\text{Footpoint movement due to horizontal convective motions}} + \underbrace{\frac{1}{\mu_0}(\mathbf{B}_p \cdot \mathbf{B}_p) v_n}_{\text{Emergence or submergence of magnetic flux}}$$

$\hat{\mathbf{n}}$ outward normal to solar surface

Energy Injection

Poynting flux per unit area through solar surface:

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Footpoint movement due to horizontal convective motions

Quiet Sun $\approx 2.5\times10^7\ \mathrm{erg\ cm^{-2}\ s^{-1}}$

Active region $\approx 1.2\times10^9\ \mathrm{erg\ cm^{-2}\ s^{-1}}$

Emergence or submergence of magnetic flux

Emergence of Quiet Sun magnetic flux $\approx 10^6\ \mathrm{erg\ cm^{-2}\ s^{-1}}$

(see Parnell & De Moortel, 2012)

Energy Injection

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Radiative and conductive losses (Withbroe & Noyes, 1977):

	Quiet Sun	Active Region
Chromosphere	4×10^6	2×10^7
Corona	3×10^5	10^7

- More than enough energy injected.
- Horizontal motions dominant over emergence.
- How is this energy transported and dissipated?

Energy Transport and Dissipation

DC heating: slow, quasi-static stressing of magnetic field:

- Twisting/braiding of magnetic field -> current sheet formation.
- Magnetic reconnection (C. Parnell talk earlier).
- Ohmic dissipation at reconnection site, viscous damping of waves, shocks, outflow jets – which mechanism(s) dominate?

Energy Transport and Dissipation

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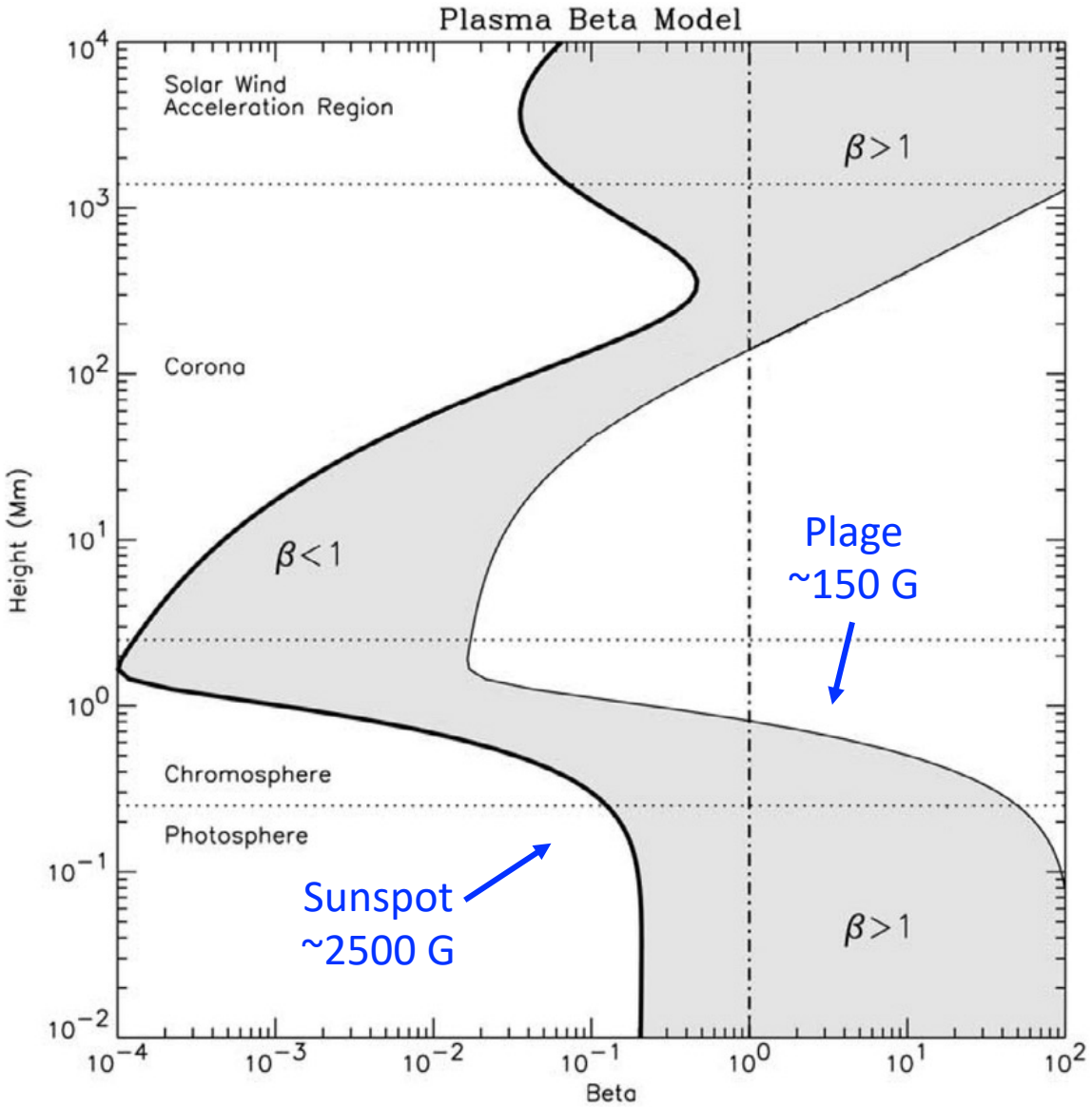
AC heating: fast, short timescale motions generate waves (T. Howson talk yesterday):

- Only a fraction of wave energy transported into corona: steep temperature/density gradients in chromosphere/TR -> strong damping, reflection, refraction.
- Alfvèn waves penetrate more effectively into corona. Mechanism(s) for dissipation?
- Waves generated within corona – can they transport sufficient energy?

Magnetic Field Structures the Corona



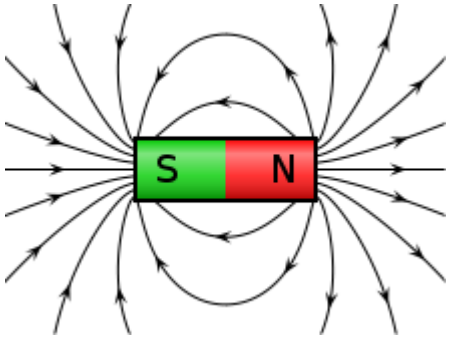
Verscharen (2012), adapted from Gary (2001)

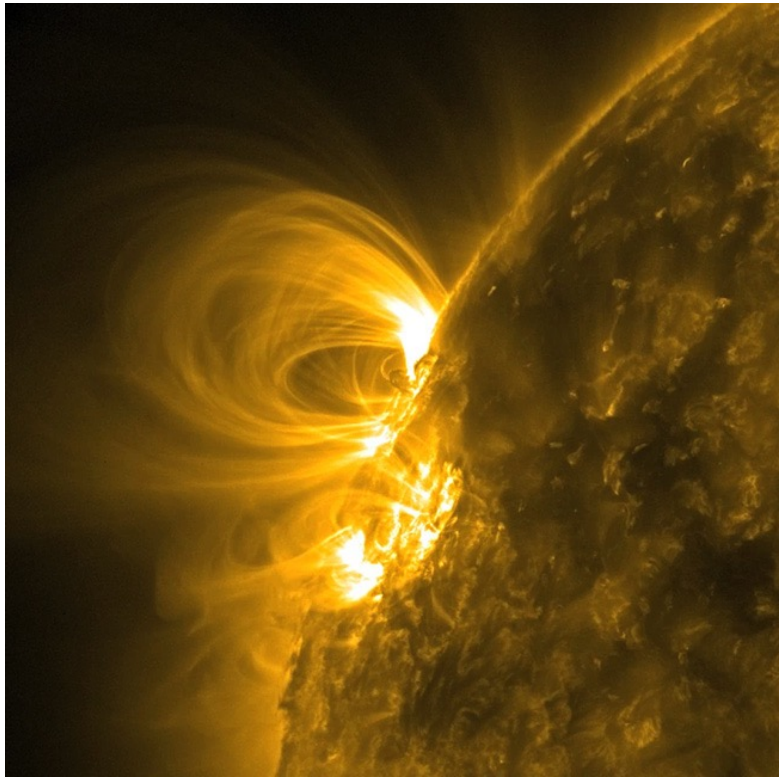
Plasma beta:

$$\beta = \frac{\text{gas pressure}}{\text{magnetic pressure}} = \frac{p}{B^2/2\mu_0}$$

$\beta \gg 1$ gas pressure dominates

$\beta \ll 1$ magnetic pressure dominates





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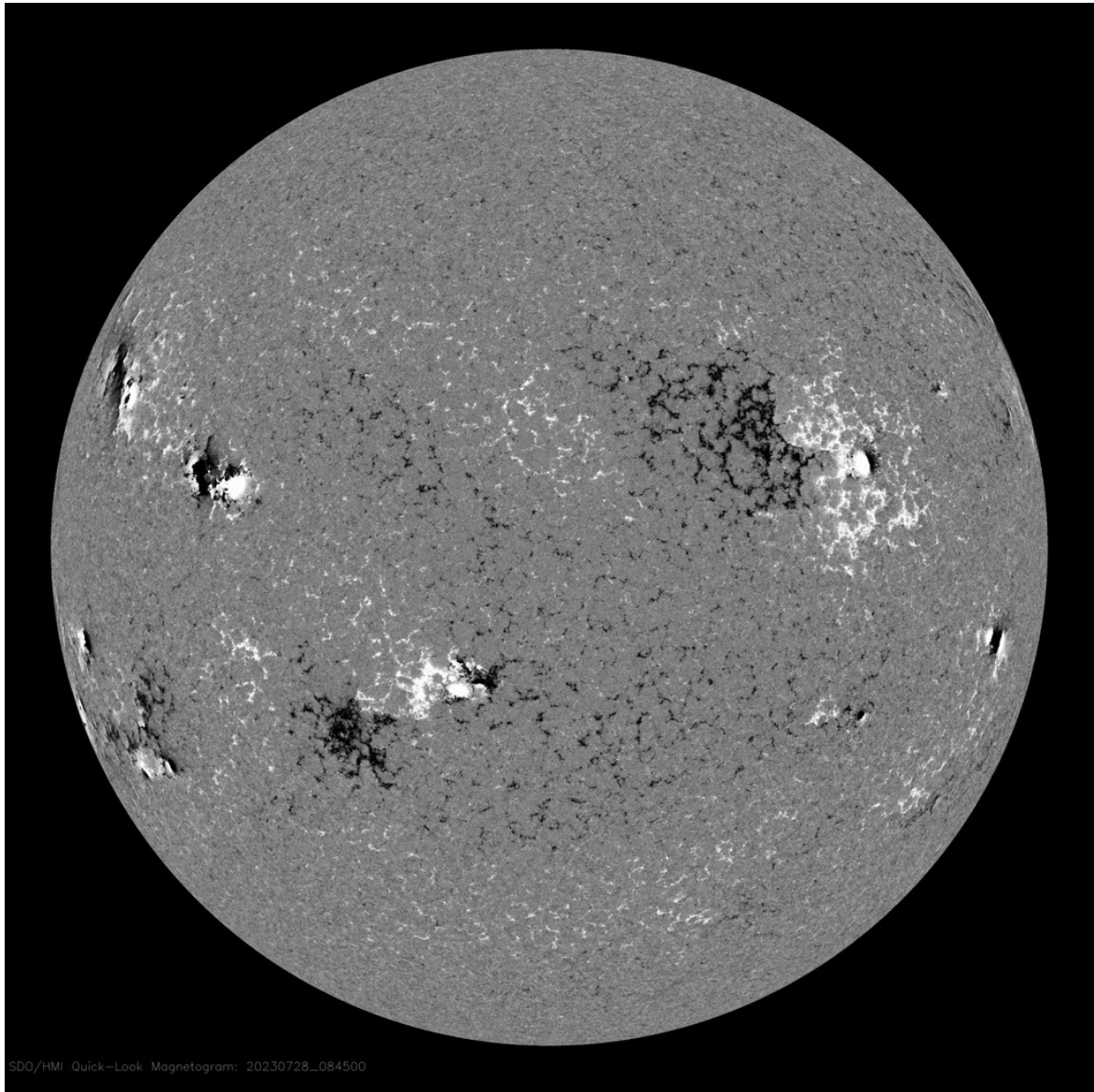
Magnetograms

- Zeeman effect: splitting of spectral lines in presence of magnetic field (Zeeman, 1896).

- 1908: George Hale observed the Zeeman effect in the spectrum of sunspots – evidence for strong magnetic fields.

- Aspects of the Zeeman splitting are used to measure Line-of-Sight (LOS) and transverse (for strong field) components of magnetic field.



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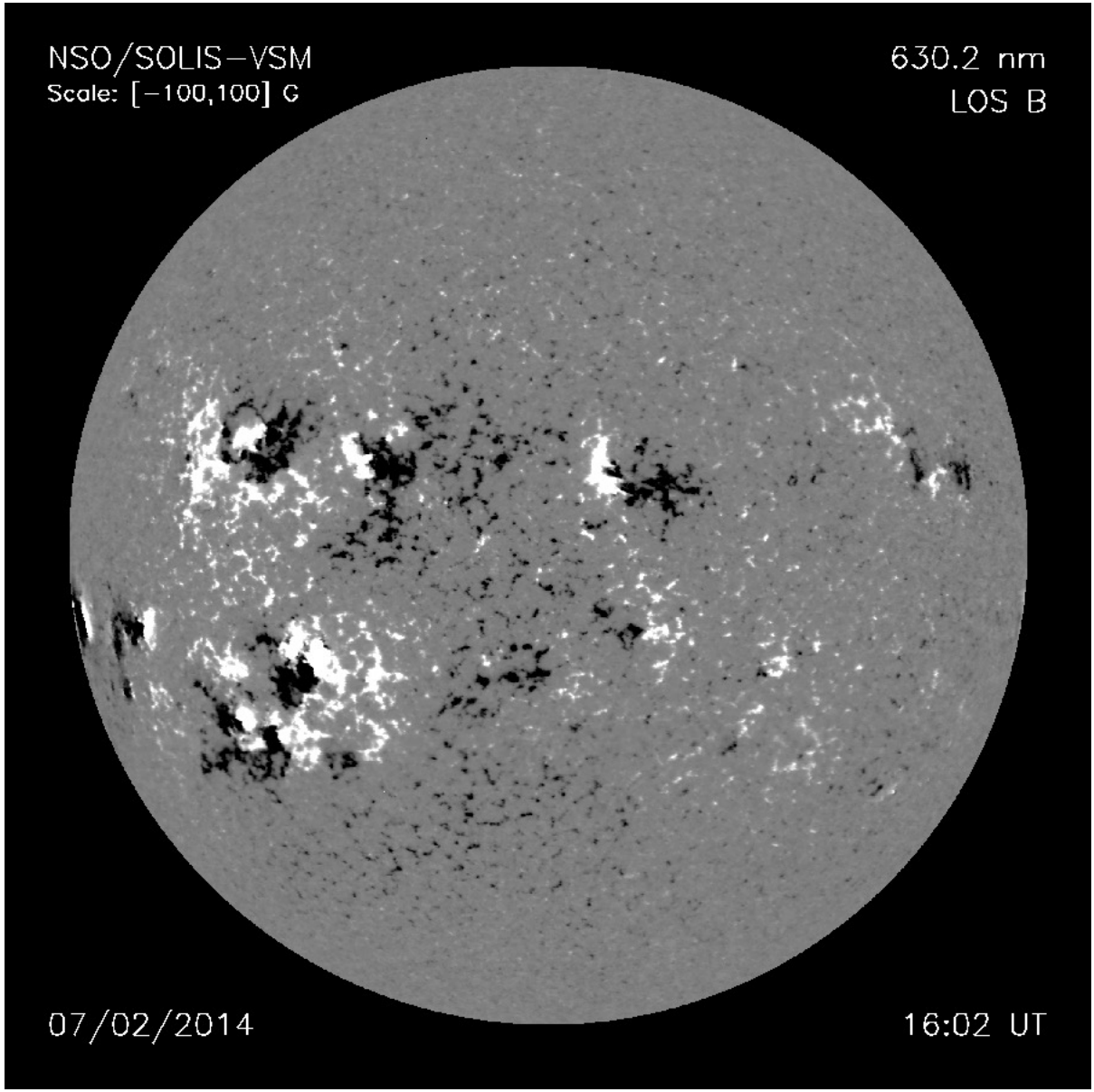
Magnetograms

- Photospheric and chromospheric magnetograms can be constructed.

