COSMIC MAGNETIC FIELDS

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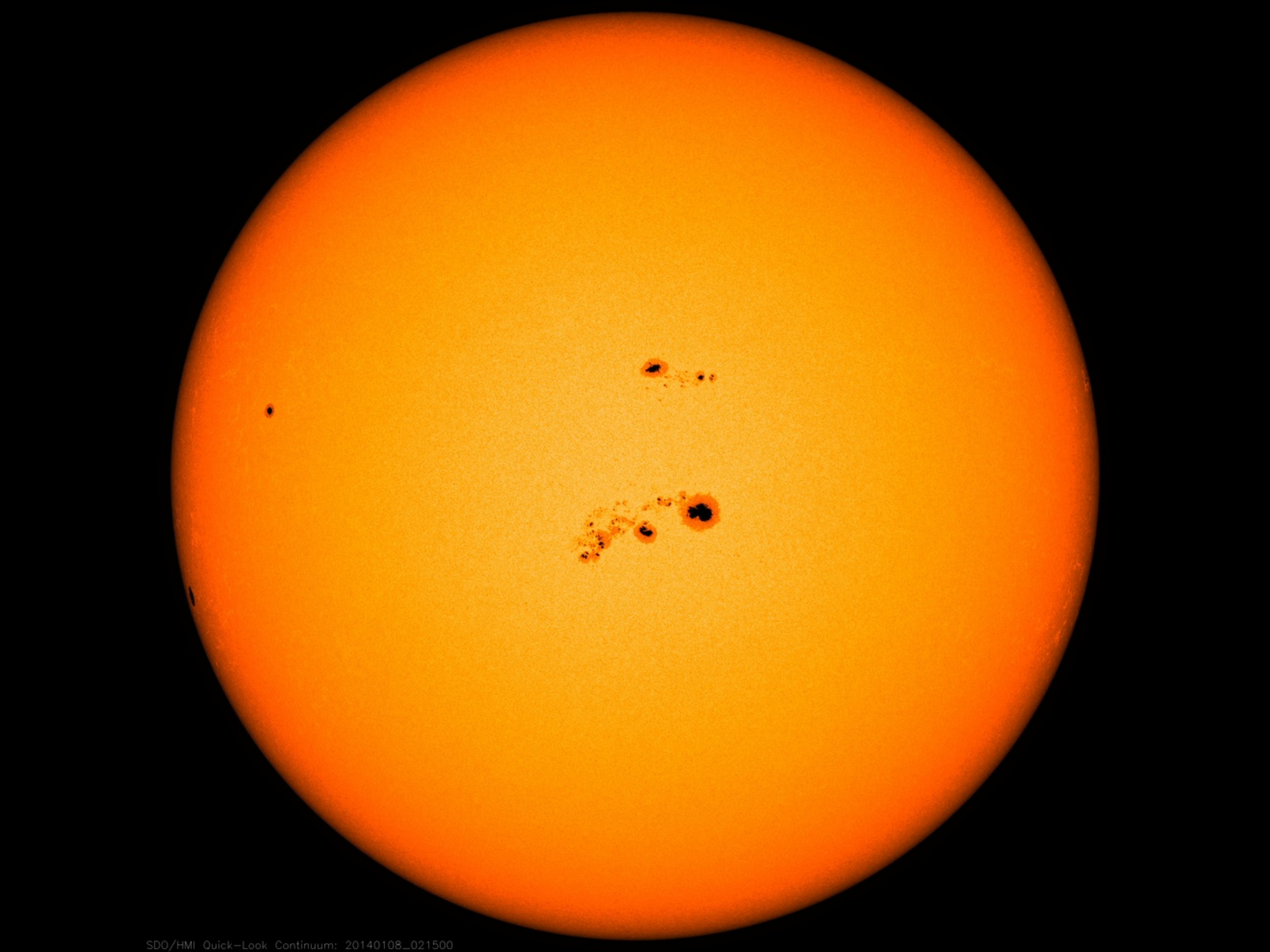
Sun


SDO/HMI Quick-Look Continuum: 20140108_021500

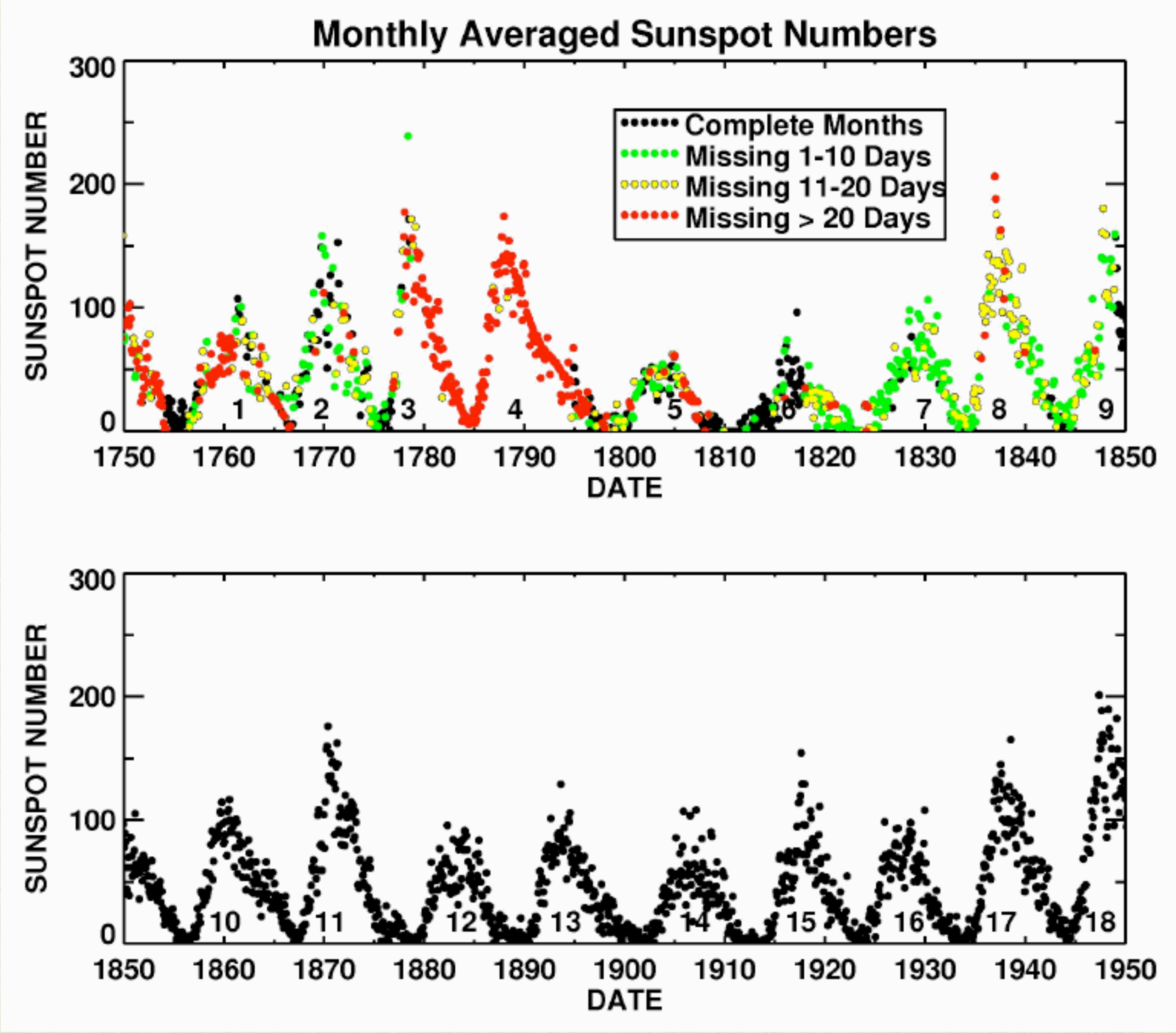
EARLY REPORTS ON SUNSPOTS

- The two oldest record of a sunspot observation are found in the Book of Changes, probably the oldest extant Chinese book, compiled in China around or before 800 BC. The text reads "A dou is seen in the Sun", and A mei is seen in the Sun". From the context, the words (i.e., chinese characters) "dou" and "mei" are taken to mean darkening or obscuration.

John of Worcester (1128)

SUNSPOT (WOLF) NUMBERS

- Samuel Schwabe observed the Sun regularly in the 1826-1843 period, discovering the 11-year cycle.
- Rudolf Wolf redefined the counting method (1848) and extended the records back to 1755.