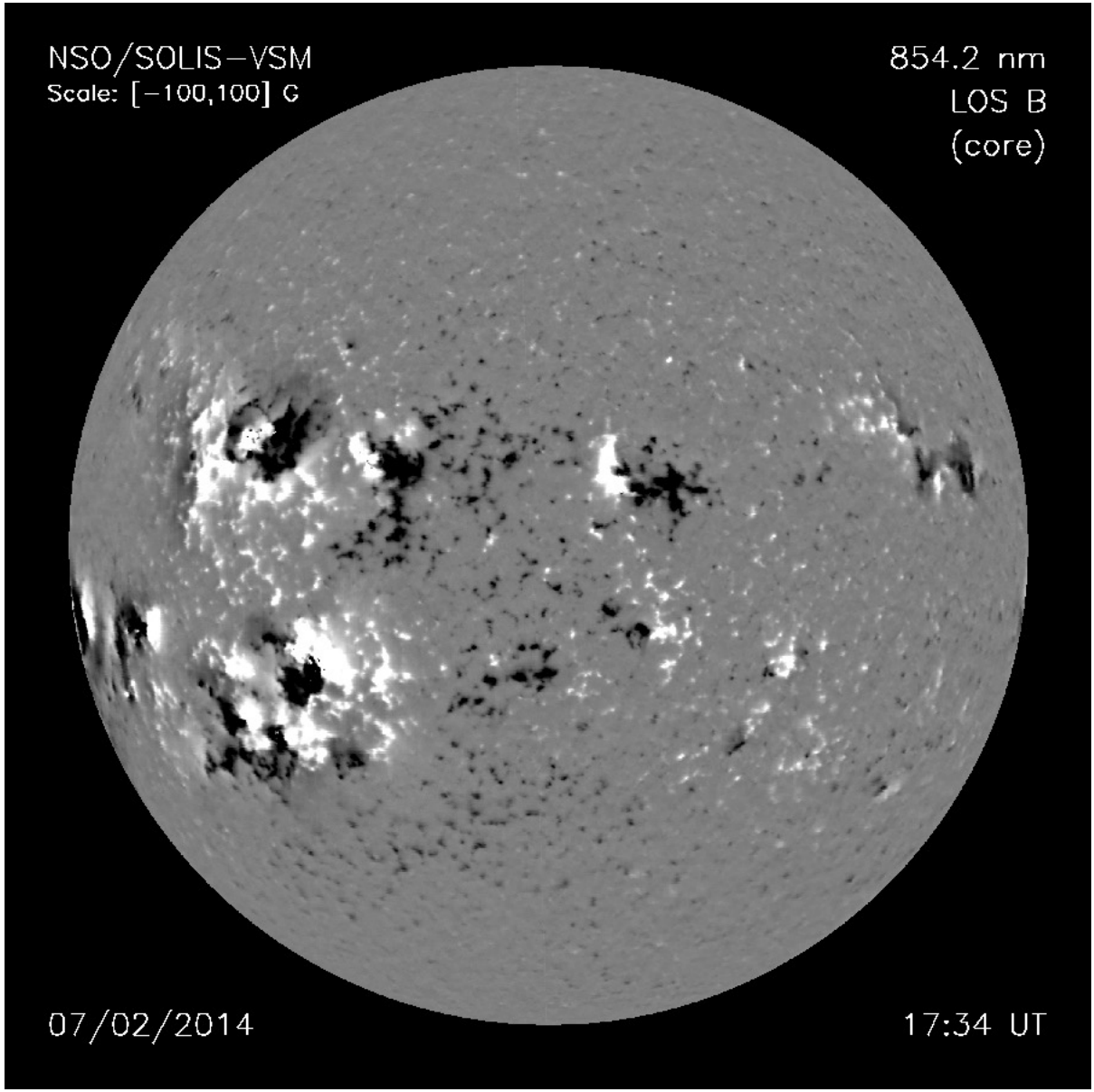
- Right: LOS photospheric magnetogram (B_r) observed by ground-based telescope SOLIS in 2014.



Magnetograms

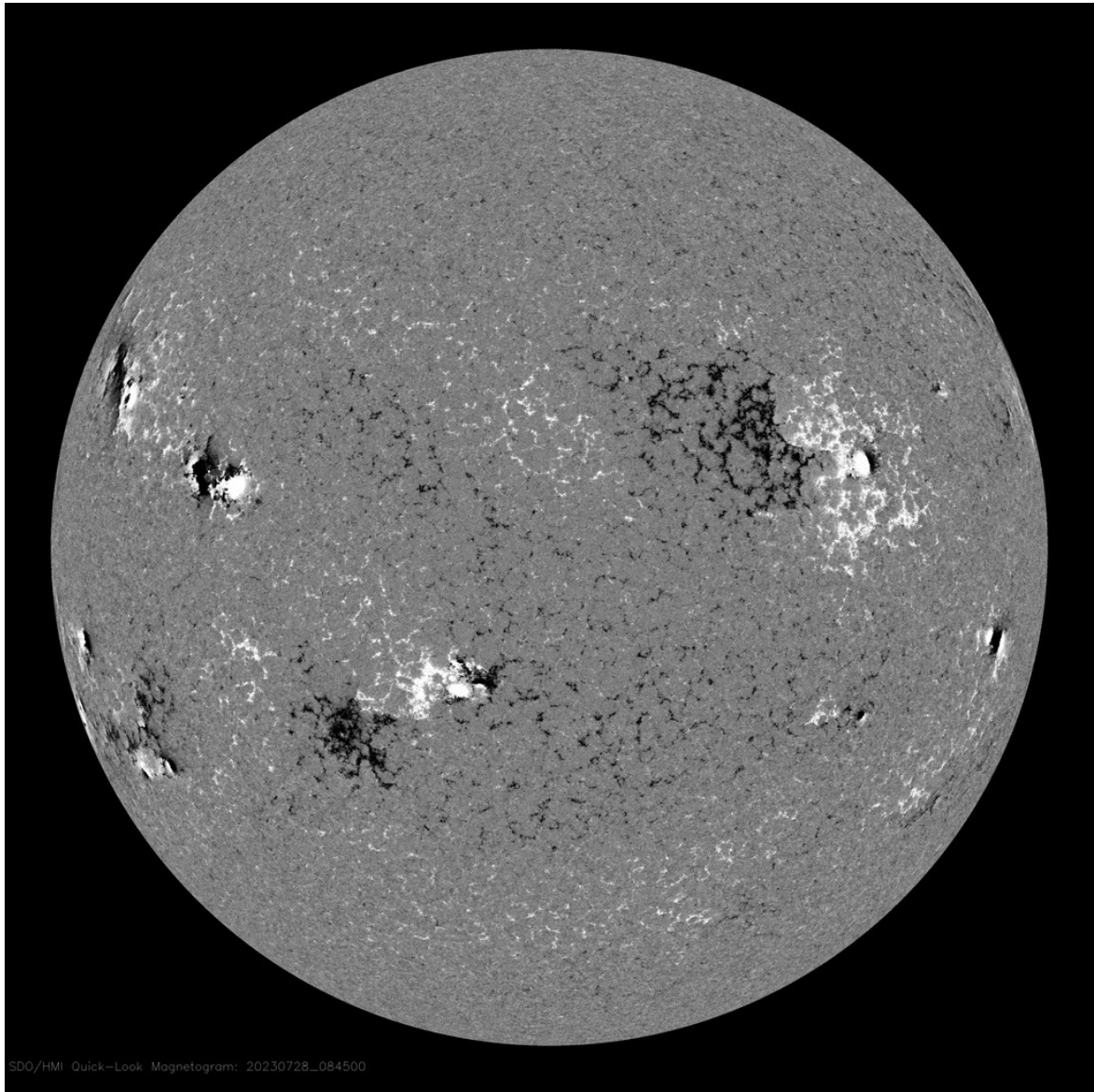
- LOS chromospheric magnetogram observed by SOLIS using Ca II 854.2 nm line.

- Can see the effect of expansion of magnetic flux tubes with height in the solar atmosphere.



Magnetograms

- Returning to the SDO magnetogram…



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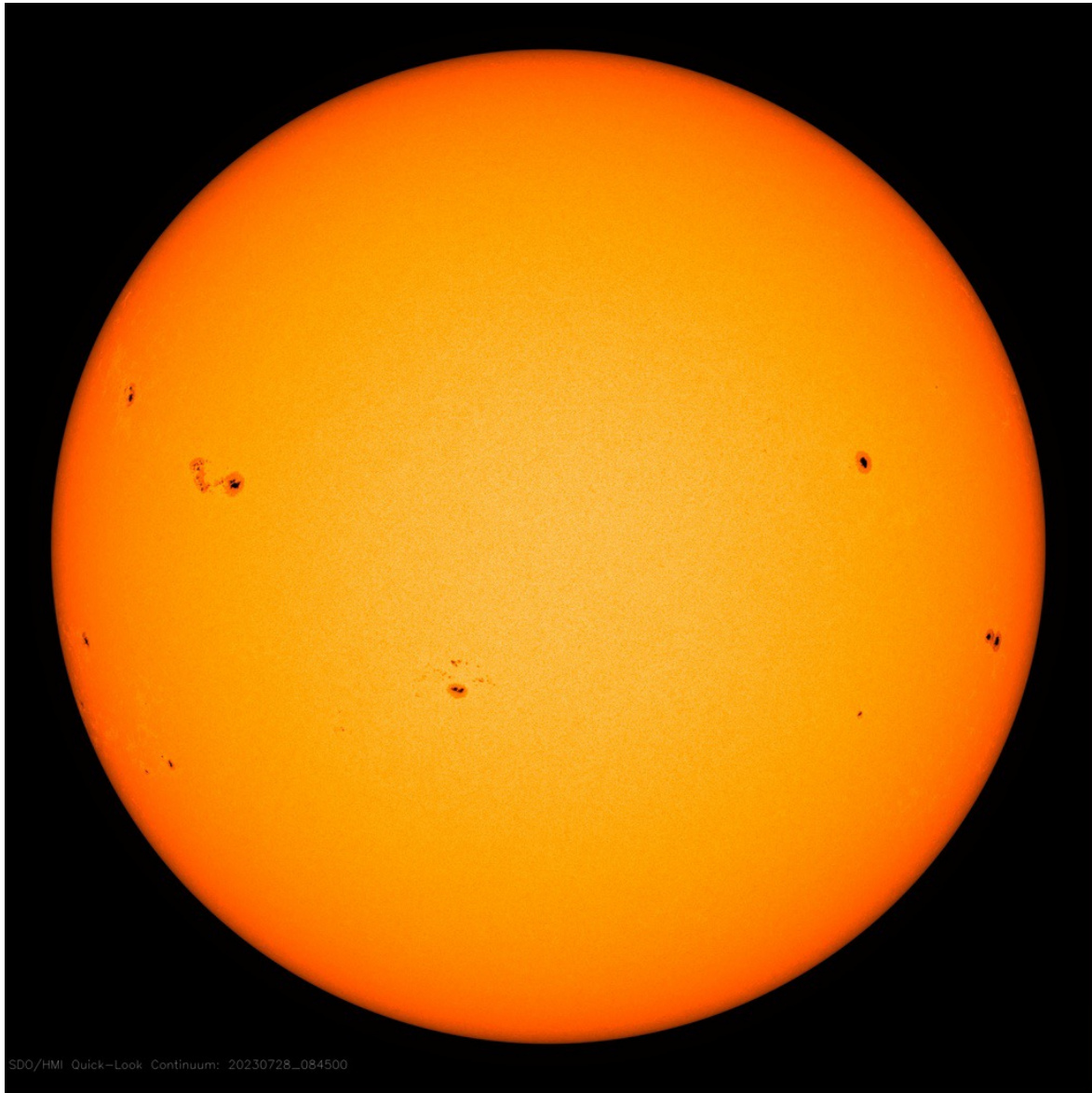
Photosphere: Visible Light

- $T \approx 6{,}600$ K
- Sunspots: peak magnetic field ~few x 1000 G.
- Intense magnetic field inhibits energy transport: 1000 – 1900 K cooler than surrounding plasma, so they appear darker.



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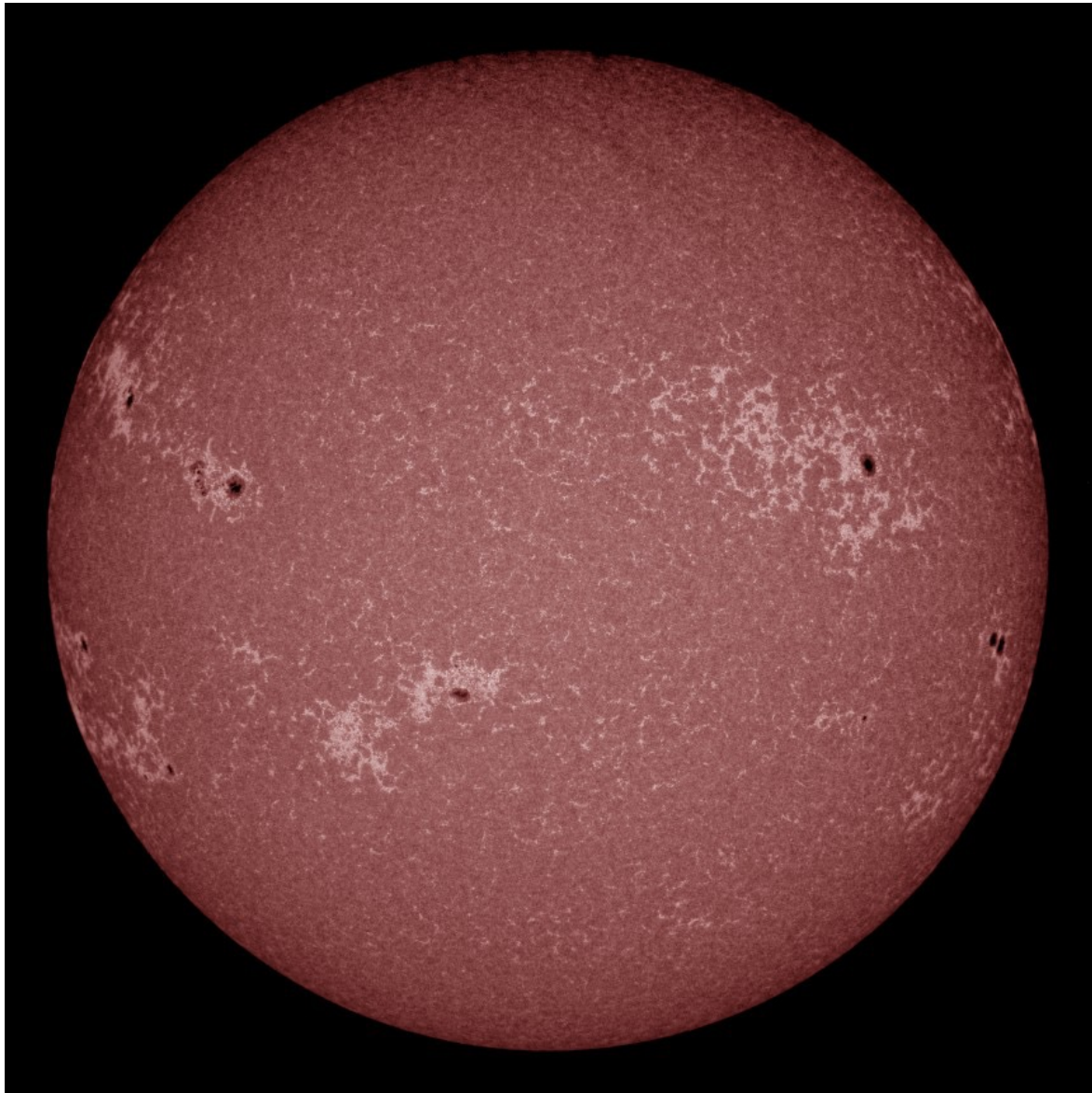
Photosphere: Temperature Min 1700 Å

- $T \approx 4{,}300$ K
- Plage: bright regions associated with magnetic field.



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Sunspots: Photosphere

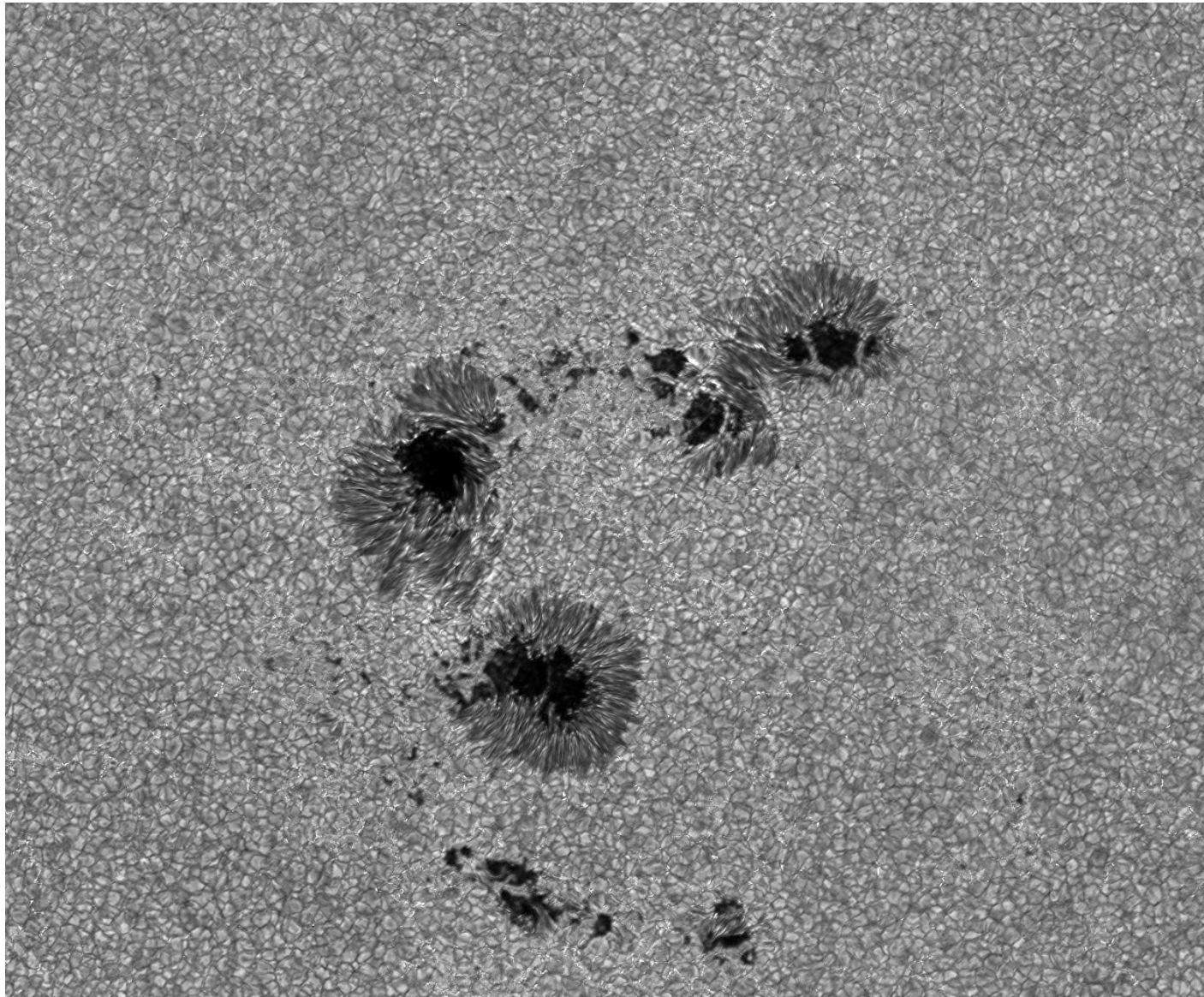
AR 10786 observed by the Dutch Open Telescope (DOT).

G-band (4305-4315 Å, ~100 km above white light photosphere).

Sunspot umbra (dark region) surrounded by penumbra.

Granules (convective cells) surround sunspot.

Bright flux tubes in intergranular lanes.



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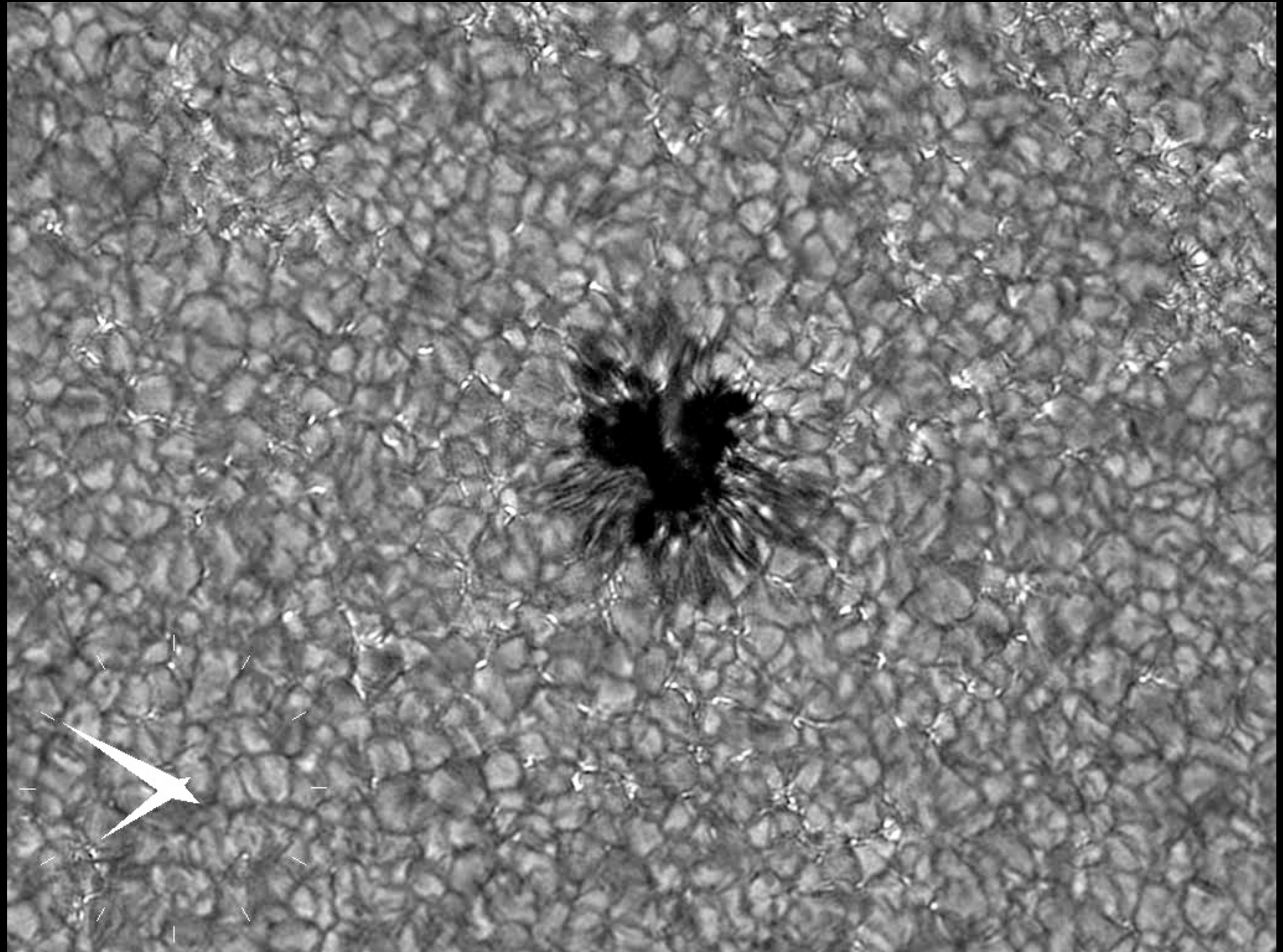
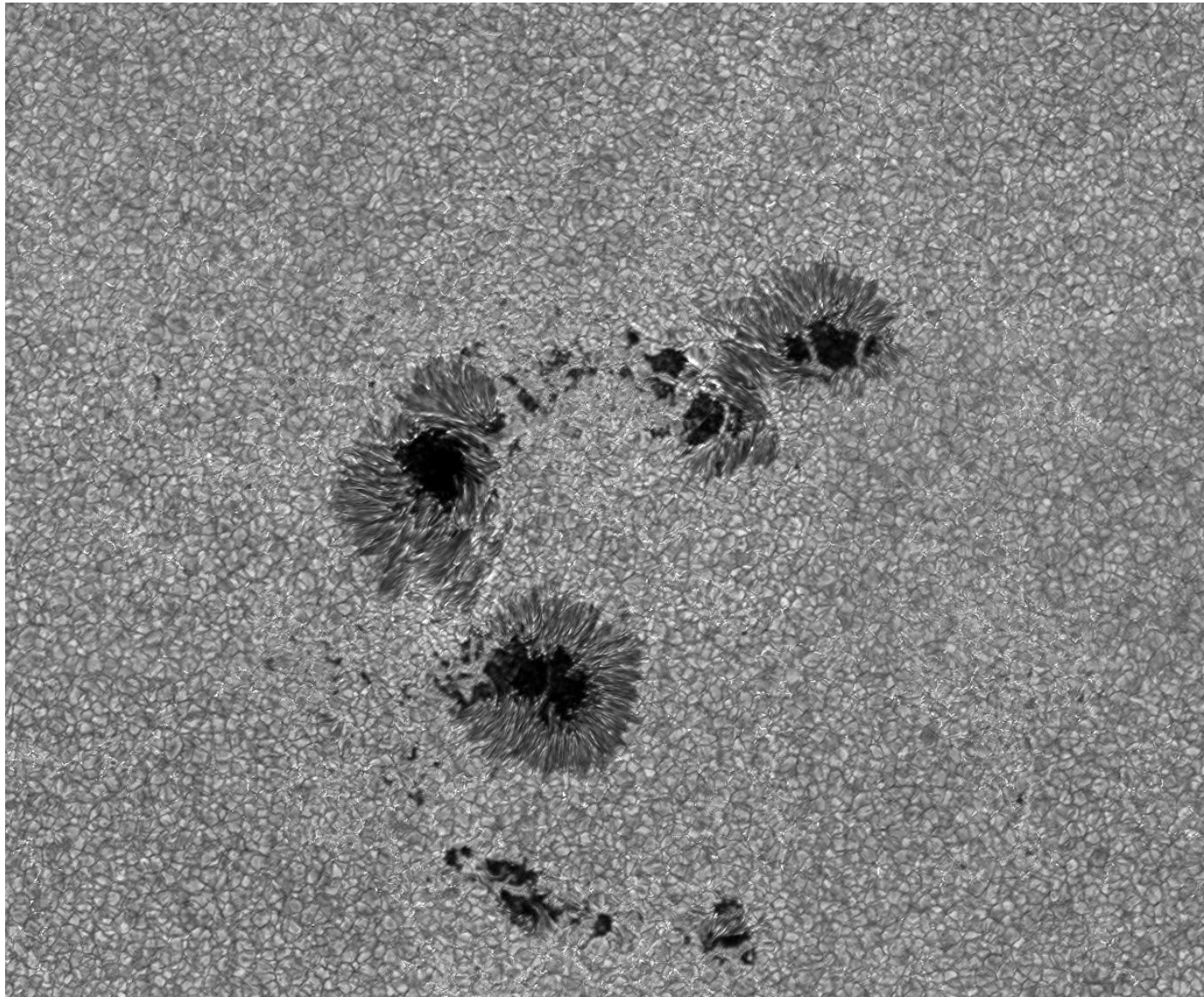
AR 10789



Sunspots: Photosphere

Returning to AR 10786…



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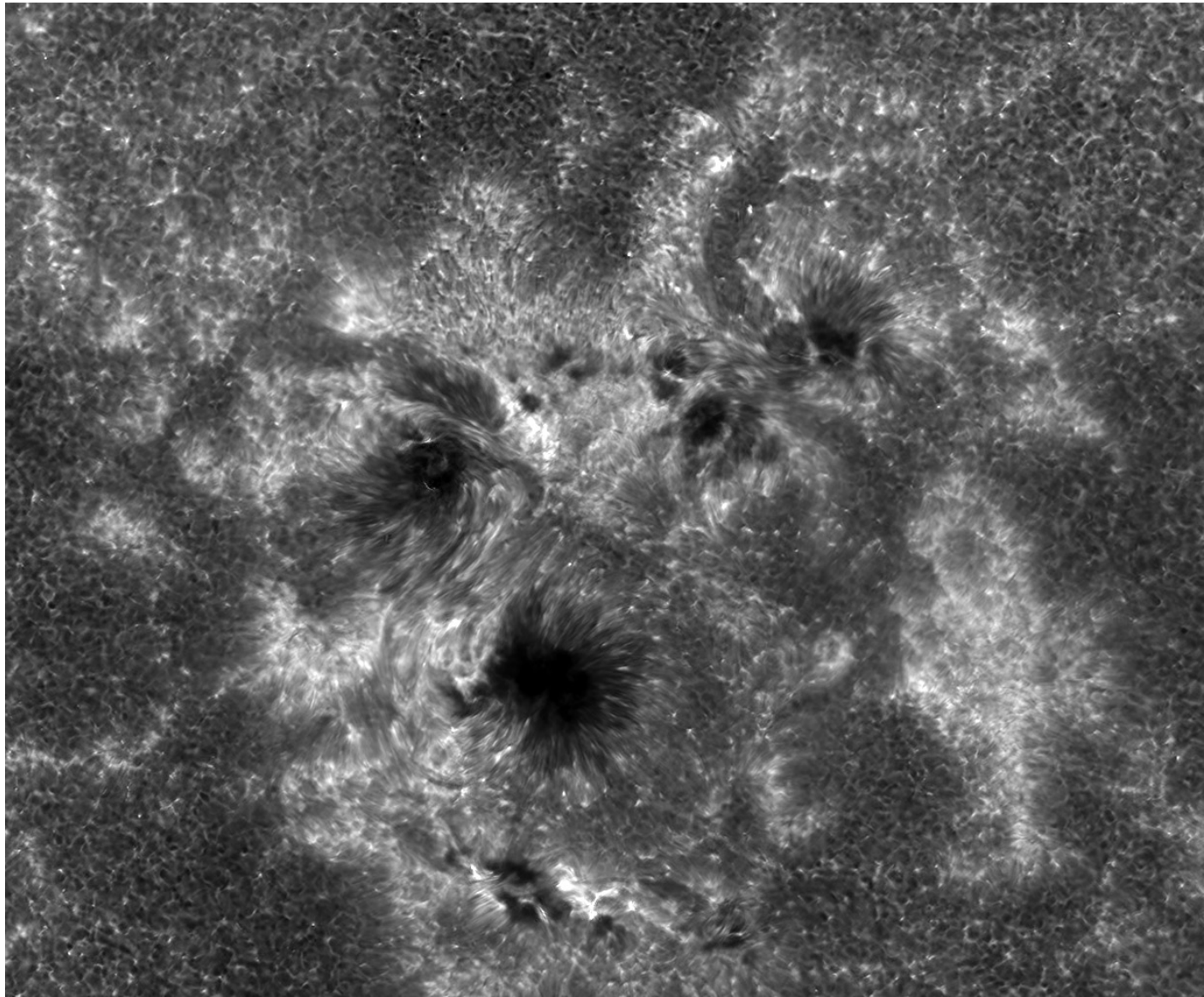
Sunspots: Photosphere

AR 10786 observed by DOT.

Ca II H line – due to once-ionized Calcium (3985 Å)

Few x 100 km above white light photosphere.

Bright magnetic plages regions.



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Sunspots: Chromosphere

AR 10786 observed by DOT.

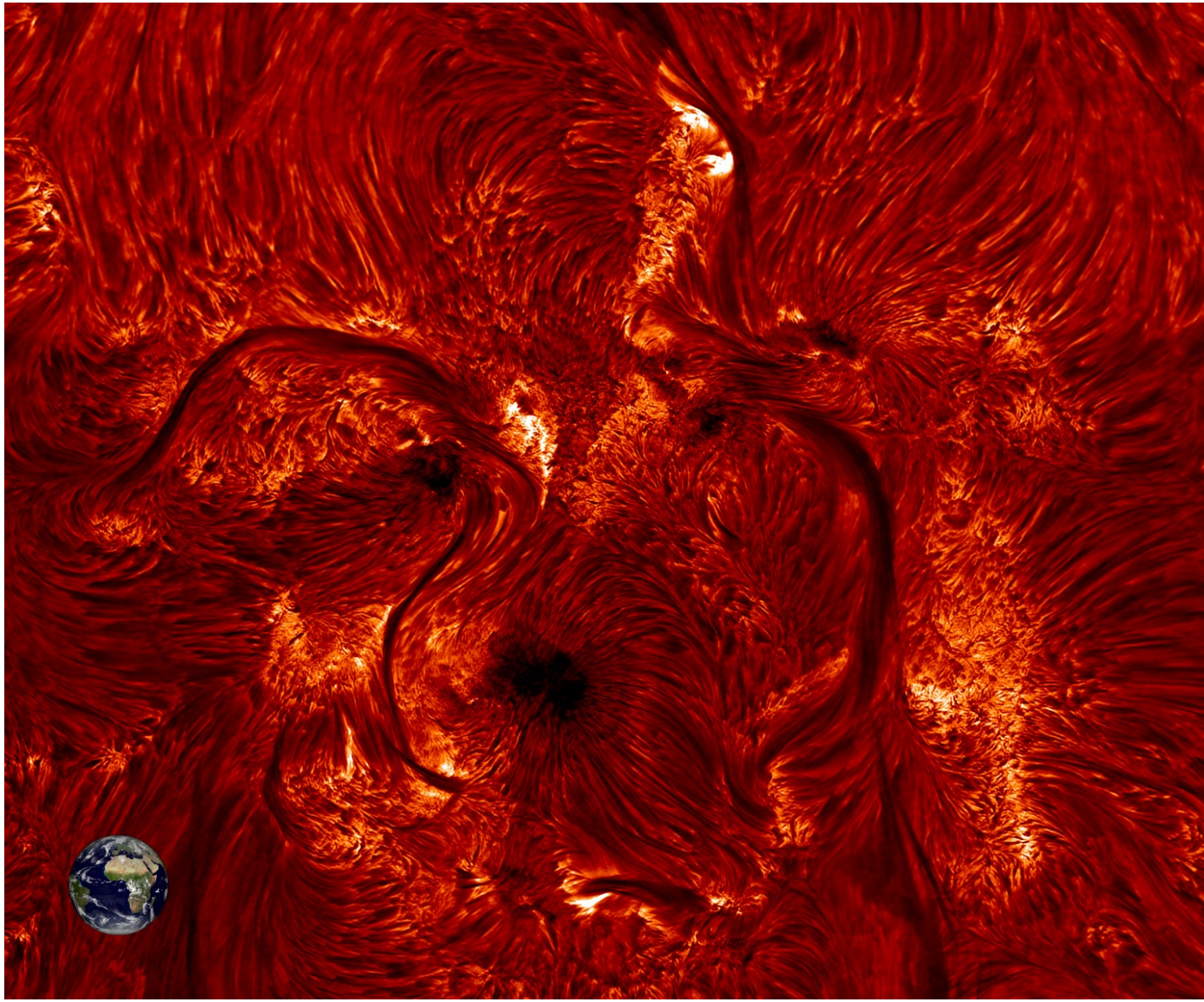
$\mathrm{H}\alpha$ – absorption line.

Fibrils emanate from sunspot.

Bright plage regions still visible.

Long, dark active region filaments.

Earth for scale.