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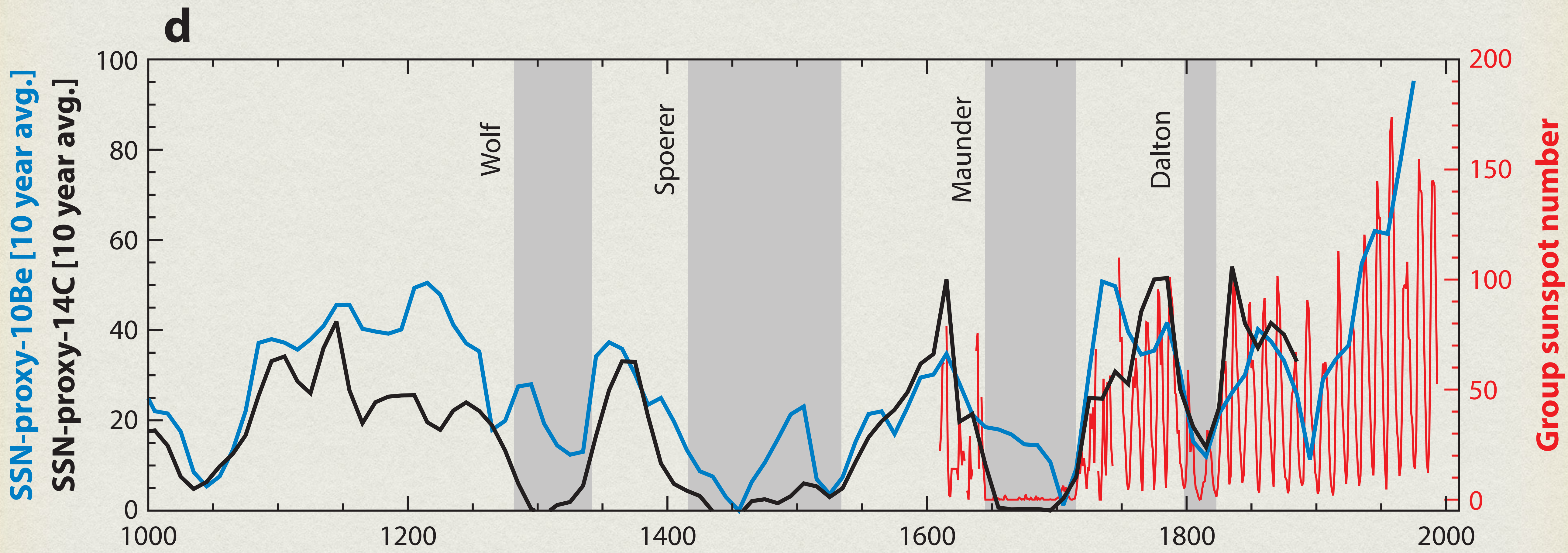
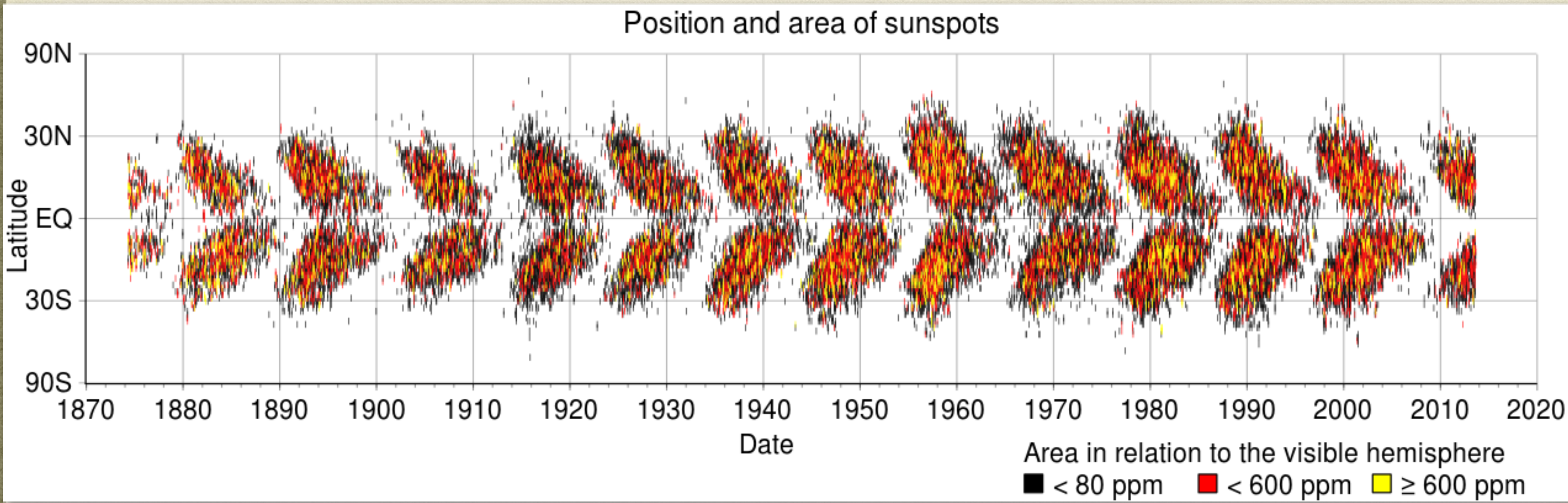
CYCLE IRREGULARITIES



Charbonneau (2014)

EQUATORIAL DRIFT



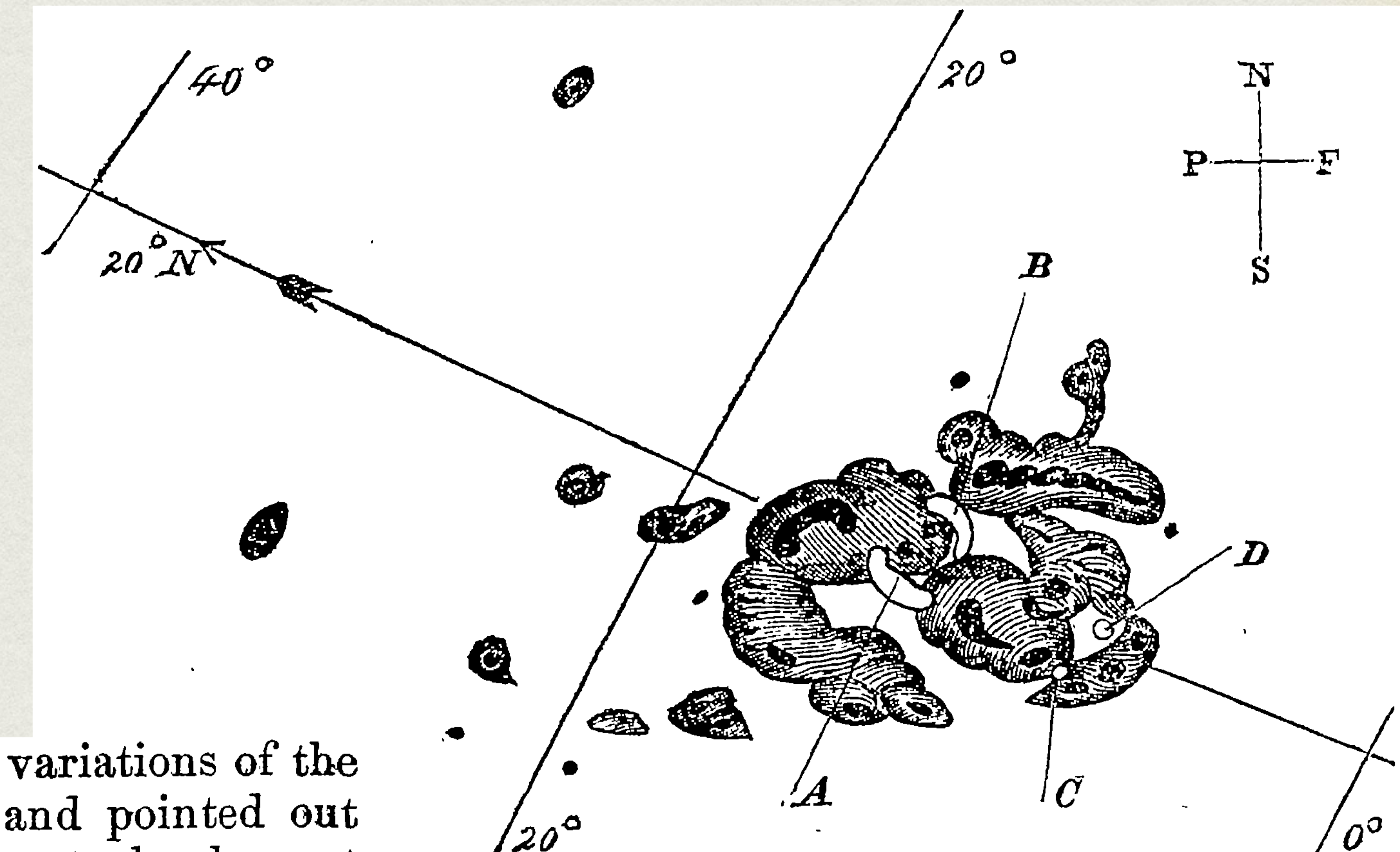
- The sunspots drift along each cycle from the ±30° latitudes towards the equator.
- Discovered by Richard Carrington (1861), it has been refined by Gustav Spörer.