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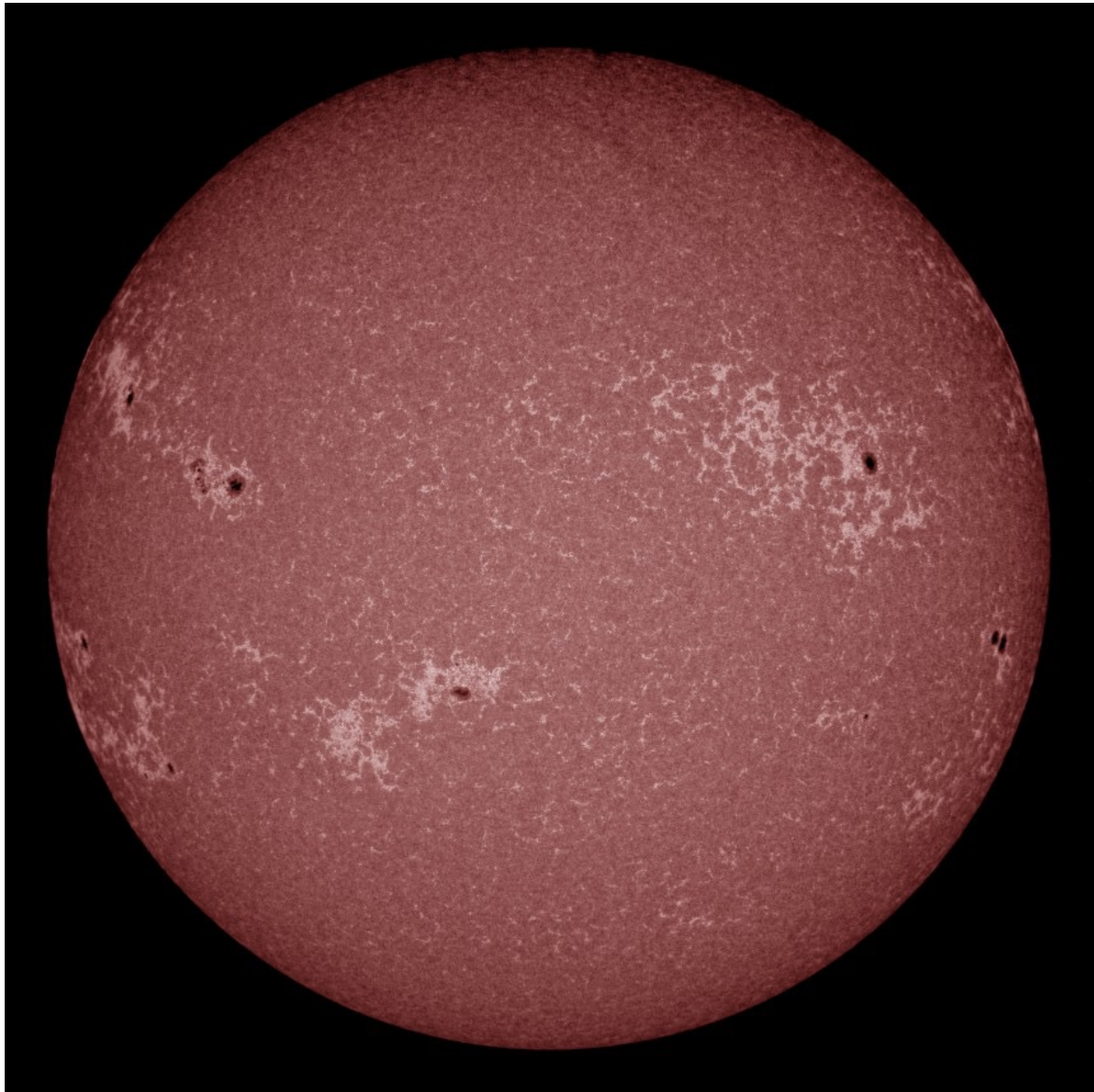
Photosphere: Temperature Min 1700 Å

- $T \approx 4{,}300$ K
- Plage: bright regions associated with magnetic field.



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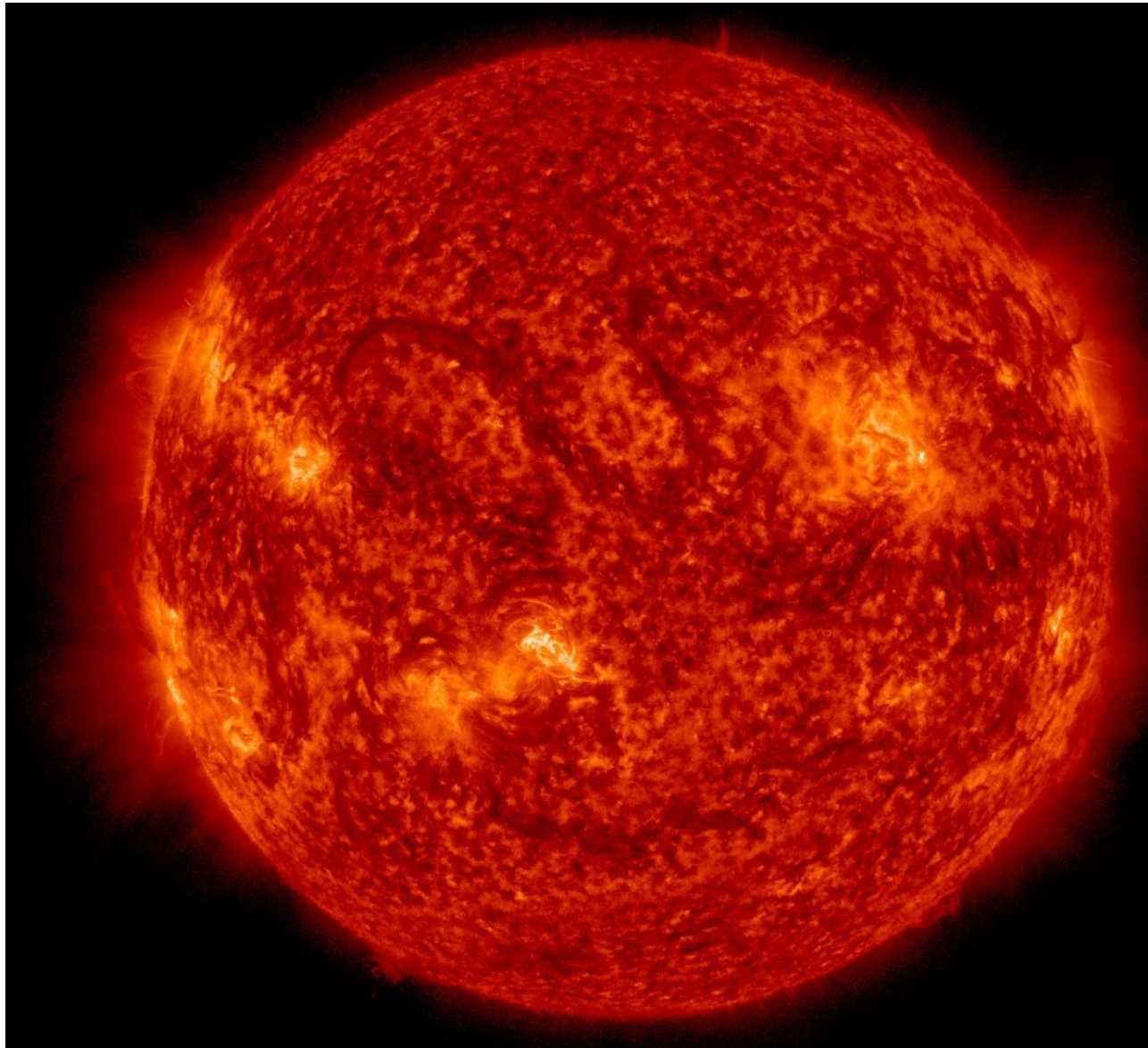
Chromosphere: 304 Å

- $T \approx \text{few} \times 10{,}000\ \text{K}$
- Partially ionised: ions and neutrals.
- Bright, hot plasma above active regions.
- Dark filaments on disk = prominences when seen off-limb.



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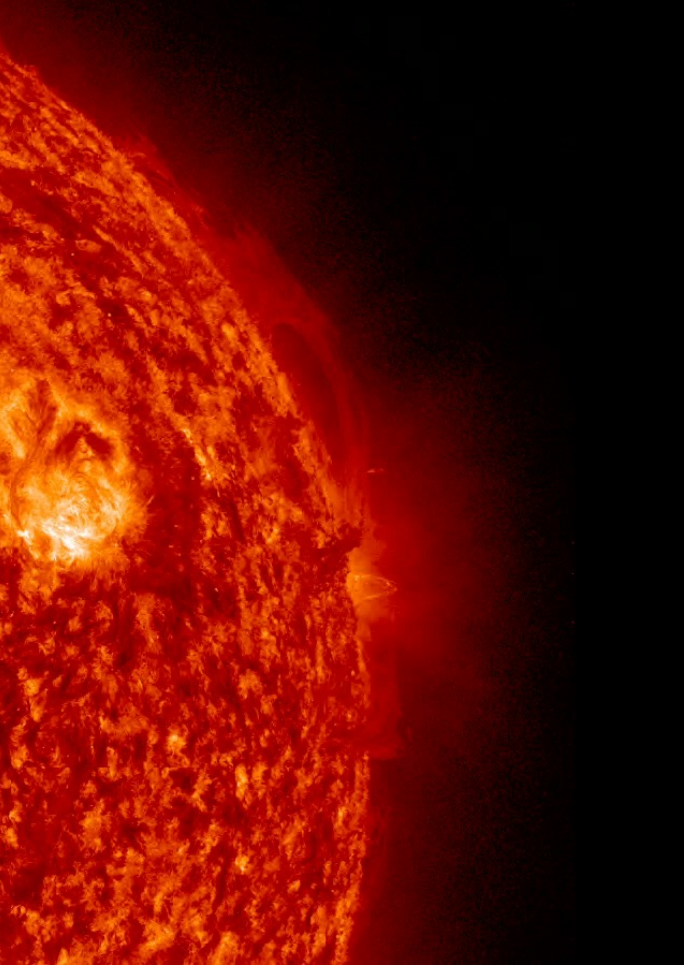
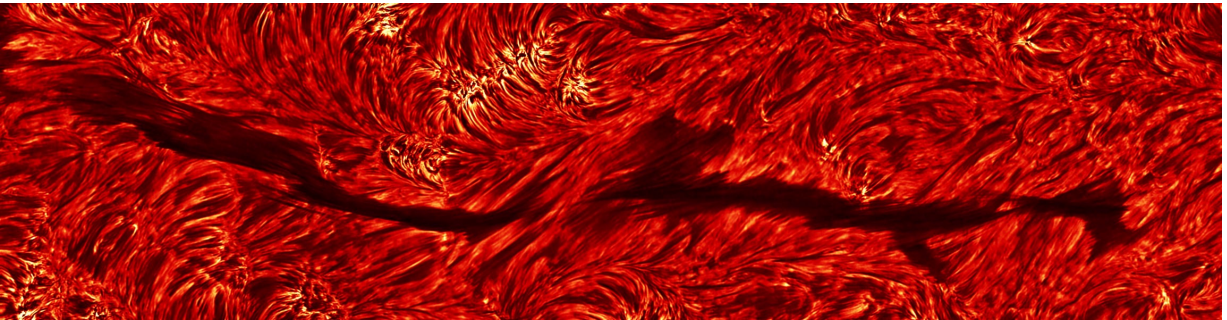


Prominences/Filaments

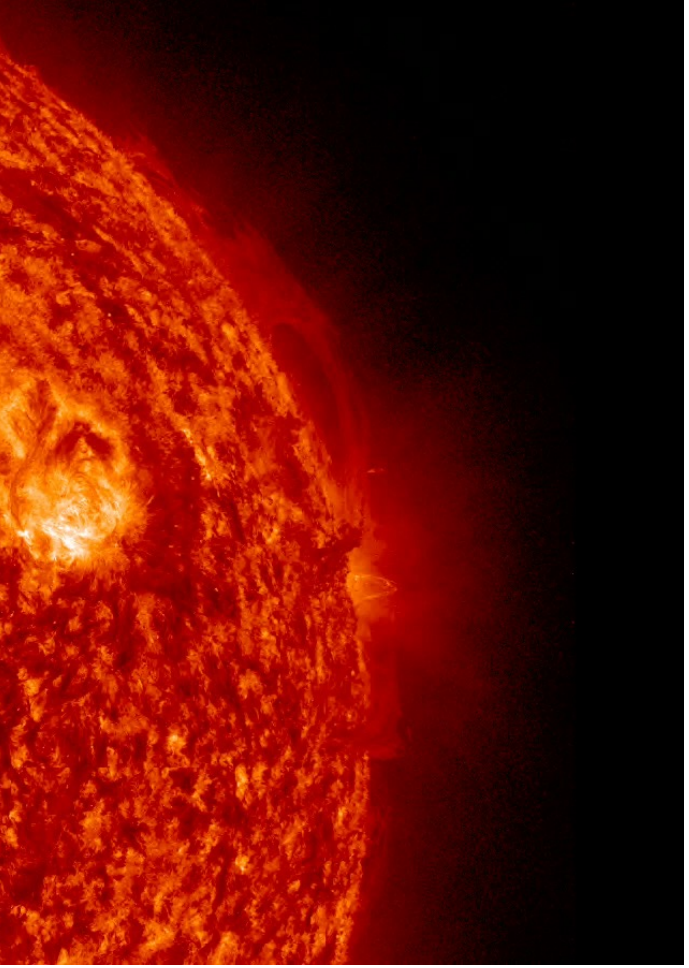
- Suspended in corona, but
  - over 100 x cooler ($\sim 7{,}500 - 9{,}000$ K), and
  - much denser (core density $\approx 10^{15} - 10^{17}\ \mathrm{m}^{-3}$ compared to TR $\approx 10^{15}\ \mathrm{m}^{-3}$ and corona $\approx 1 - 50 \times 10^{14}\ \mathrm{m}^{-3}$)

  than surrounding coronal plasma.

Above: prominence observed by SDO/AIA 304 on 16-18/01/12.
Below: filament observed by DOT in Hα on 6/10/04.



- Supported by highly sheared, mainly horizontal magnetic field.
- See, e.g. Parenti (2014) LRSP.



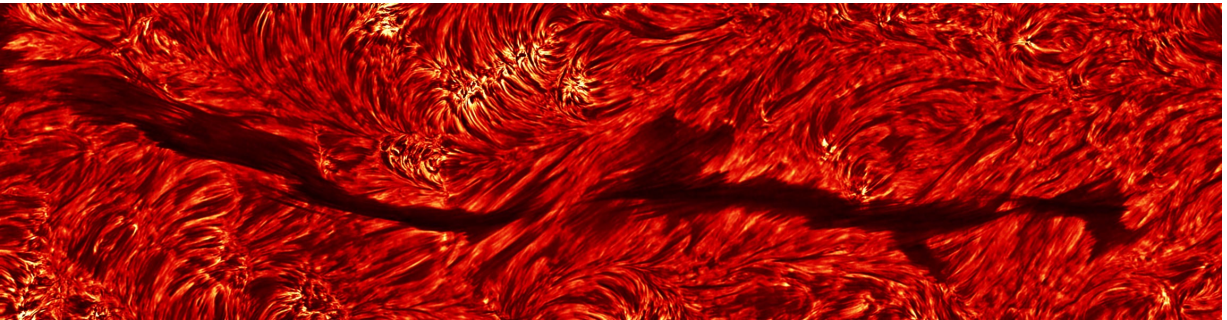
Prominences/Filaments

- Located at polarity inversion lines (PILs):
  1. Around border of polar coronal hole.
  2. Between or surrounding active regions.
  3. Inside active regions.

1 & 2: quiescent prominences -

- Larger (can be 100 Mm in length).
- Magnetic field $\sim 8 - 80$ G.

Above: prominence observed by SDO/AIA 304 on 16-18/01/12.
Below: filament observed by DOT in $\mathrm{H}\alpha$ on 6/10/04.



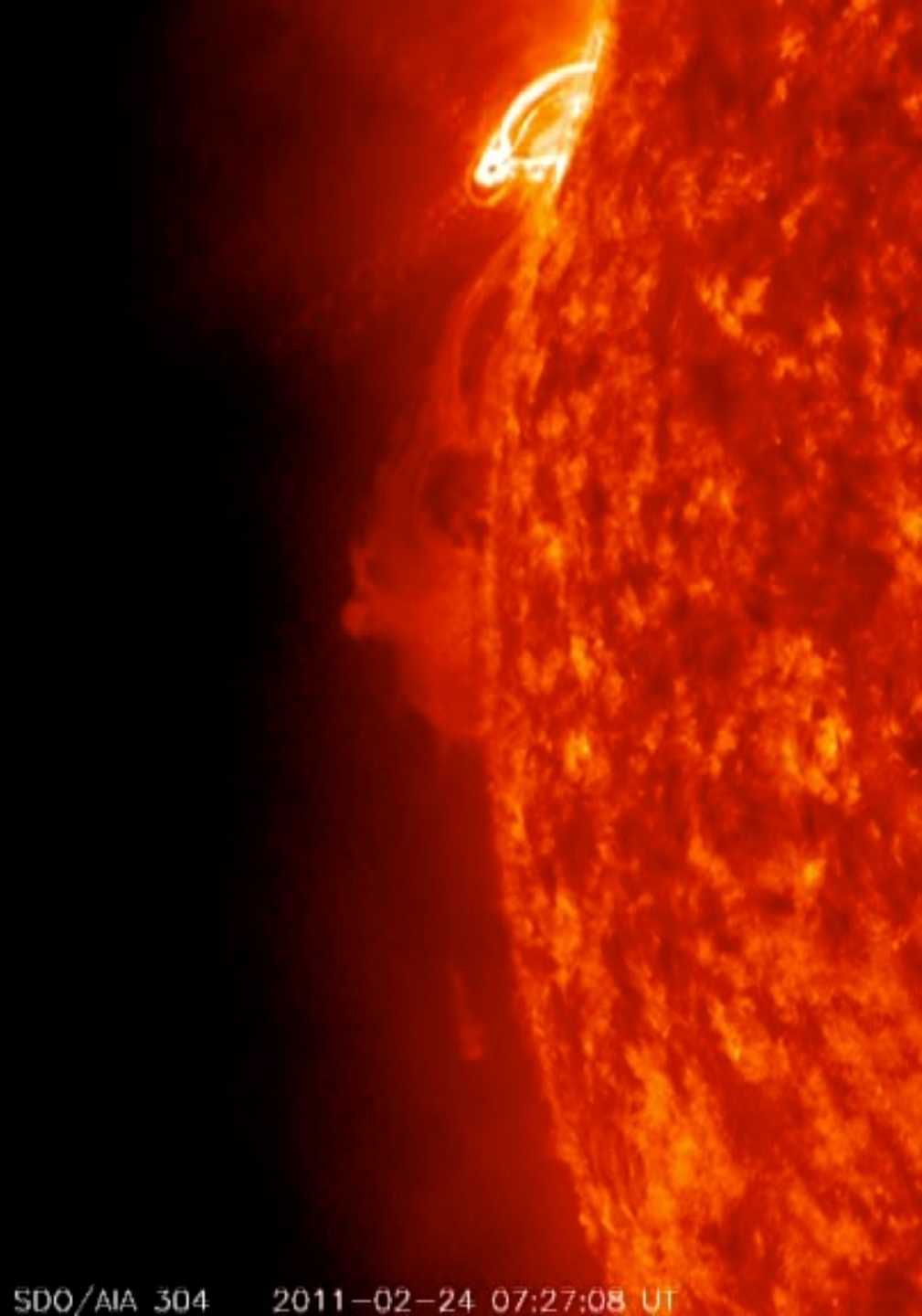
3: active prominences -

- ~10 Mm in length.
- Denser ($\geq 10^{17}\ \mathrm{m}^{-3}$).
- Magnetic field few x 100 G.

Sometimes prominence material may drain away.

Sometimes they may become unstable and erupt.

Prominence eruption observed by SDO/AIA 304 on 24/02/11.



Spicules

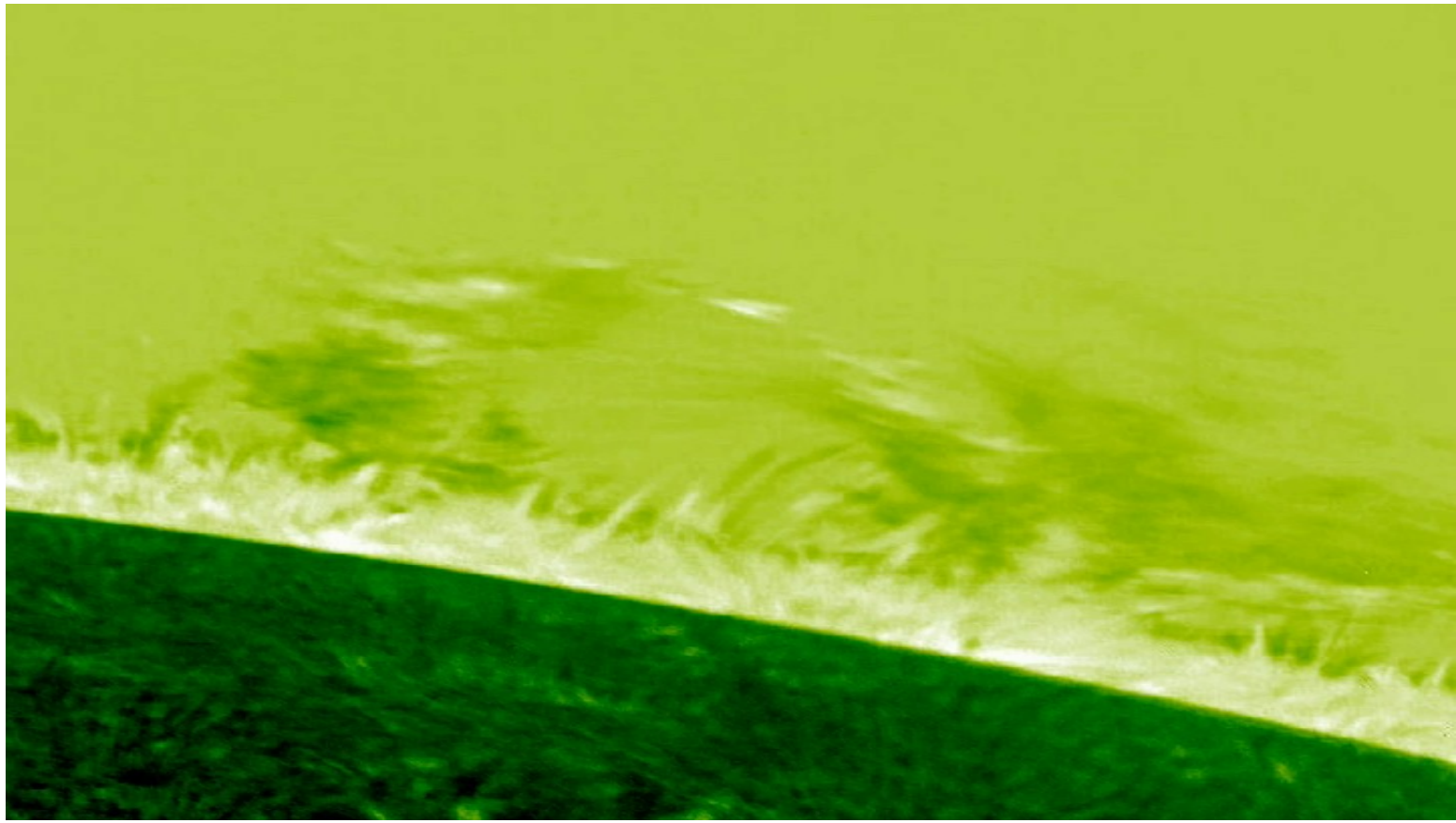
Small jets observed in the chromosphere
(2-10 Mm, 10-180 s).

Plasma transported up to corona at 50-150 km/s.

Plasma heated to TR temperatures (>10^4 K) before falling downwards.

Transport Alfvènic waves.

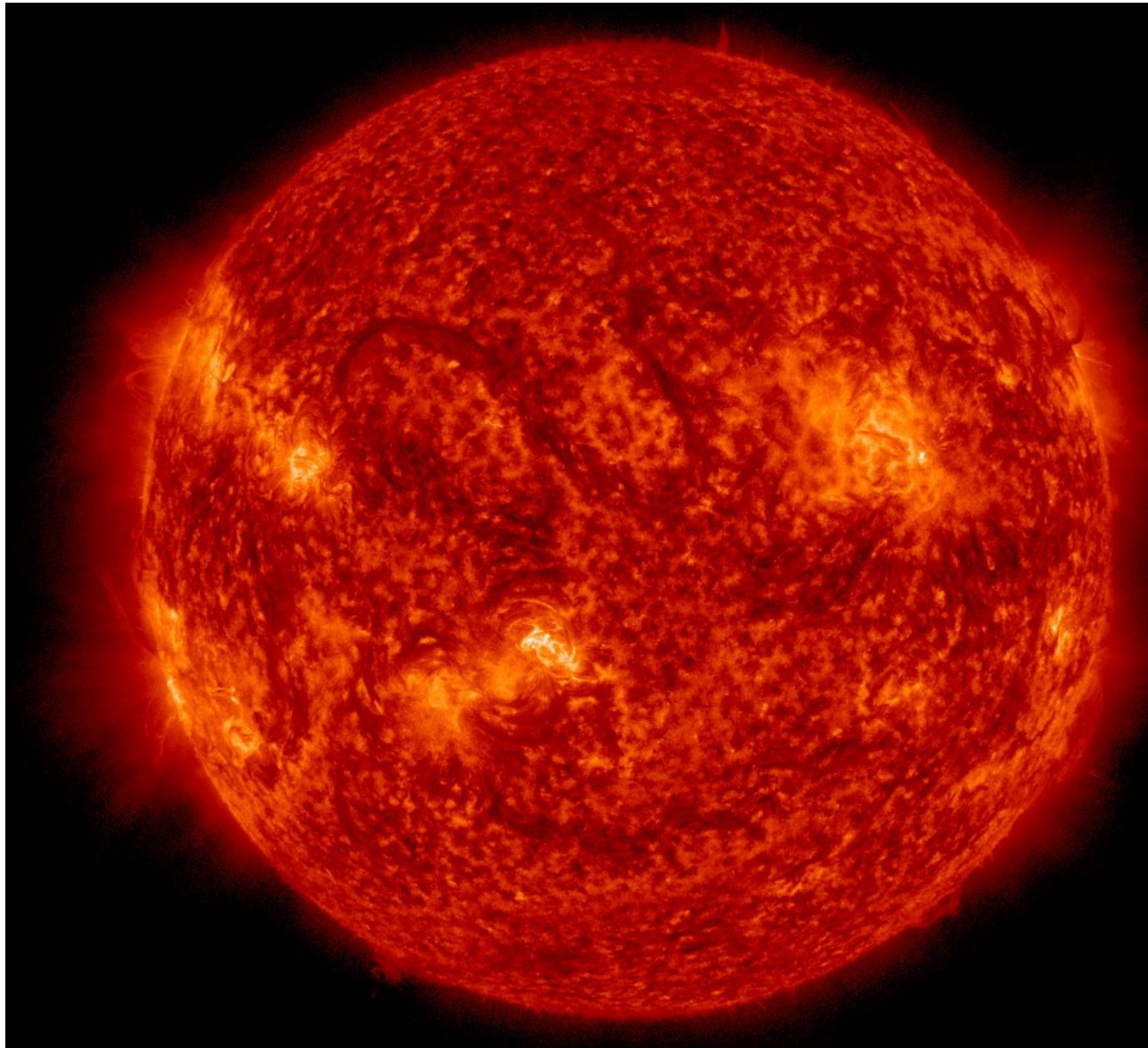
See, e.g. De Pontieu et al. (2011), Martinez-Sykora et al. (2017).



Spicules observed by Hinode spacecraft: svs.gsfc.nasa.gov/12604

Chromosphere: 304 Å

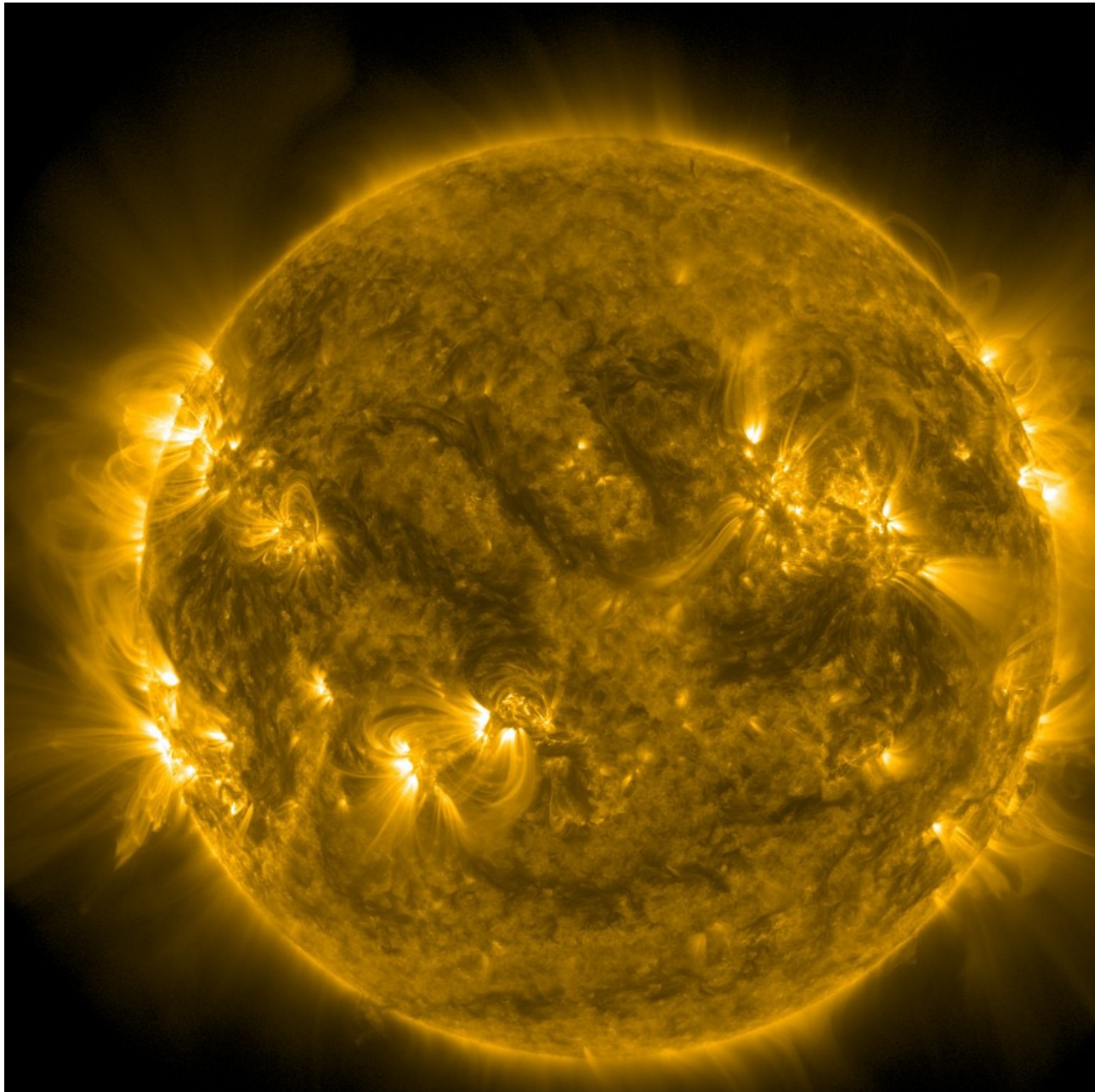
- Returning to the chromosphere observed by SDO…



sdo.gsfc.nasa.gov/data/

Corona: 171 Å

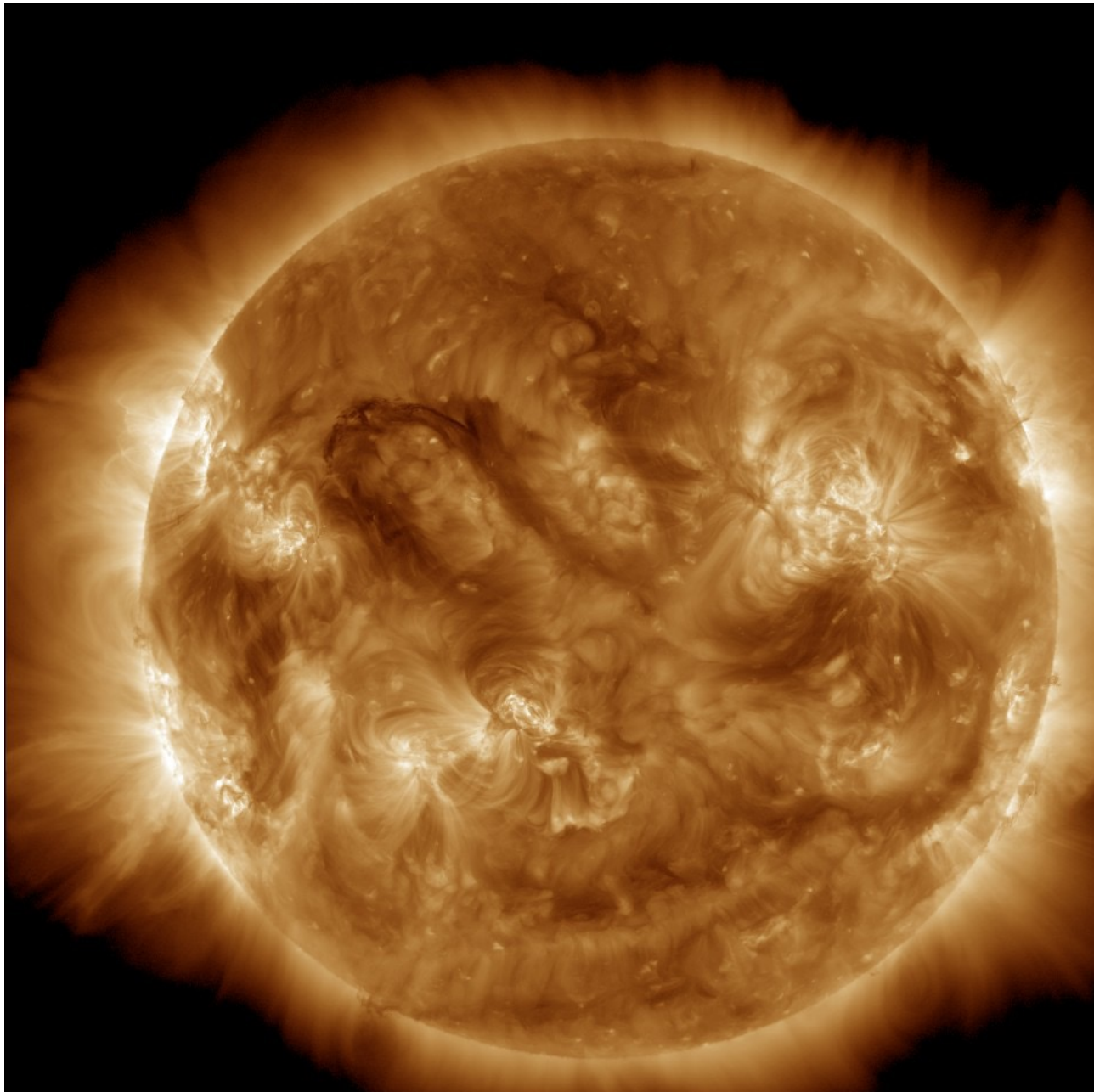
- $T \approx 1{,}000{,}000$ K
- Emits in EUV and X-ray – absorbed by Earth's atmosphere, so we mainly image the corona from space.
- Bright active region coronal loops, structured by magnetic field



sdo.gsfc.nasa.gov/data/

Corona: 193 Å

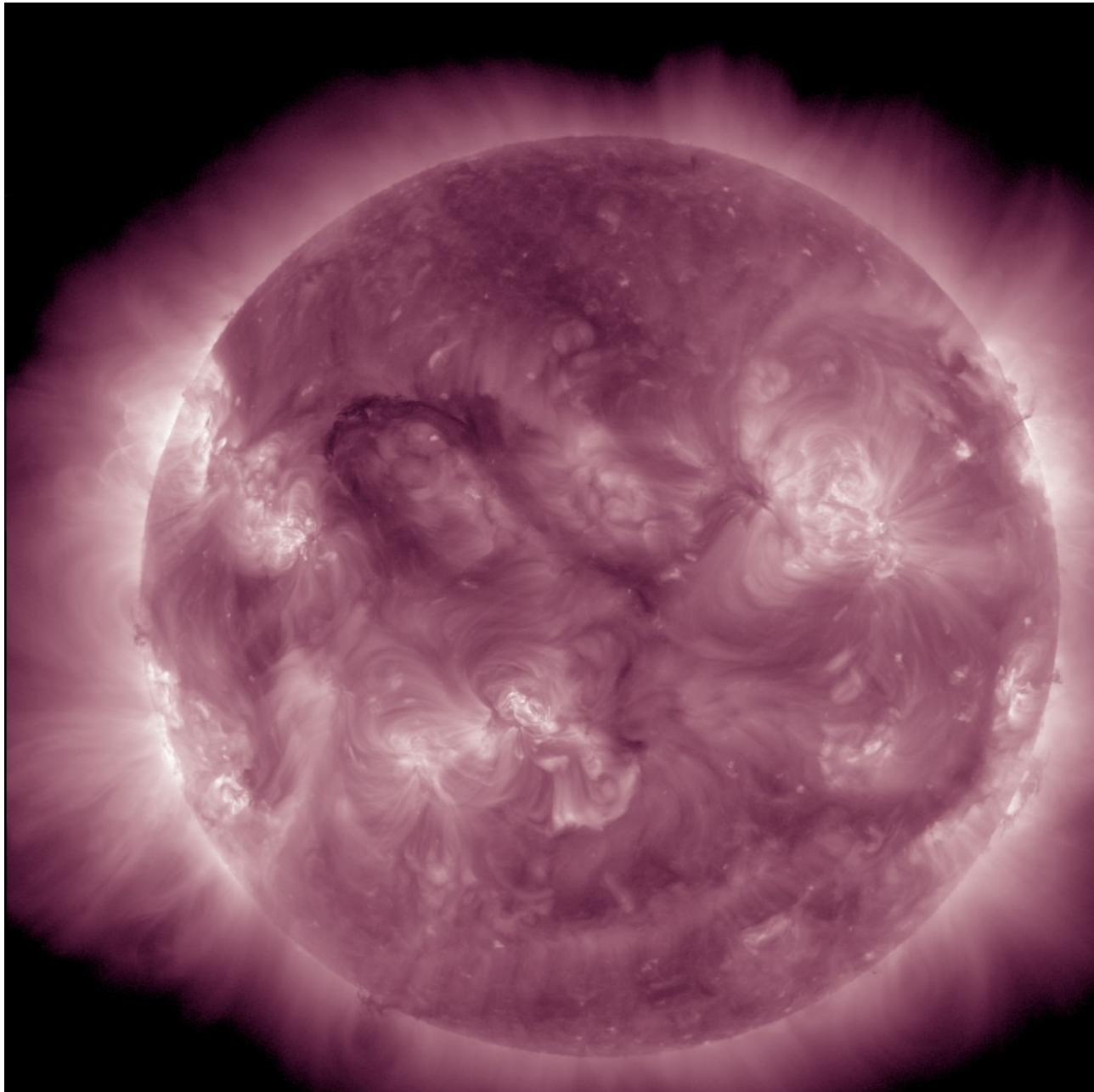
- “Corona and hot flare plasma”
- Contributions from 10^6 K and 10^7 K plasma.



sdo.gsfc.nasa.gov/data/

Corona: 211 Å

- "Active region corona"
- $T \approx 2{,}500{,}000$ K



sdo.gsfc.nasa.gov/data/

Coronal Seismology

Waves and oscillations observed throughout solar atmosphere.