Description of a Singular Appearance seen in the Sun on September 1, 1859. By R. C. Carrington, Esq.

MNRAS, vol. 20, p. 13

CARRINGTON EVENT

used in the observation, when within the area of the great north group (the size of which had previously excited general remark), two patches of intensely bright and white light broke out, in the positions indicated in the appended diagram by the letters A and B, and of the forms of the spaces left white. My



and copies of the photographic records of the variations of the three magnetic elements, as obtained at Kew, and pointed out that a moderate but very marked disturbance took place at about $11^h\ 20^m$ A.M., Sept. 1st, of short duration; and that towards four hours after midnight there commenced a great magnetic storm, which subsequent accounts established to have been as considerable in the southern as in the northern hemi-

ZEEMAN EFFECT

- Splitting of spectral lines due to magnetic field.
- Discovered by Pieter Zeeman in 1896 (Nobel Prize 1902).
- Applied to interpret spectroscopic observations of sunspots by George Hale in 1908.
- The field strength estimated at 2.6-2.9 kG.

(1) Southern spot, showing red components of doublets. Nicol 29° W. (2) One umbra of northern spot, showing violet components of doublets. Nicol 29° W. (3) Other umbra of northern spot, showing violet components of doublets. Nicol 29° W. (4) Some umbra of northern spot, showing red components of doublets. Nicol 61° E. (5) Spot spectrum without rhomb or Nicol, showing both components of doublets. Scale: 1 Ångström=6 mm.

HALE'S POLARITY LAW

- Hale et al. (1919) established that close sunspot pairs are oppositely polarized, the polarity of leading sunspot.
- Moreover, inclination of sunspot pairs decreases with latitude (Joy's law).

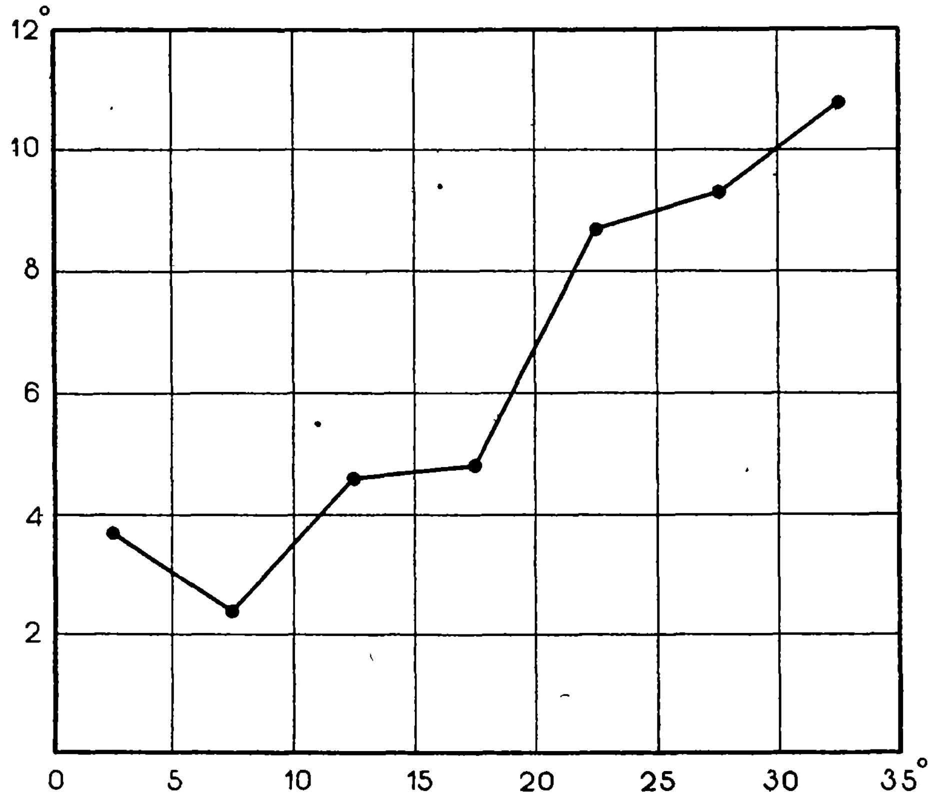
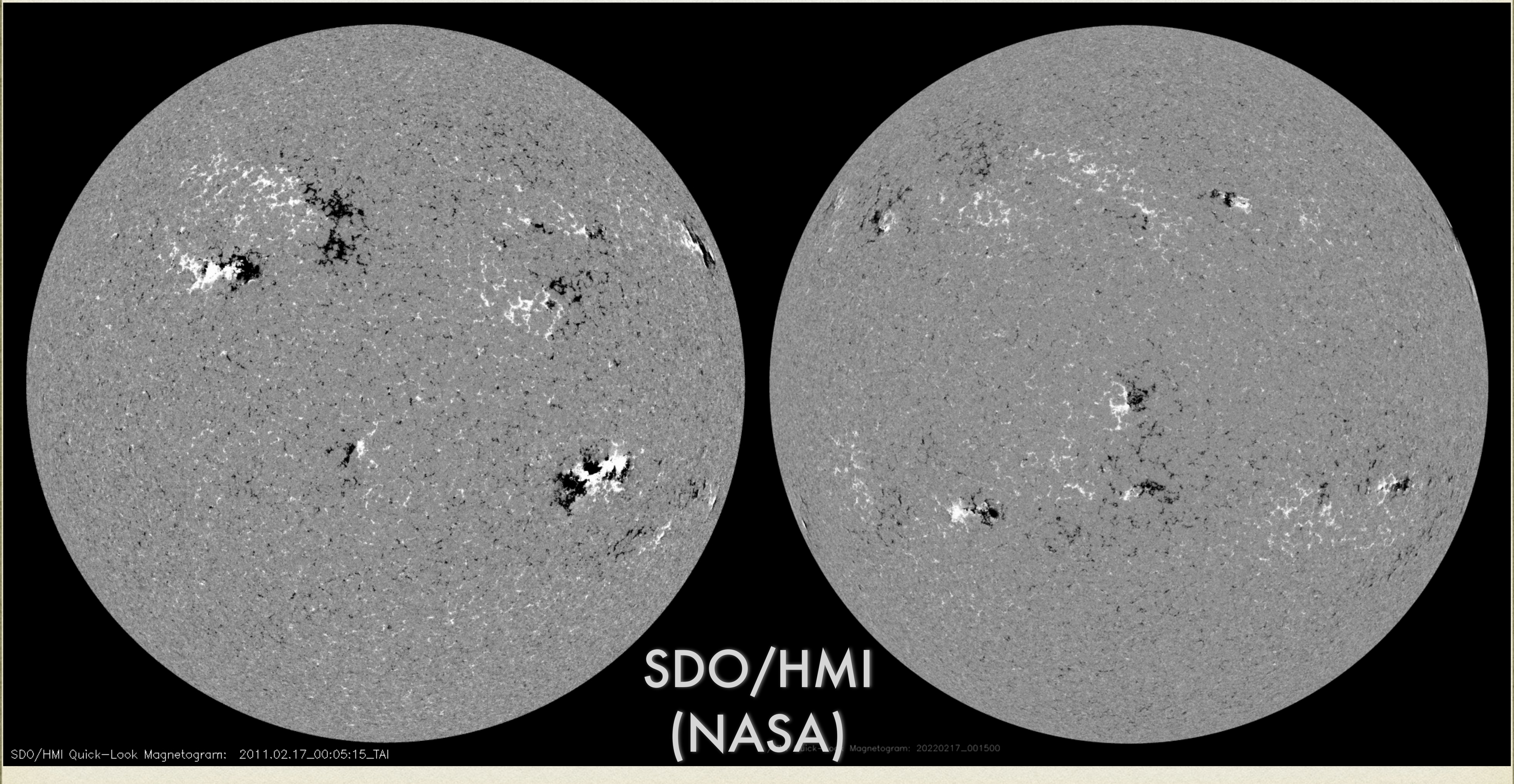


FIG. 5.—Summary of a statistical study of the sun-spot drawings of Carrington and Spörer showing the variation with latitude (abscissae) in the preferential inclination (ordinates) of the axis of bipolar sun-spot groups. In low latitudes the axes are nearly parallel to the sun's equator, but with increasing latitude the mean inclination increases to a maximum of about 11°.