Use MHD theory to estimate plasma properties.

Nakariakov & Verwichte (2005):

- Measure properties of MHD waves and oscillations
- Theoretical modelling of wave phenomena
- Determine mean physical parameters of corona

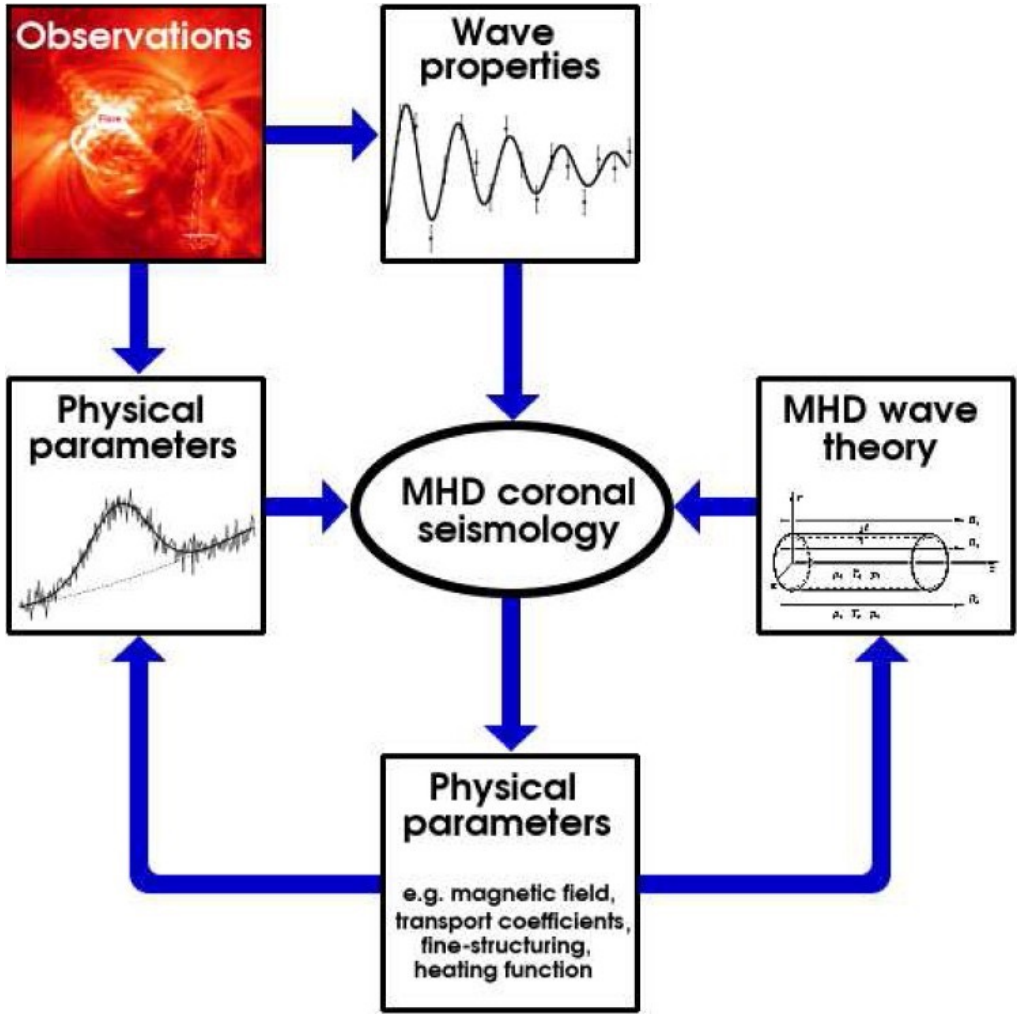
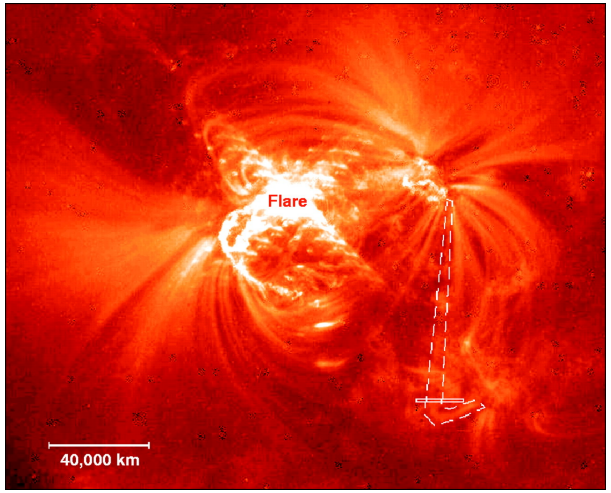
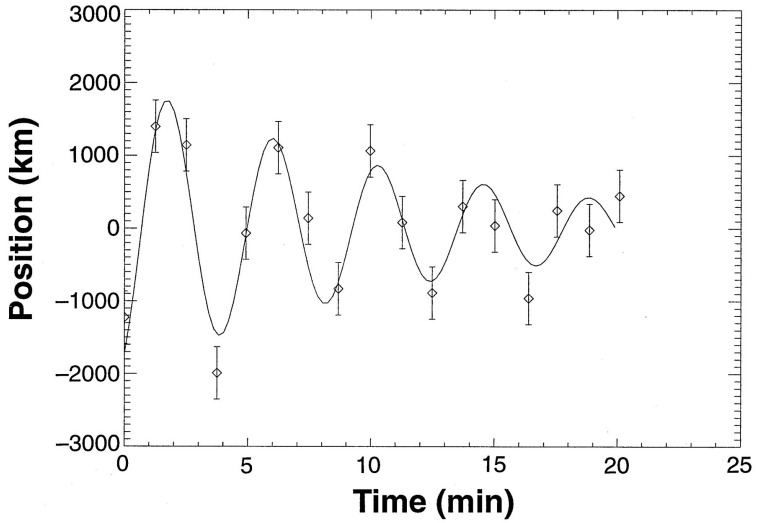


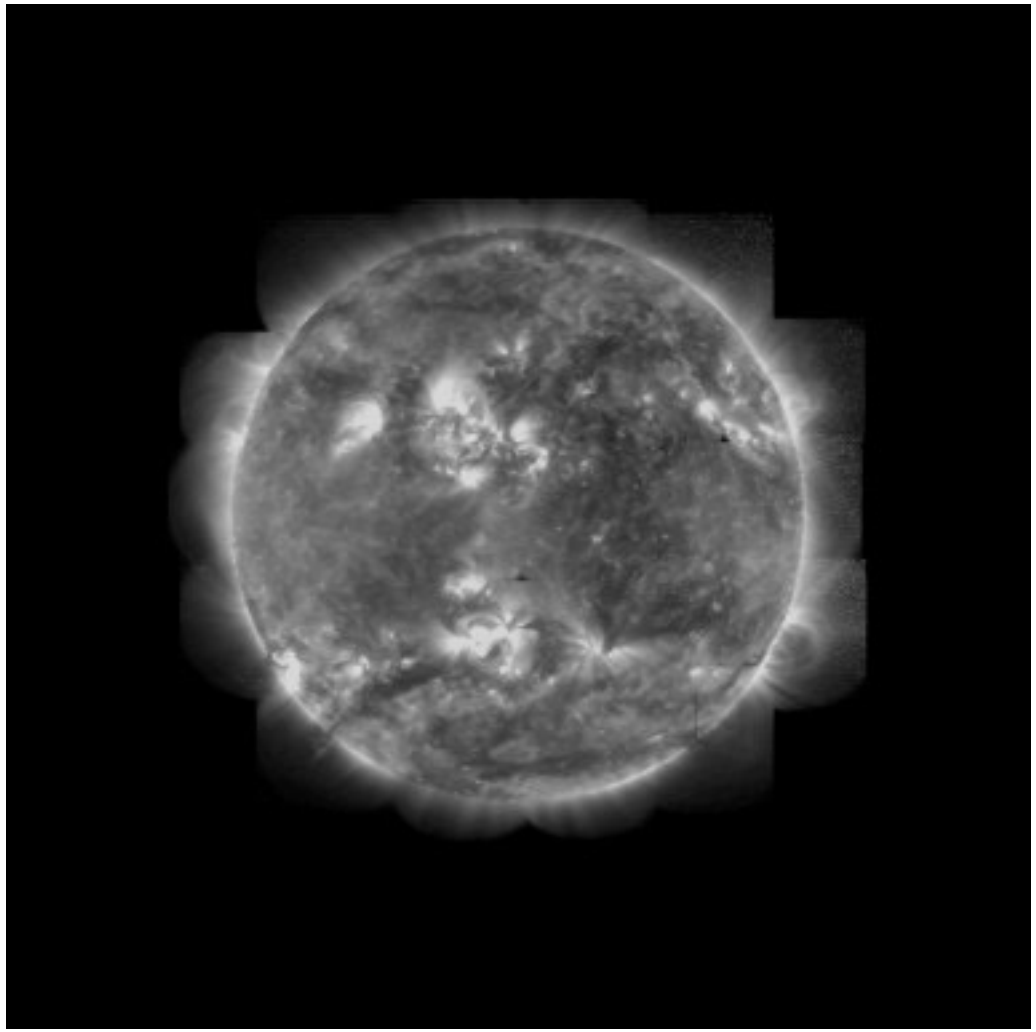
Figure 1 from Nakariakov & Verwichte (2005): "Coronal Waves and Oscillations", LRSP

Coronal Seismology

- Example from Nakariakov et al. (1999).
- Oscillations excited by solar flare.
- Interpreted as kink global standing mode with $C_k = 1040 \pm 50\ \mathrm{km\ s^{-1}}$.
- Strong damping: decay time 14.5 ± 2.7 min.

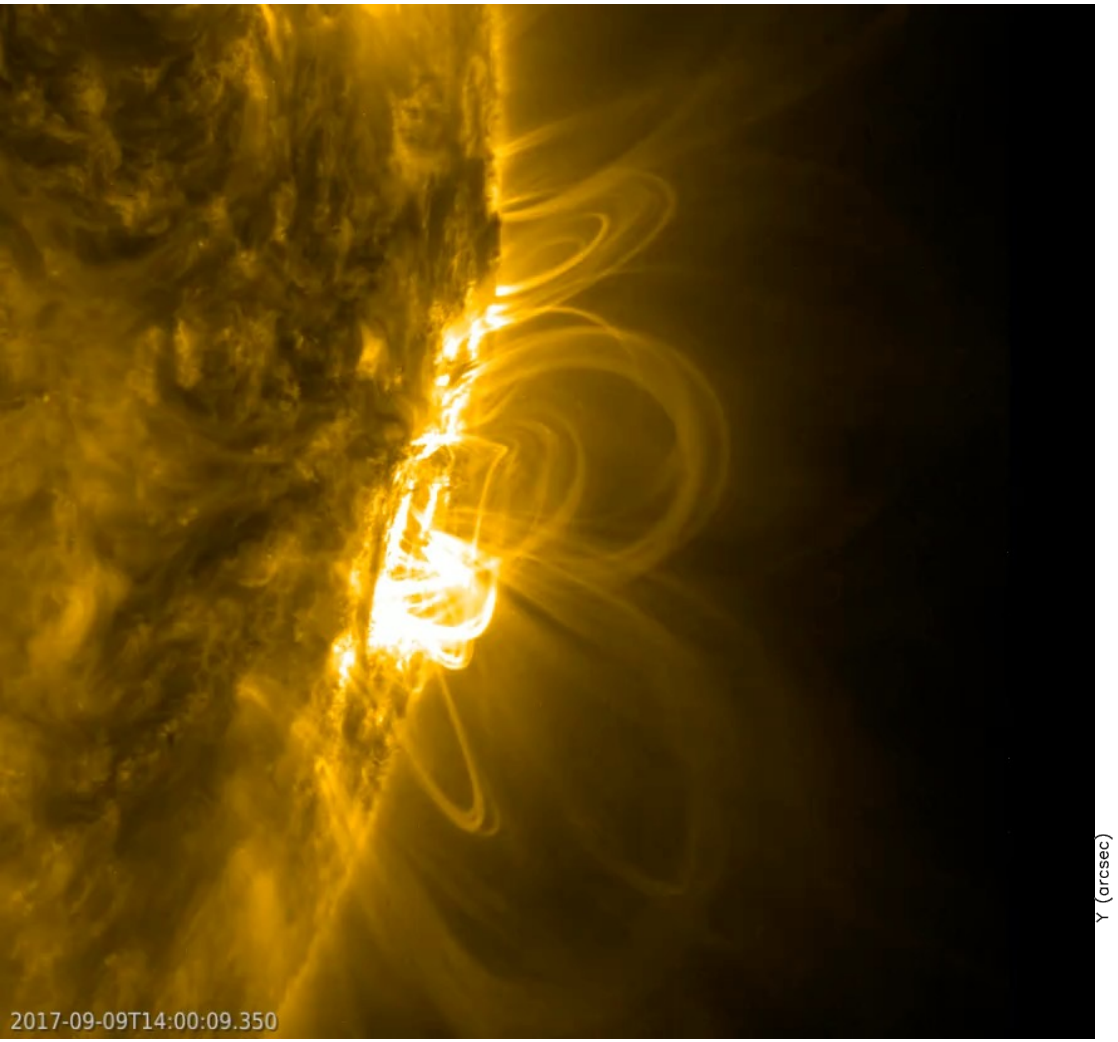






Transition Region and Coronal Explorer (TRACE) EUV observations sdowww.lmsal.com/TRACE/

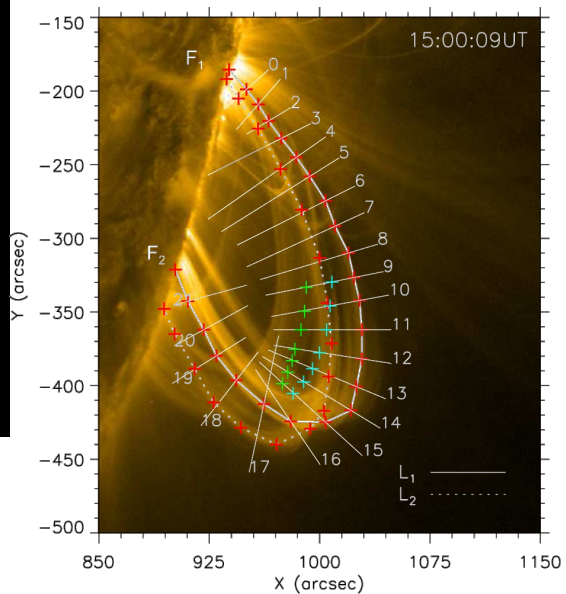
Coronal Seismology

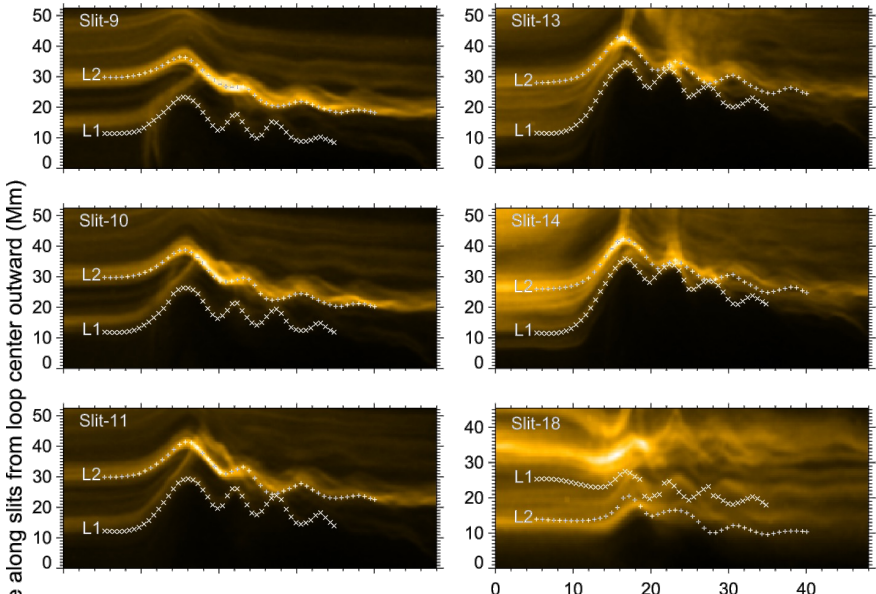


AR 12673 9-10 Sept 2017 observed by SDO/AIA: studied by Safna Banu, Maurya & Jain Jacob (2022)