HALE'S POLARITY LAW

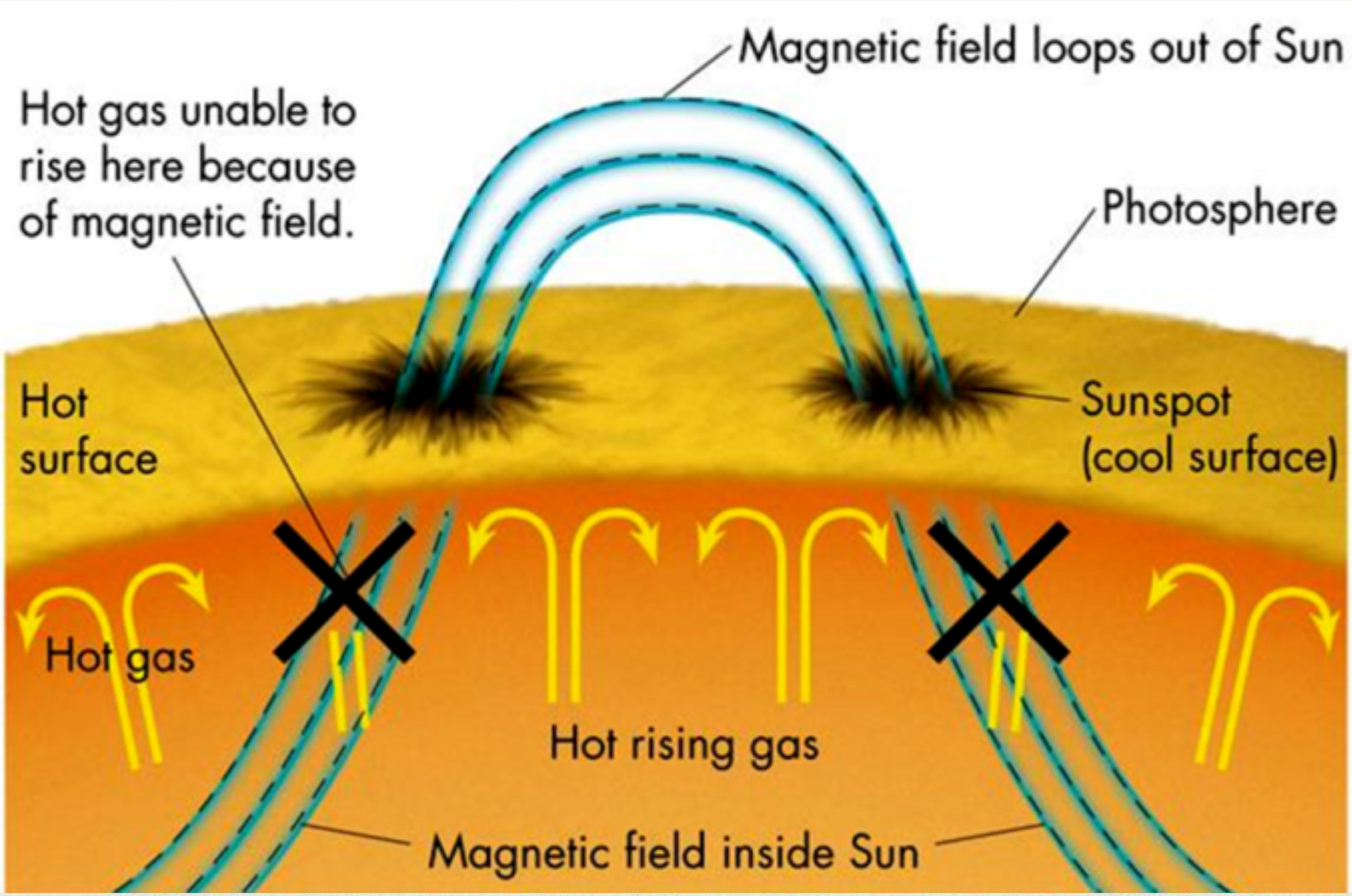
Feb 17th, 2011

Feb 17th, 2022

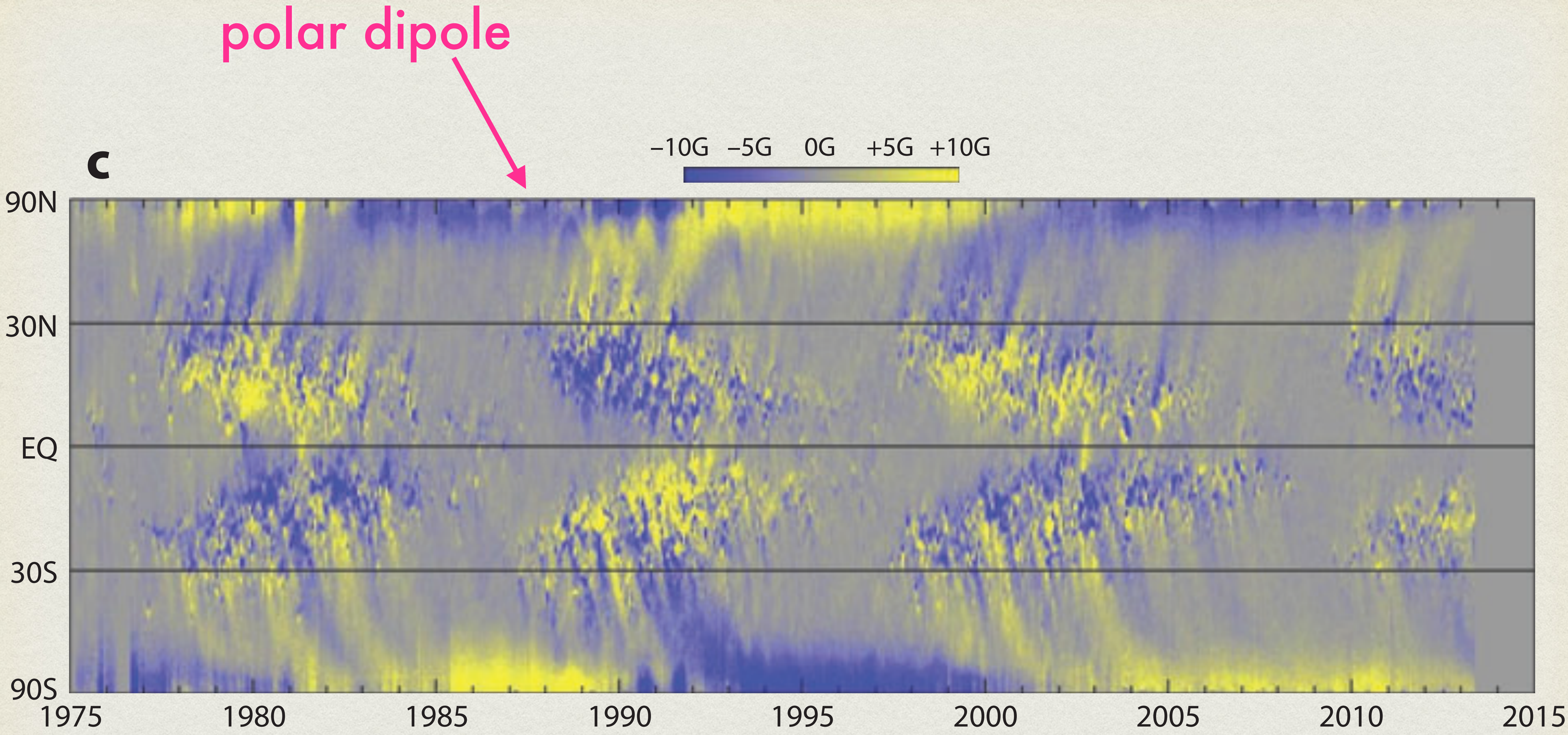


SUNSPOTS AS MAGNETIC FLUX TUBES

- sunspots:
  B ~ 3 kG
  T ~ 3000 - 4500 K
- standard photosphere:
  B ~ 1-2 G,
  T = 5800 K



22-YEAR MAGNETIC CYCLE



Charbonneau (2014)

HEMISPHERIC MAGNETIC FLUXES

magnetic flux

$$\Psi_B = \oint B_\perp \, \mathrm{d}S$$

magnetic helicity transfer

$$\frac{\mathrm{d}}{\mathrm{d}t} \int \vec{A} \cdot \vec{B} \, \mathrm{d}V$$

Mx (maxwell) $\equiv$ G cm^2

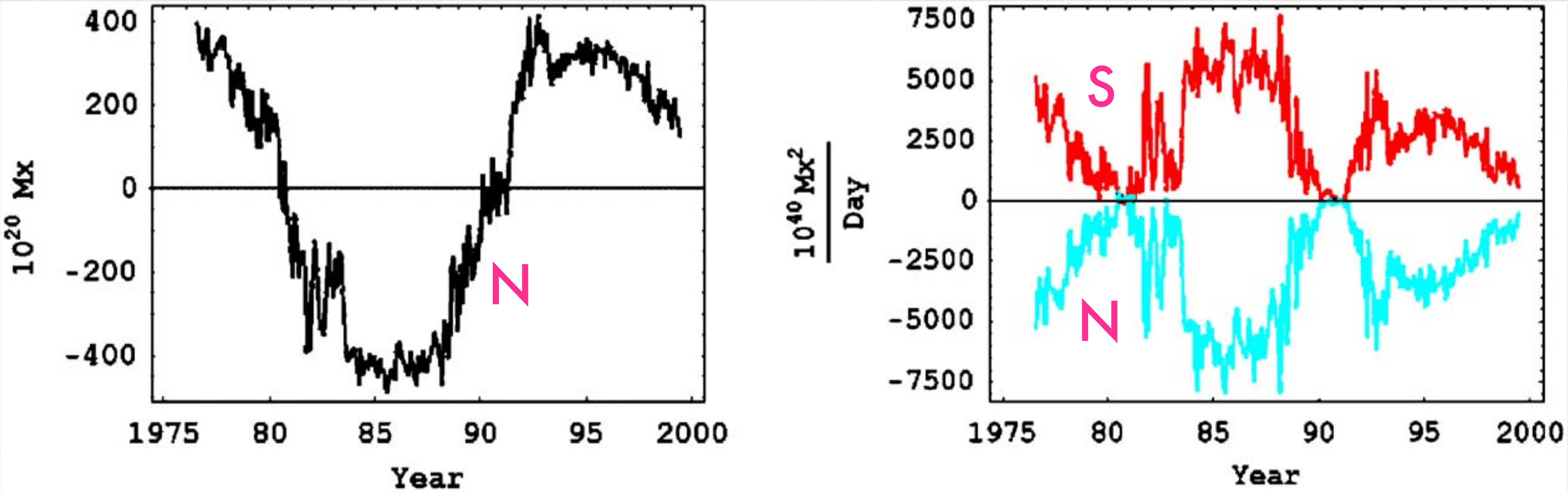


Fig. 2.4. Net magnetic flux through the solar surface at the northern hemisphere (left hand panel) and magnetic helicity flux for northern and southern hemispheres (right hand panel, lower and upper curves, respectively). Adapted from Berger and Ruzmaikin [43].

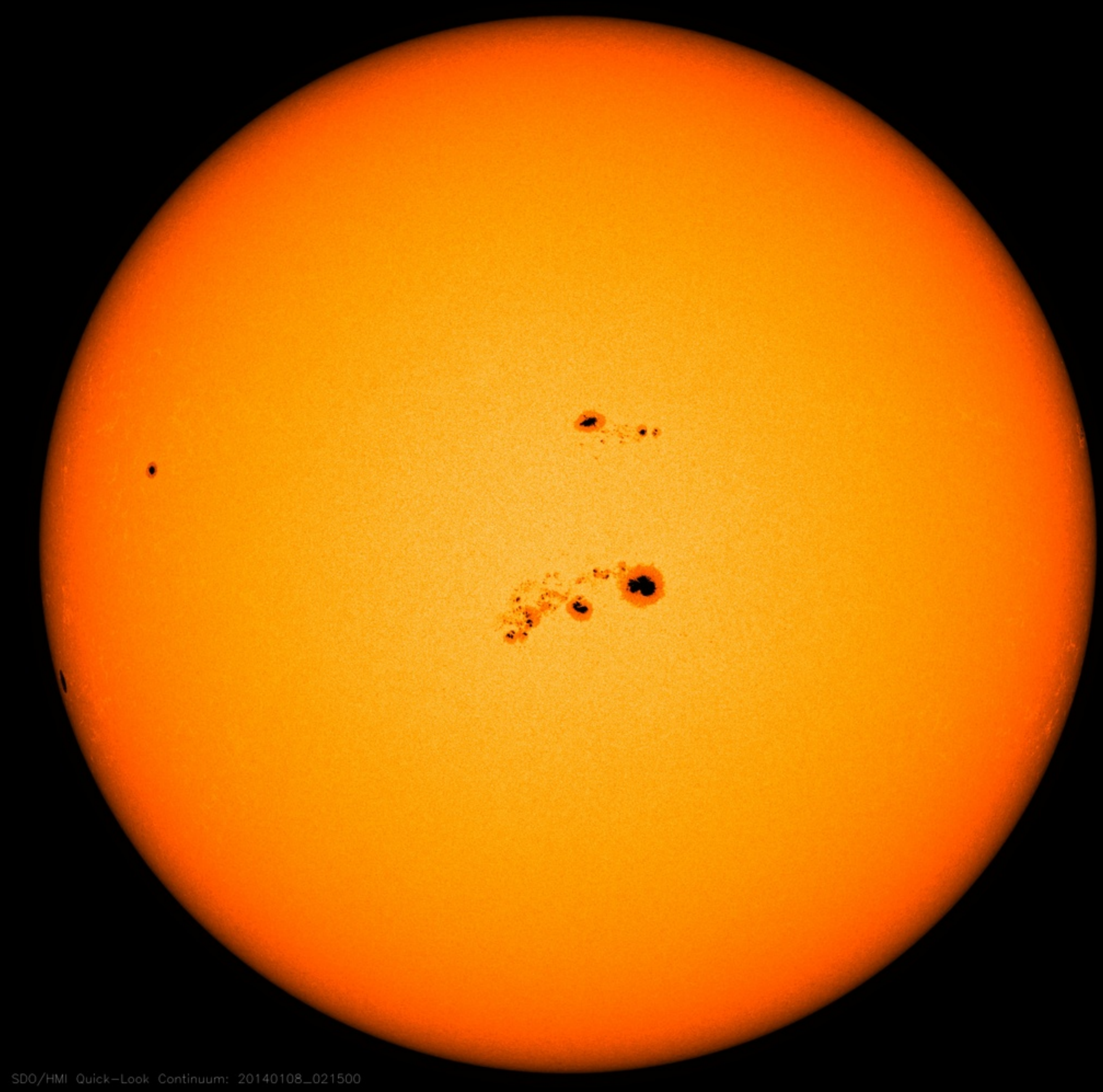
Berger & Ruzmaikin (2000)