- Example from Safna Banu, Maurya & Jain Jacob (2022).
- Plasmoid ejection triggered loop oscillations.
- Estimated parameters:

Loop	Period (min)	Length (Mm)	Kink speed (km s^{-1})	Alfvén speed (km s^{-1})	Magnetic field (G)
L_1	6.31	195	1029	763	36
L_2	7.93	199	836	620	29

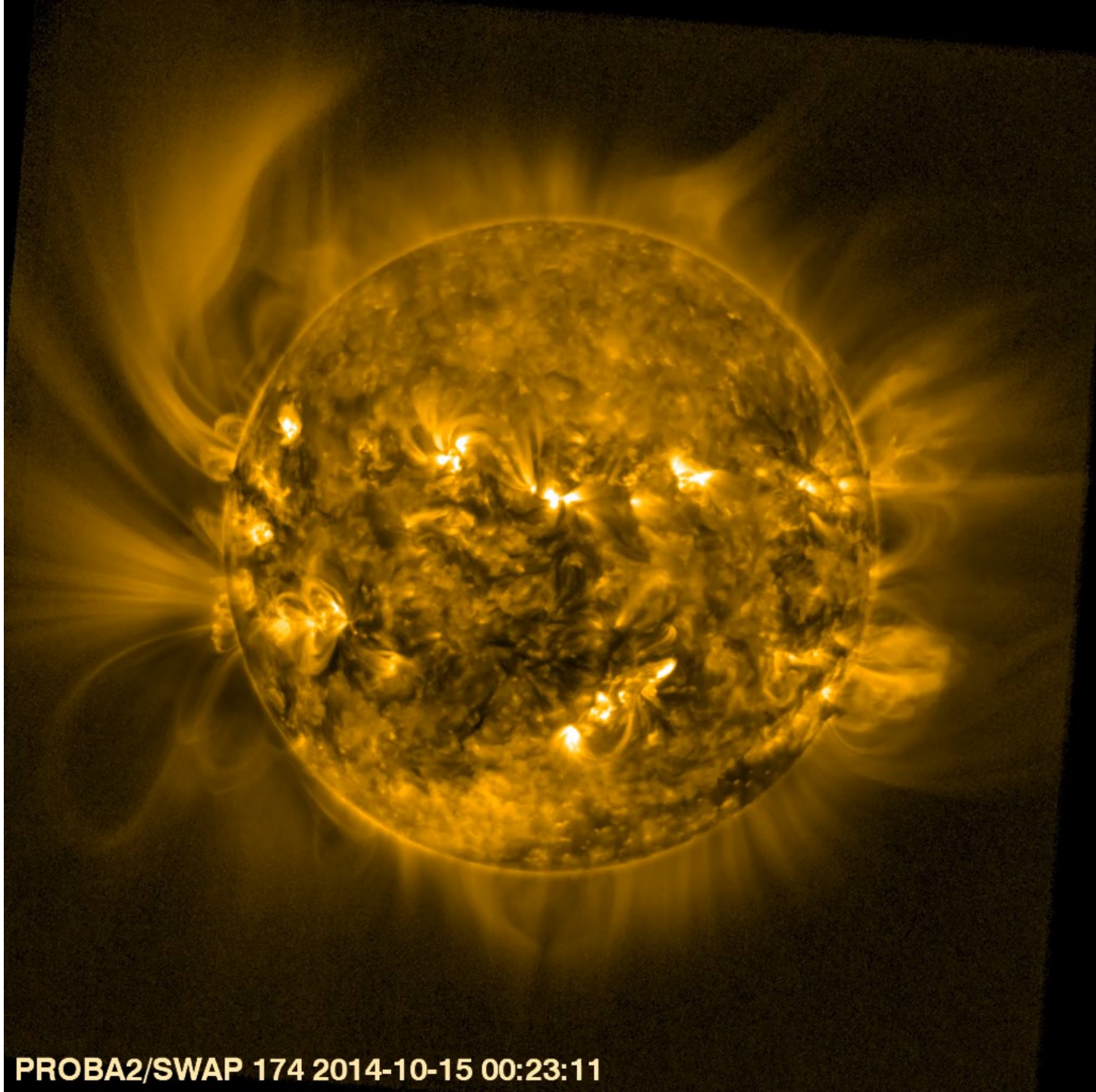




Extended Corona

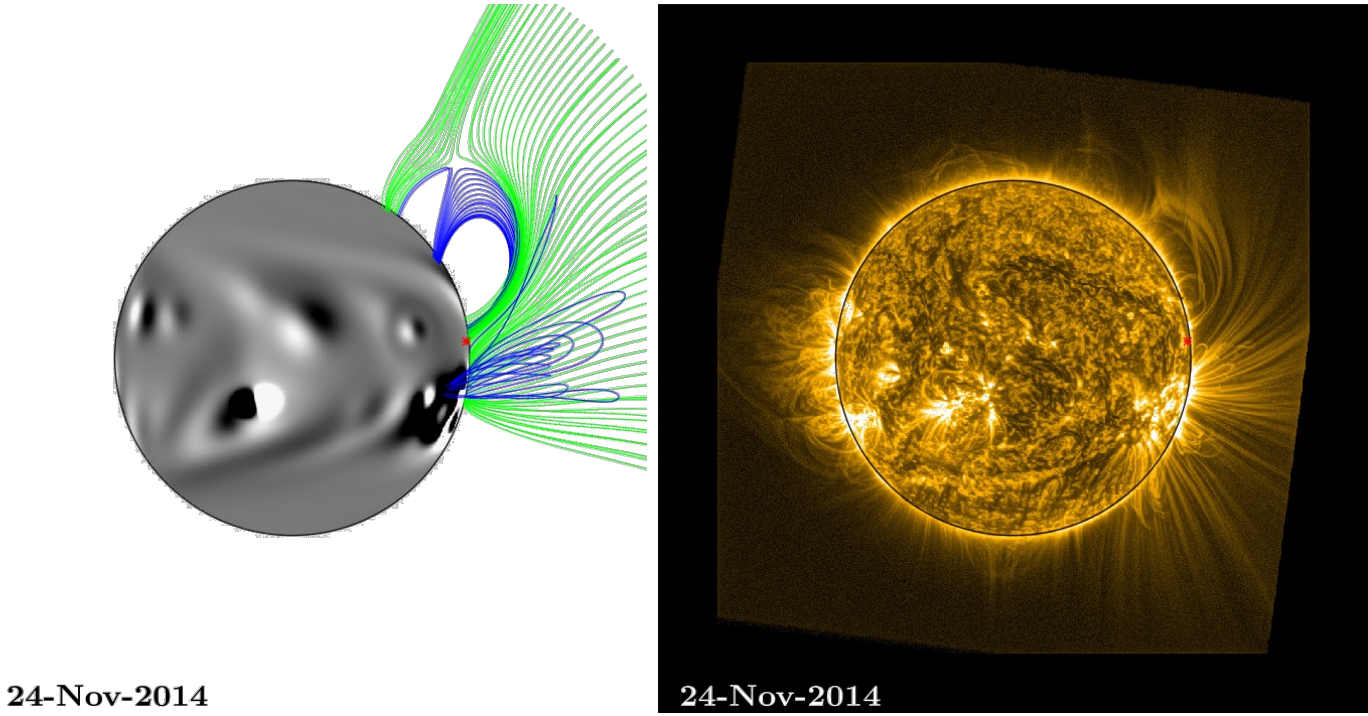
- AIA FOV ~ $1.3 \times 1.3\ R_\odot$
- PROBA2: ESA micro-satellite launched 2009.
- SWAP: EUV imager with $1.7 \times 1.7\ R_\odot$ FOV ($2.5\ R_\odot$ along diagonal).
- Lots of extended coronal structures, particularly at solar maximum.

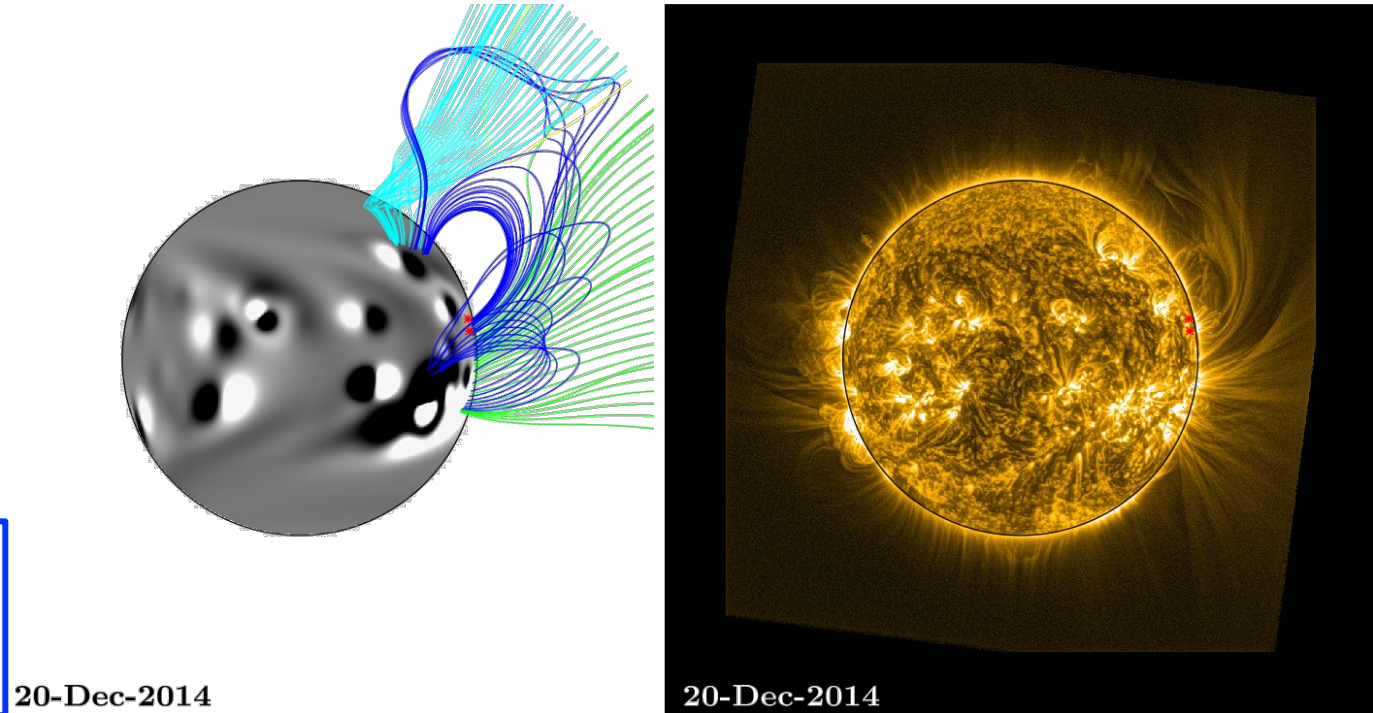
proba2.sidc.be/data/SWAP



Magnetic Structure

- Coronal magnetic field difficult to measure.
- Infer from coronal seismology, some observations possible off limb and/or where very strong field.
- Models approximate structure and evolution of magnetic field.
- E.g. left: pseudostreamer and streamer structures.

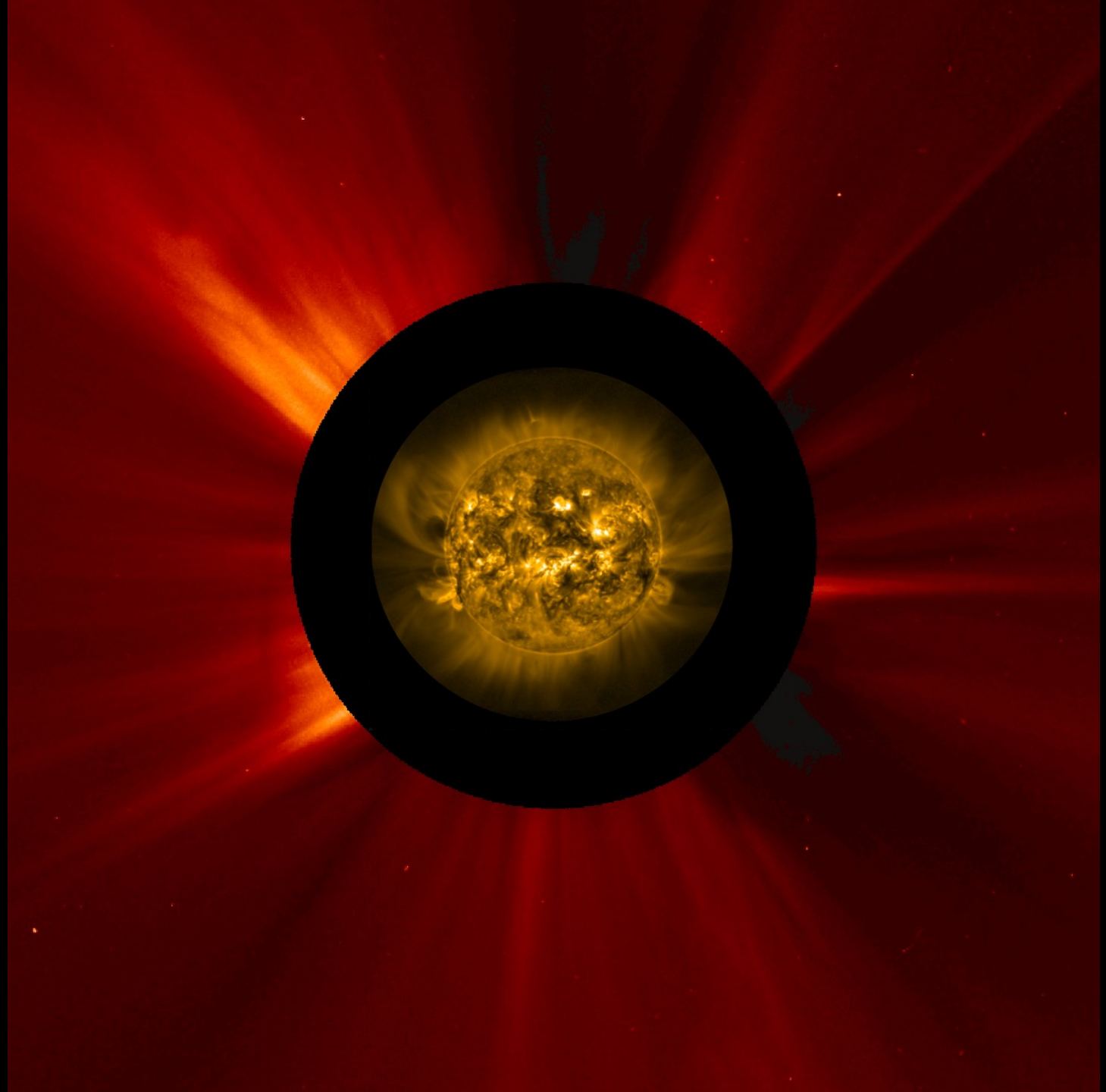




Dark blue: closed
Green: open positive
Light blue: open negative

Meyer et al. (2020)

SWAP and LASCO composite image from West et al. (2023), highlighting the *middle corona*.