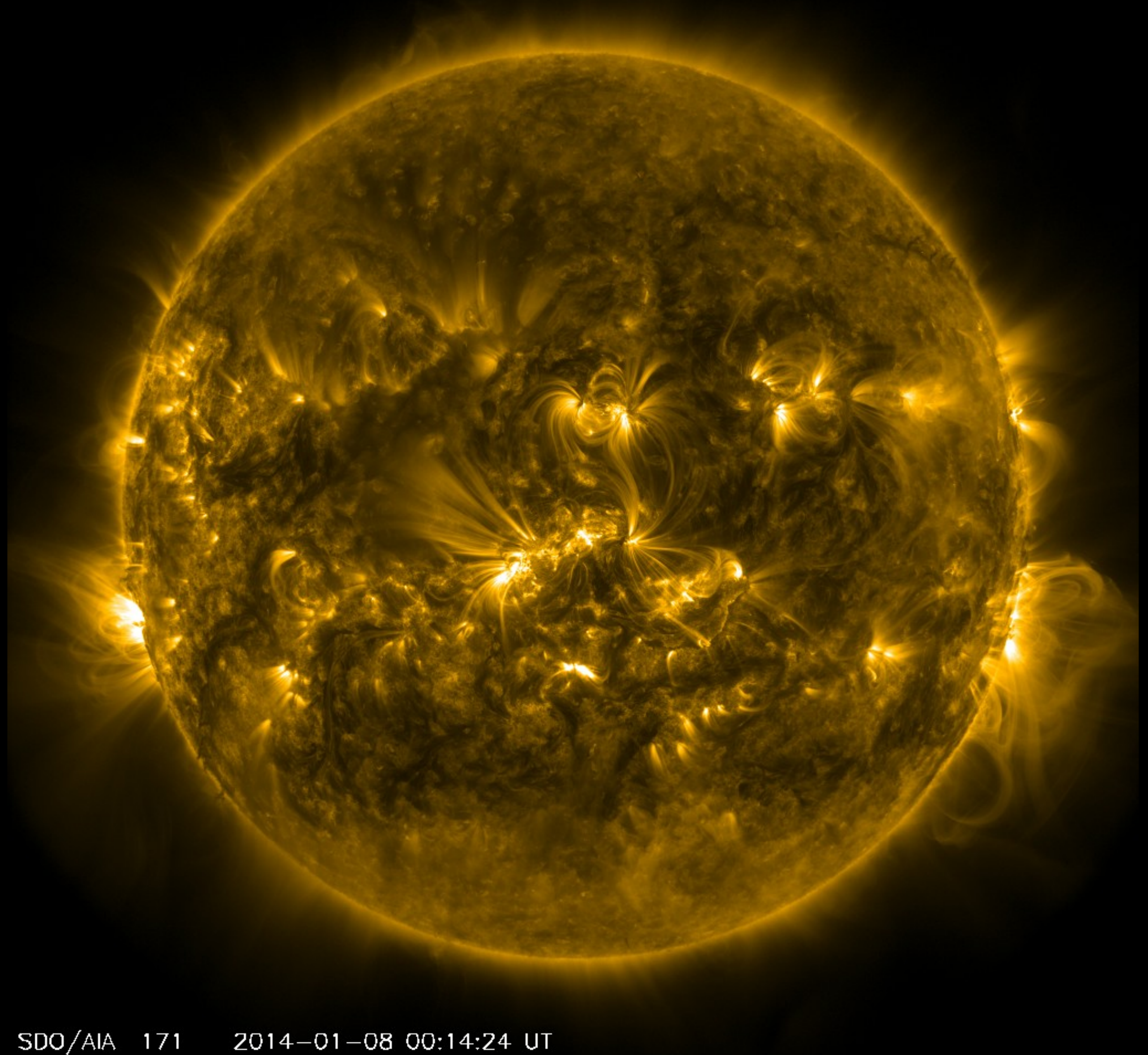
Brandenburg & Subramanian (2005)

Solar Dynamics Observatory (NASA, since 2010)

visual

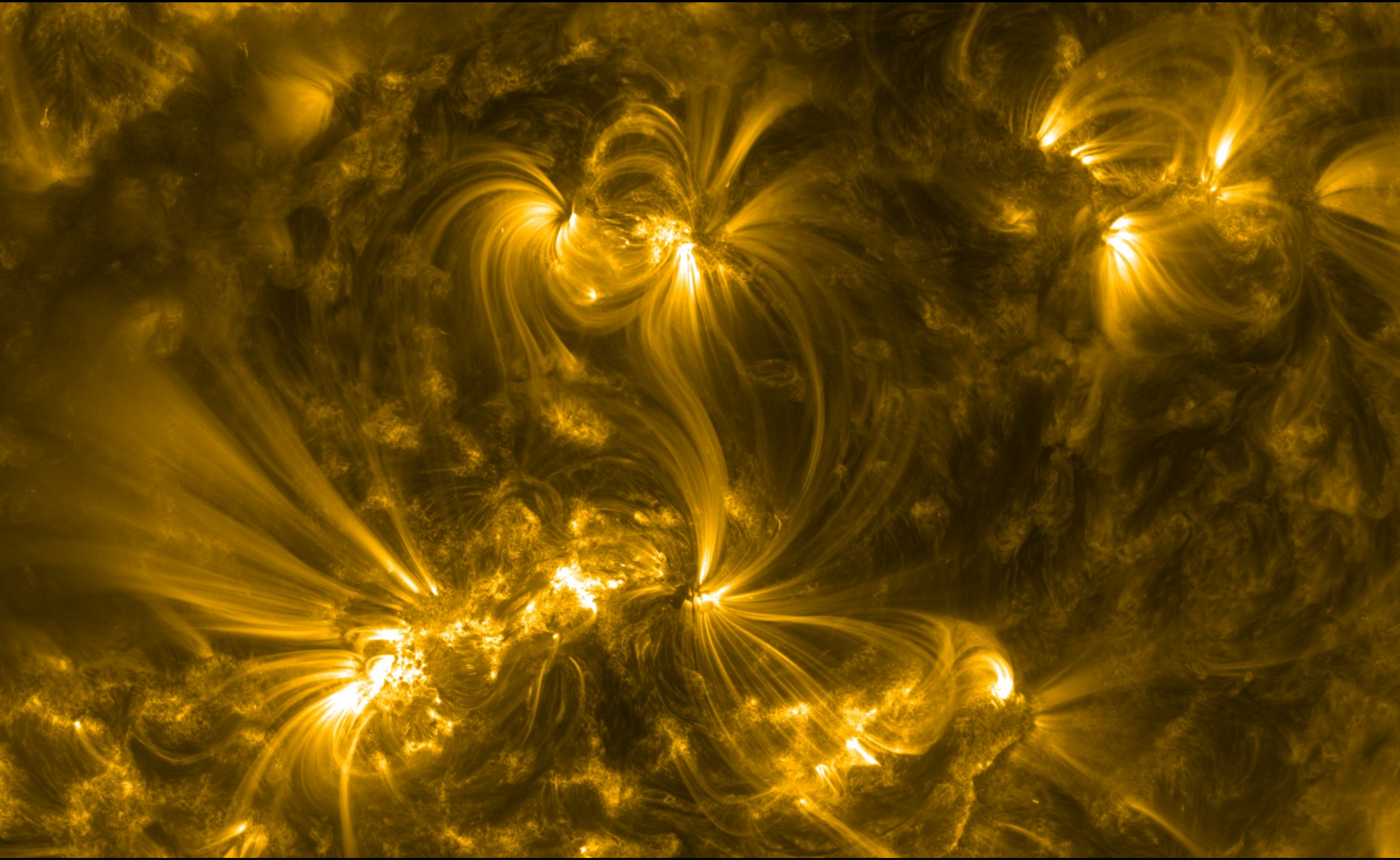
extreme ultraviolet (EUV, 171A)