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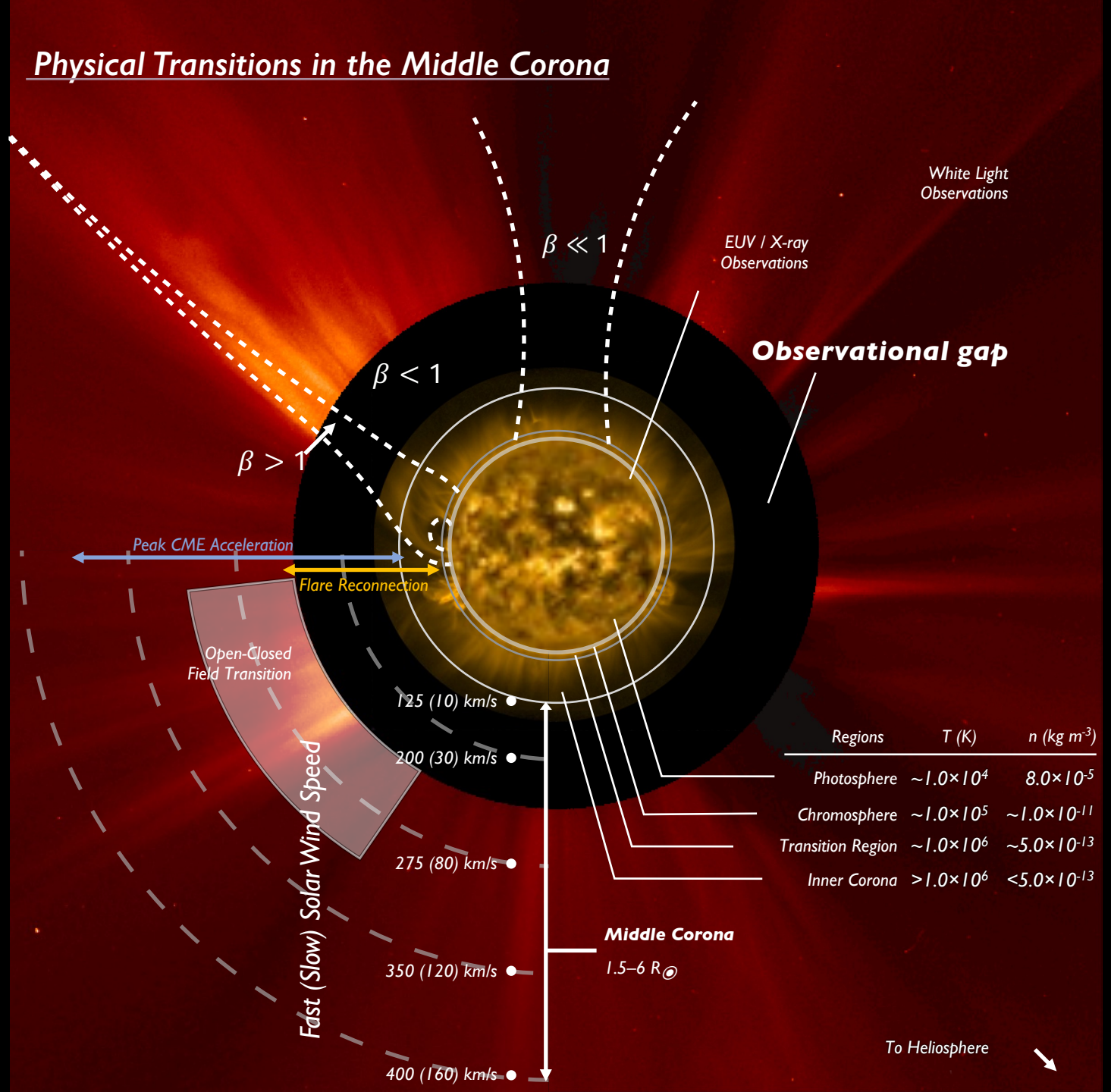
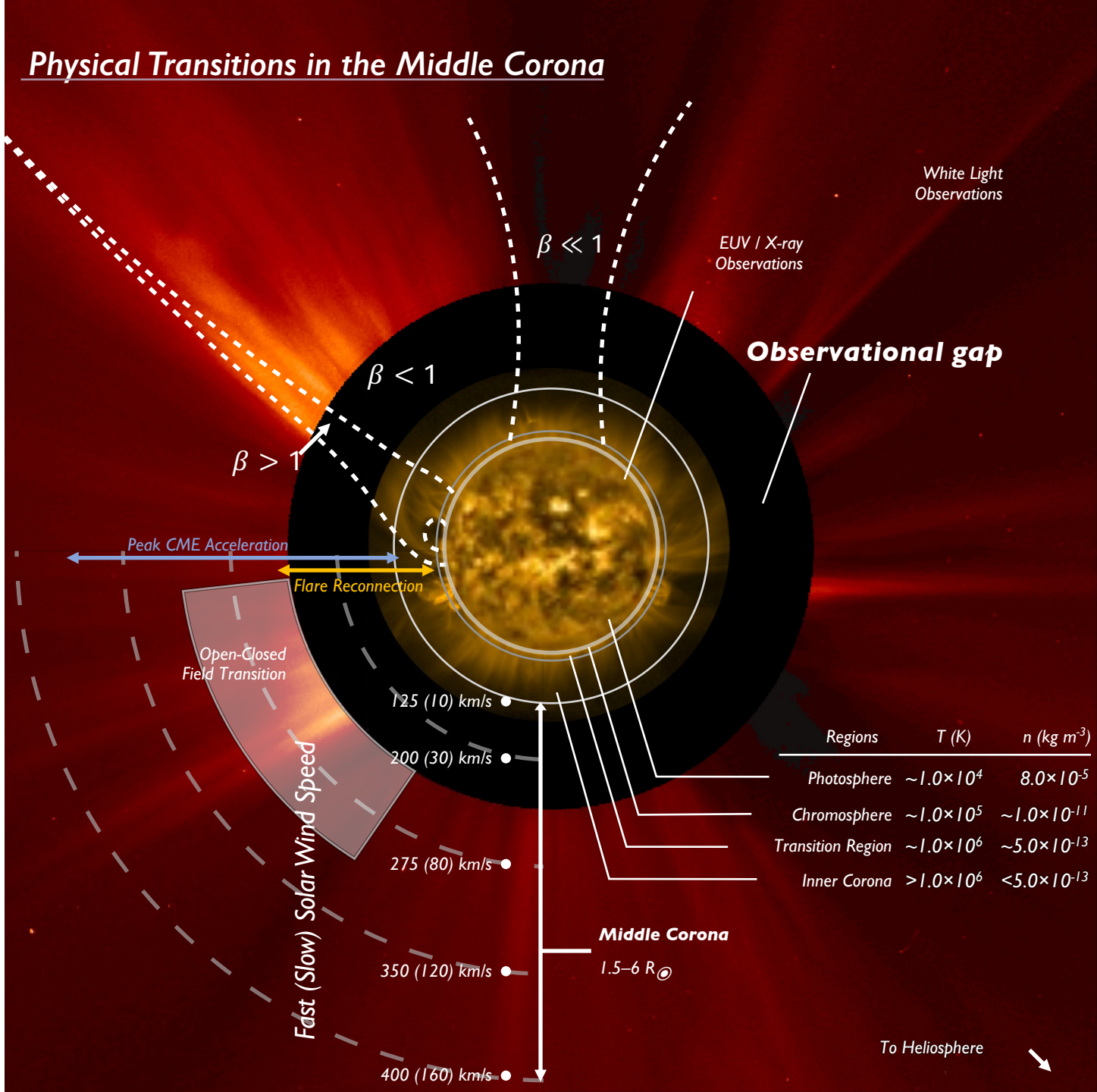


Defining the Middle Corona, Solar Physics Journal (2023)

Middle Corona

- Transition from predominantly closed to predominantly open magnetic field.
- Change from low to high β in some regions (e.g. streamers).
- Primary solar wind acceleration region.
- Essential for comprehensively connecting corona to heliosphere in models.

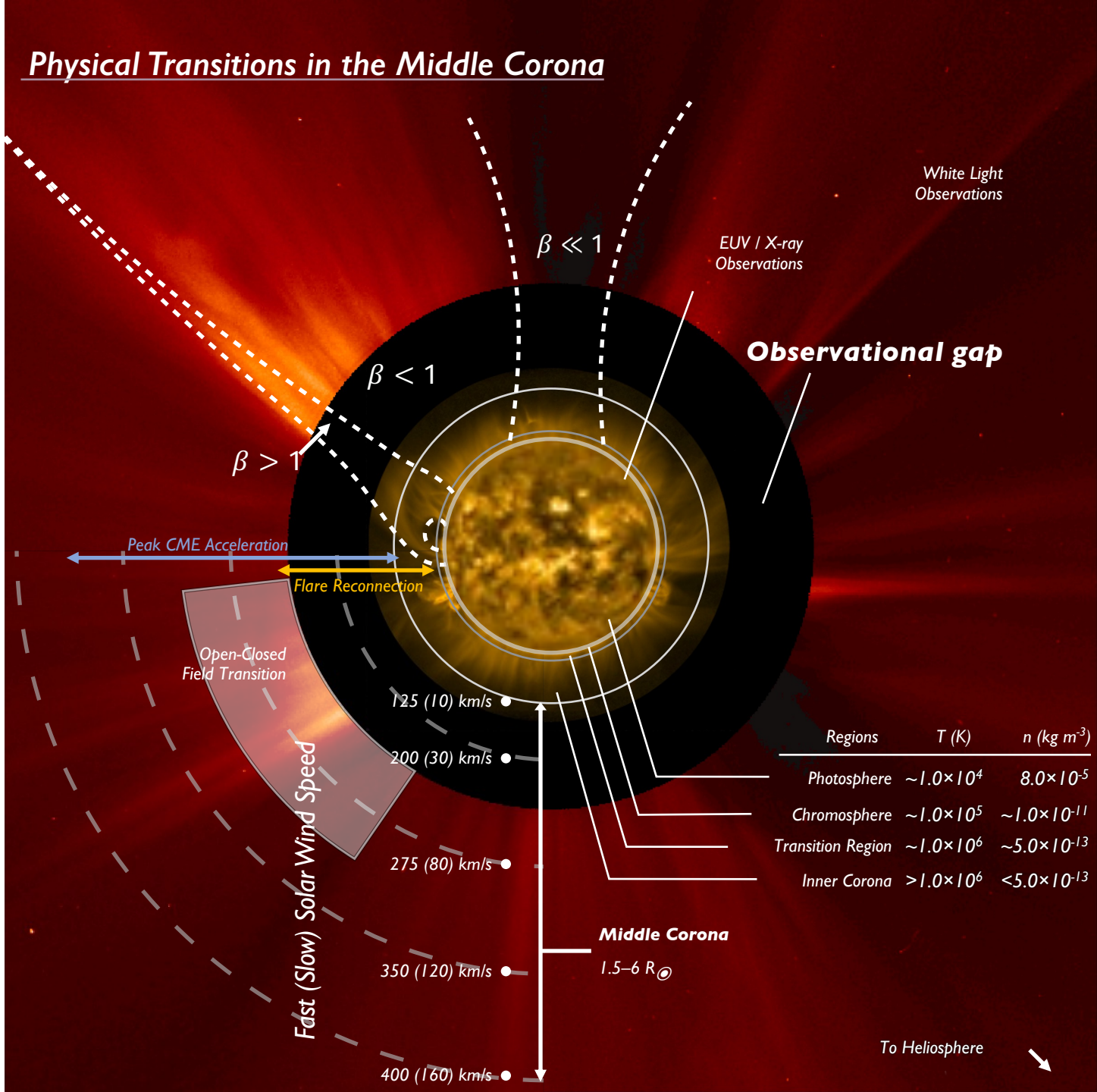


Regions	T (K)	n (kg m^{-3})
Photosphere	$\sim 1.0\times10^{4}$	8.0×10^{-5}
Chromosphere	$\sim 1.0\times10^{5}$	$\sim 1.0\times10^{-11}$
Transition Region	$\sim 1.0\times10^{6}$	$\sim 5.0\times10^{-13}$
Inner Corona	$>1.0\times10^{6}$	$<5.0\times10^{-13}$

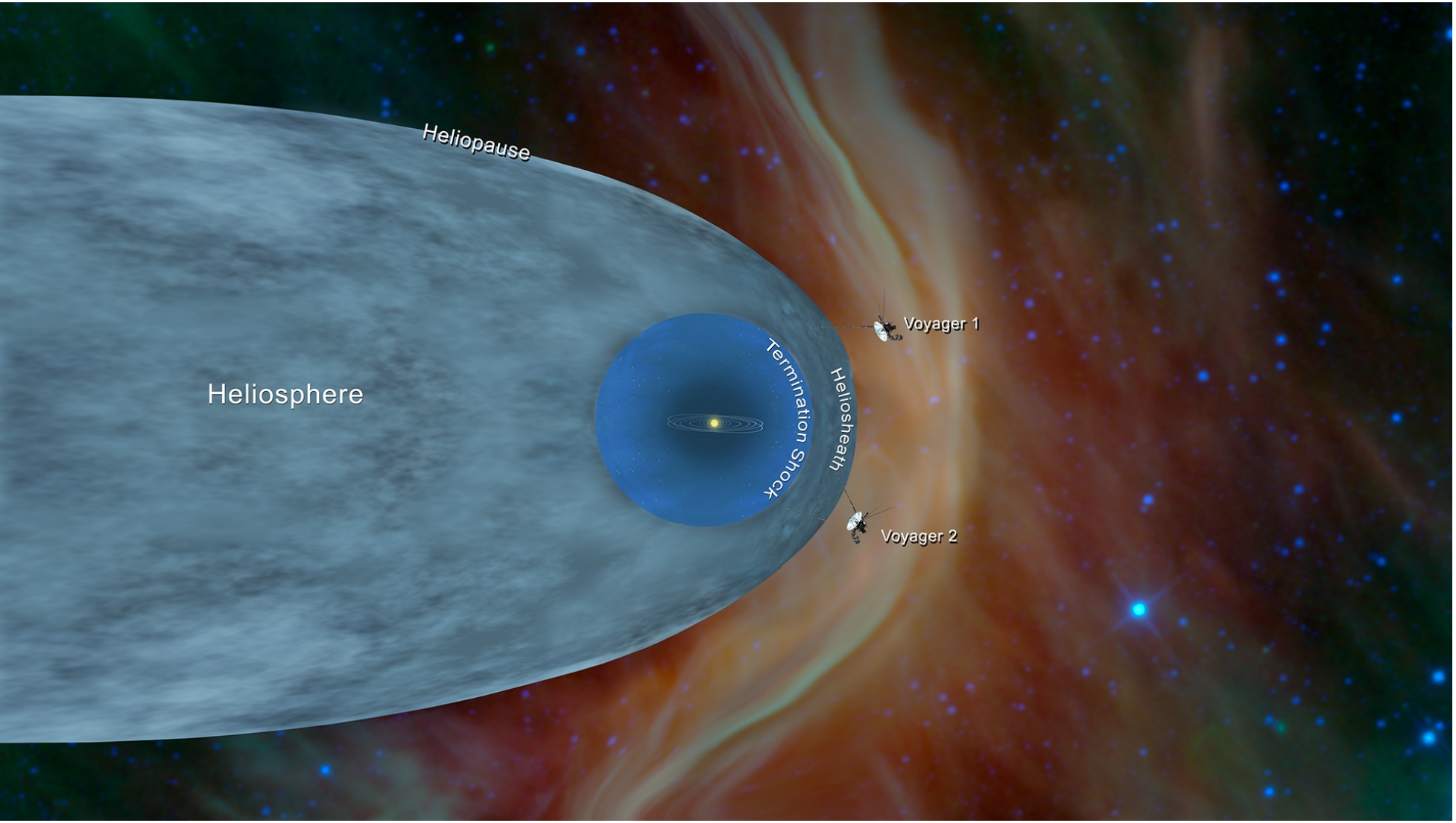
Middle Corona

Defining the Middle Corona, Solar Physics Journal (2023)

Monthly Middle Corona discussion group – let me know if you are interested in joining!



The Heliosphere



We are inside the Sun's atmosphere!

Voyager 1 and 2 crossed the Heliopause in 2012 and 2018.

>18 billion km from Earth.

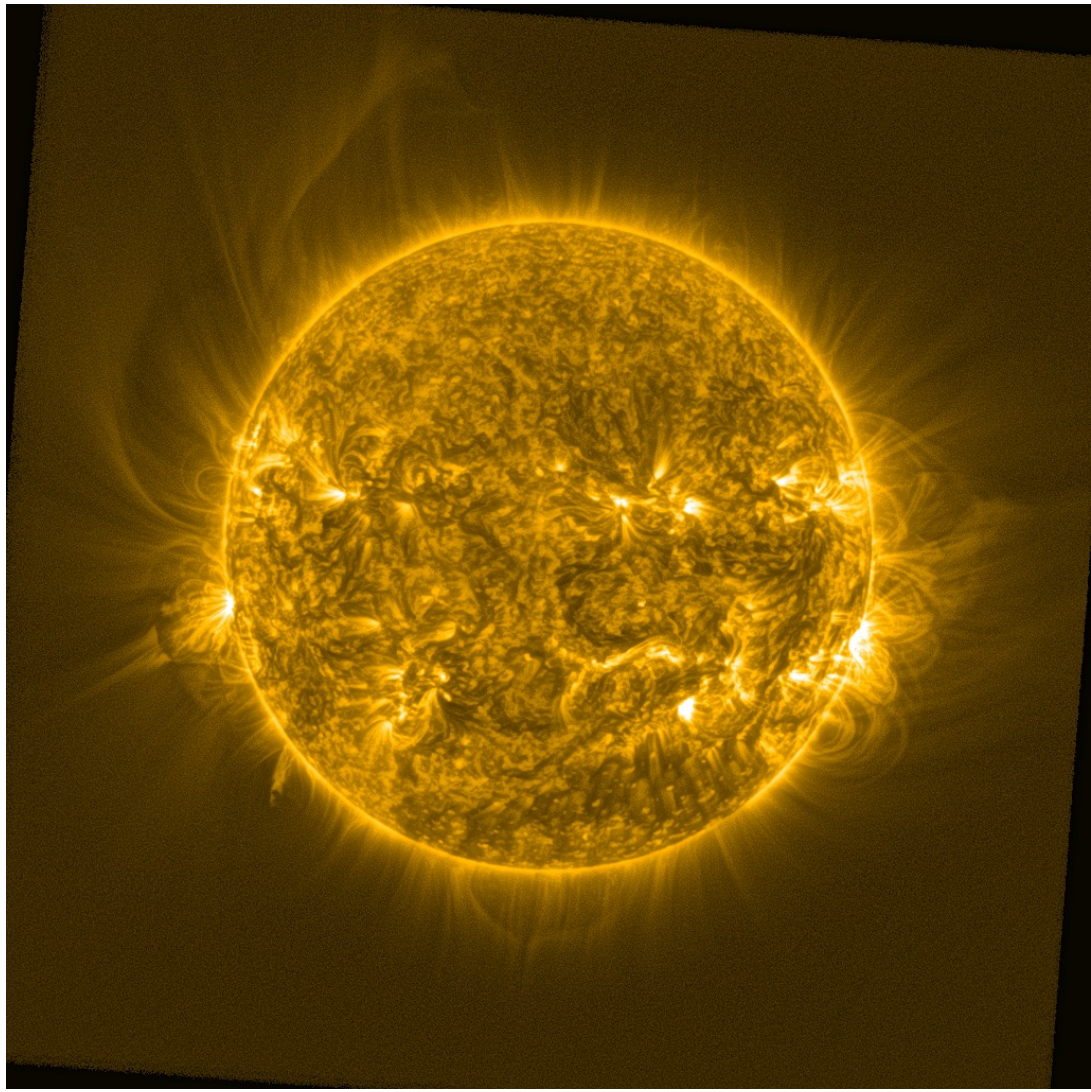
www.nasa.gov/press-release/nasa-s-voyager-2-probe-enters-interstellar-space

Thanks for listening!

kmeyer001@dundee.ac.uk

Middle corona definitional paper:

Monthly Middle Corona discussion group – let me know if you are interested in joining!



SWAP observation from 11/10/14, proba2.sidc.be/data/SWAP