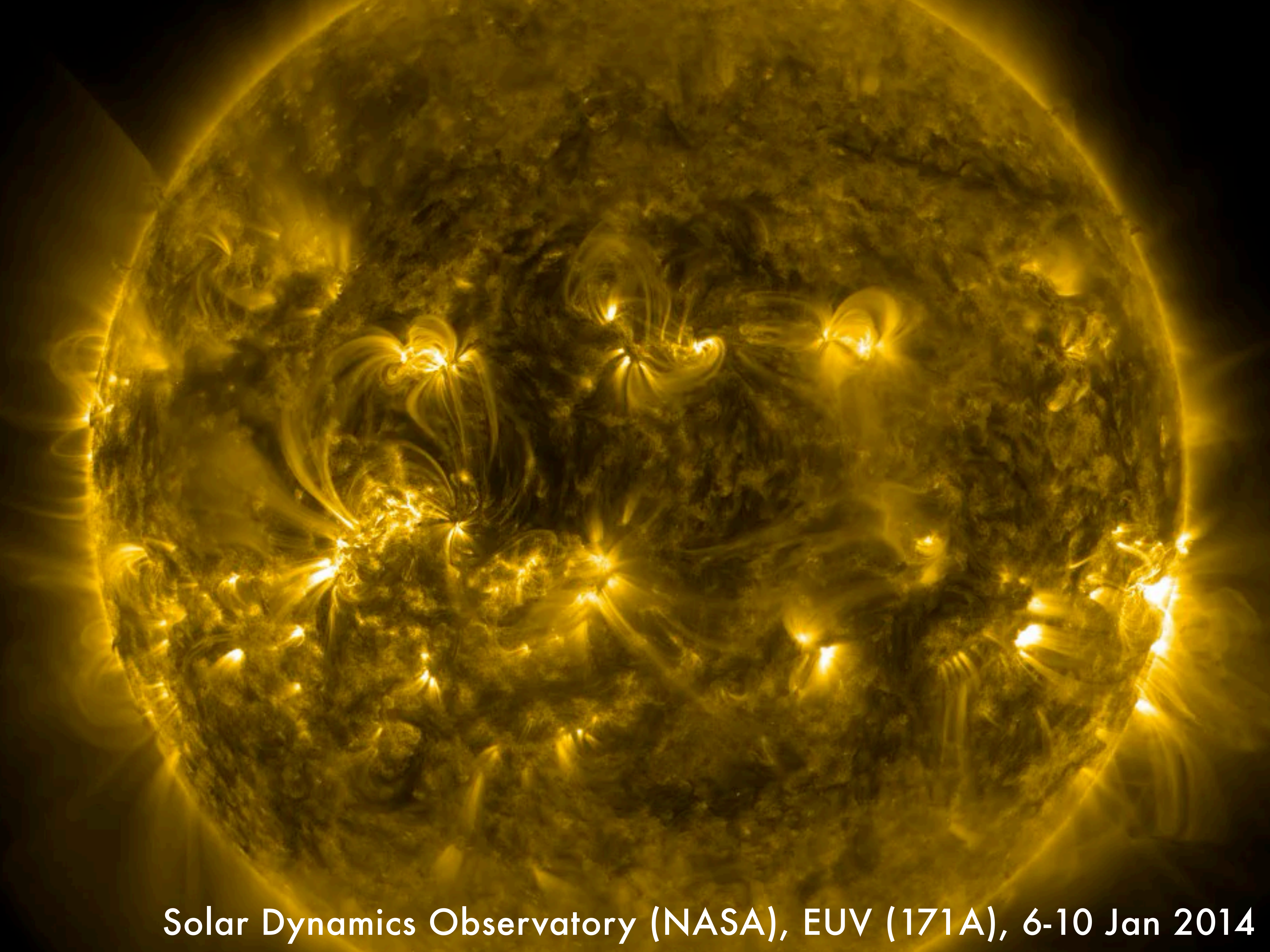


https://www.nasa.gov/feature/goddard/2020/watch-a-10-year-time-lapse-of-sun-from-nasa-s-sdo

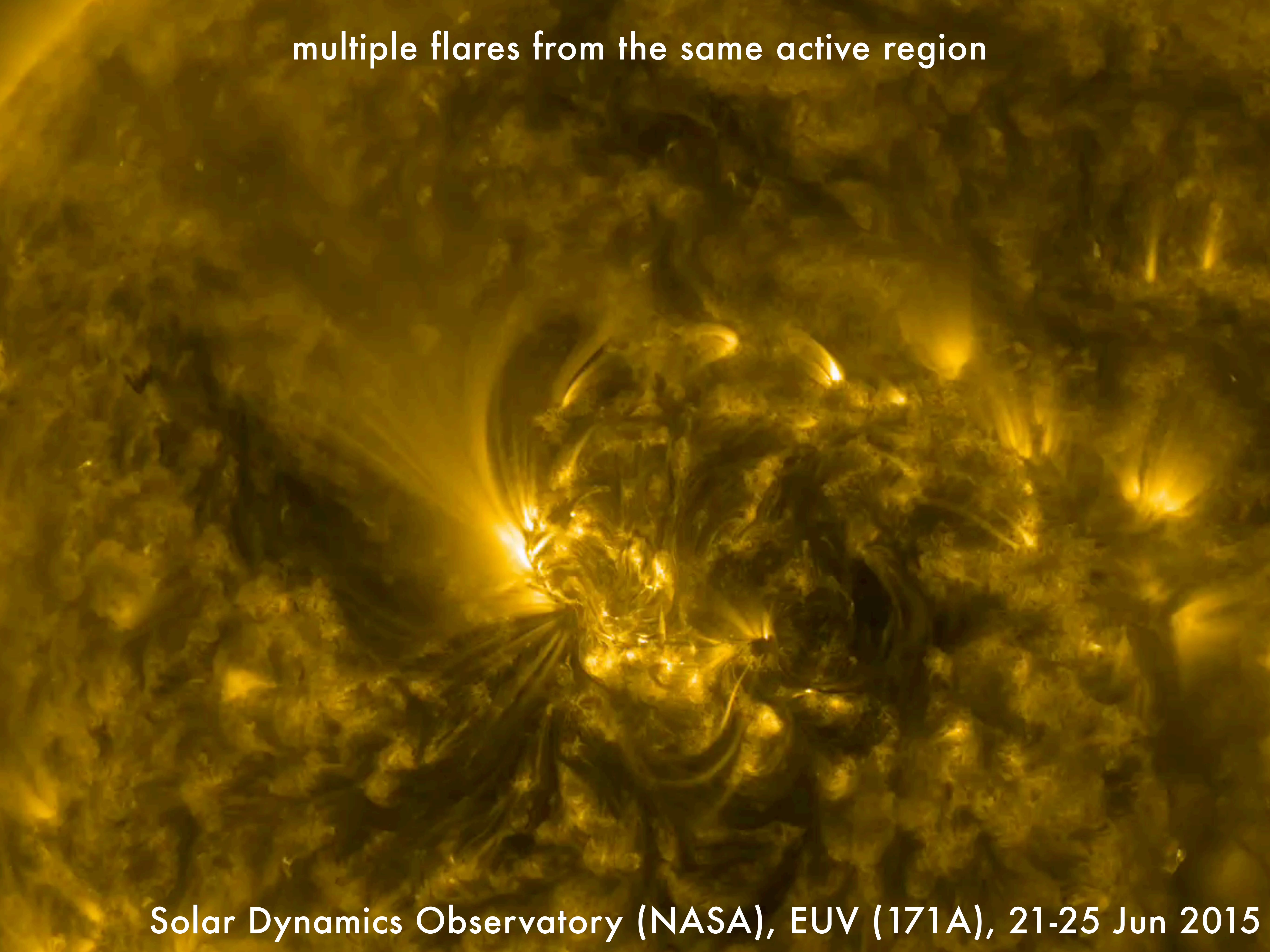
solar active regions



Solar Dynamics Observatory (NASA), EUV (171A), 8 Jan 2014



Solar Dynamics Observatory (NASA), EUV (171A), 6-10 Jan 2014 multiple flares from the same active region

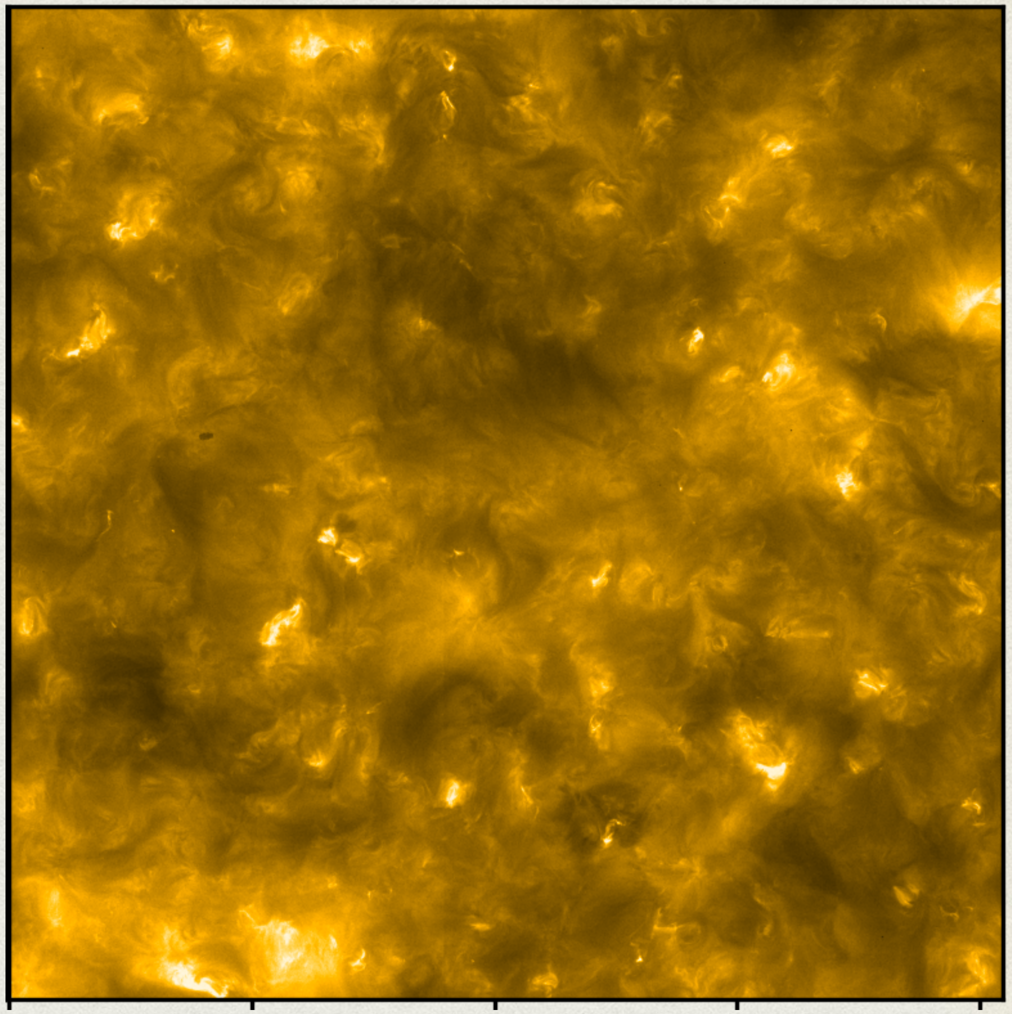


Solar Dynamics Observatory (NASA), EUV (171A), 21-25 Jun 2015

SOLAR ORBITER CAMPFIRES

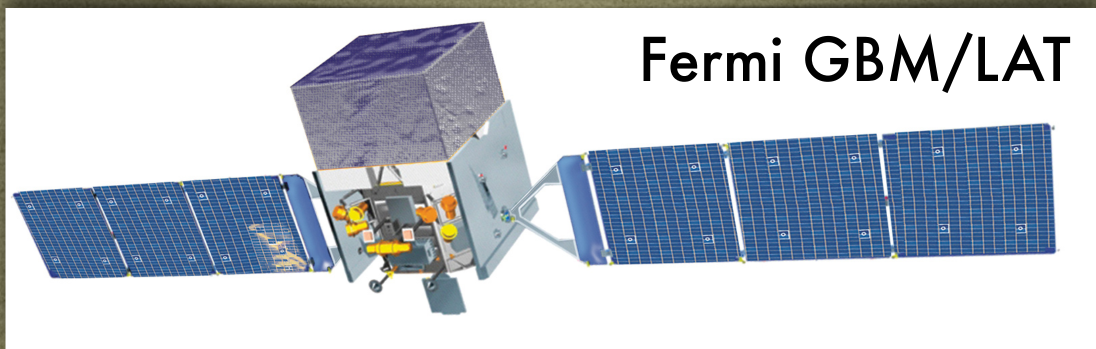
- Solar Orbiter, ESA mission launched in Feb 2020, closest approach 0.29 AU

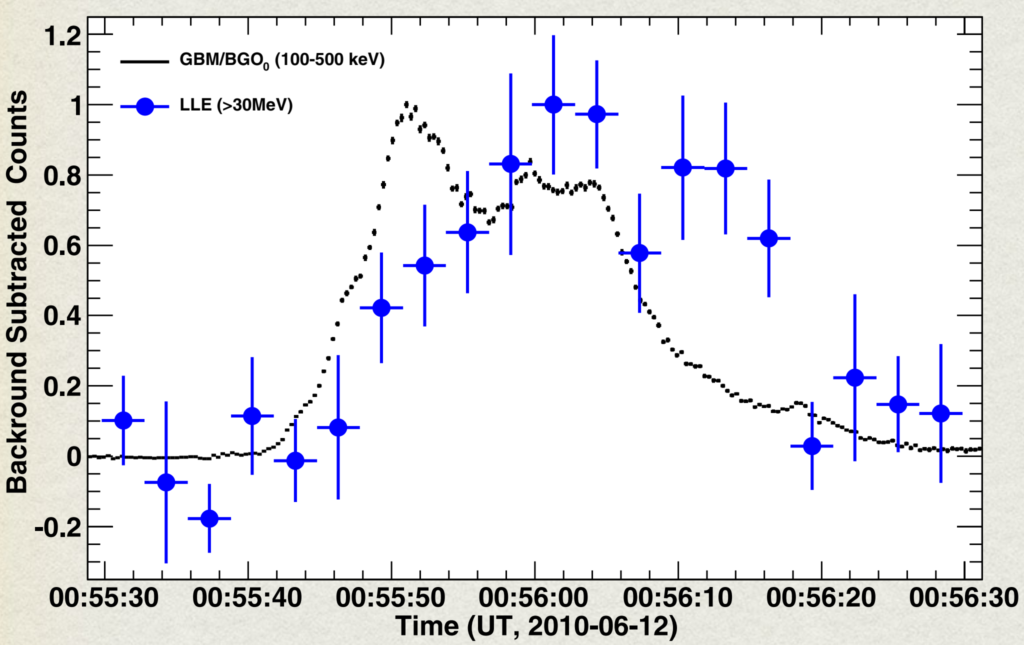
- campfires are small EUV brightenings observed in the quiet regions of the solar chromosphere



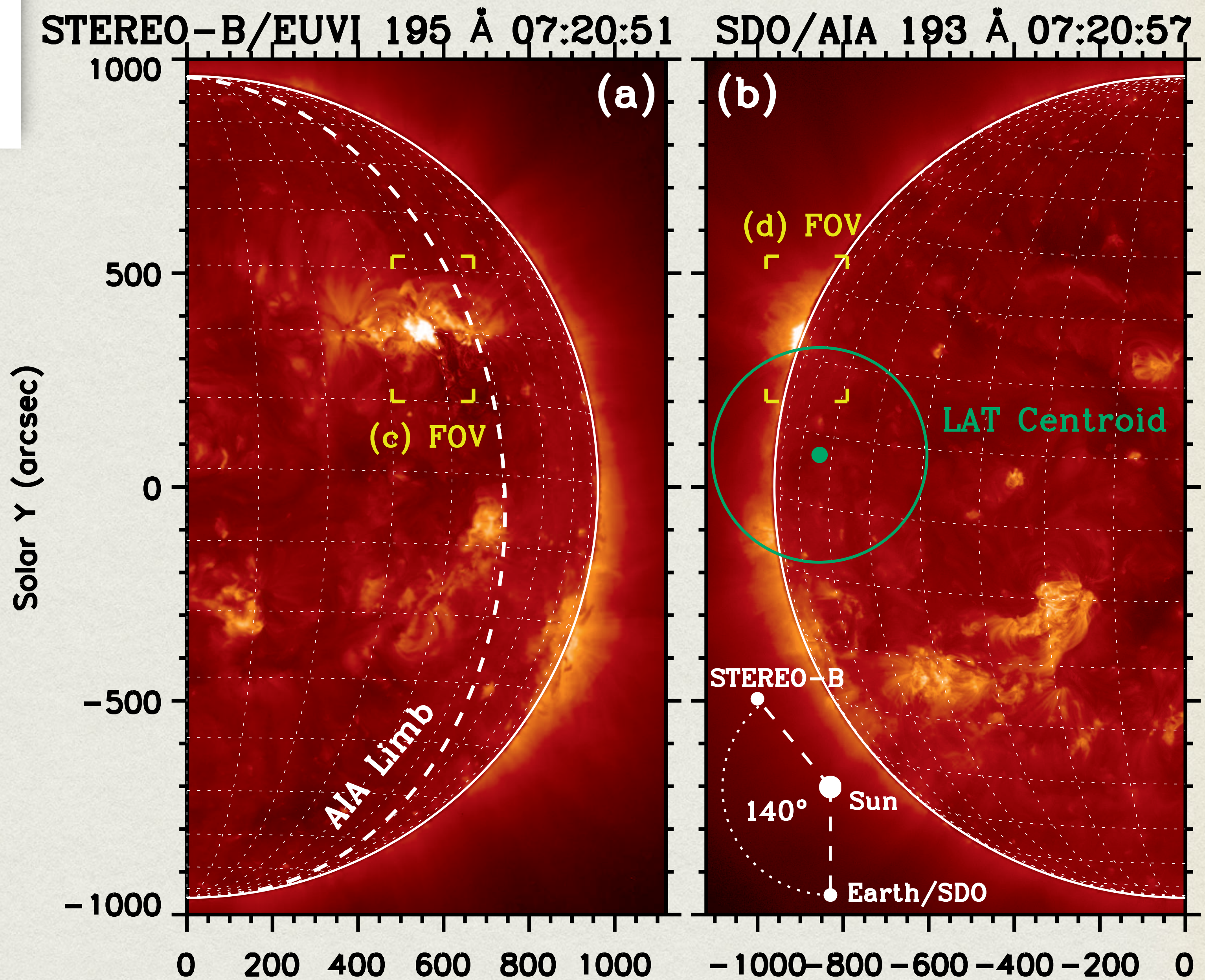
EUV image
at the scale of 400 Mm $\sim 0.3R_{\odot}$
(Kahil et al. 2022)

SOLAR GAMMA-RAY FLARES





Ackermann et al. (2012)



Pesce-Rollins et al. (2015)

PROBLEM 4: MAGNETIC HELICITY

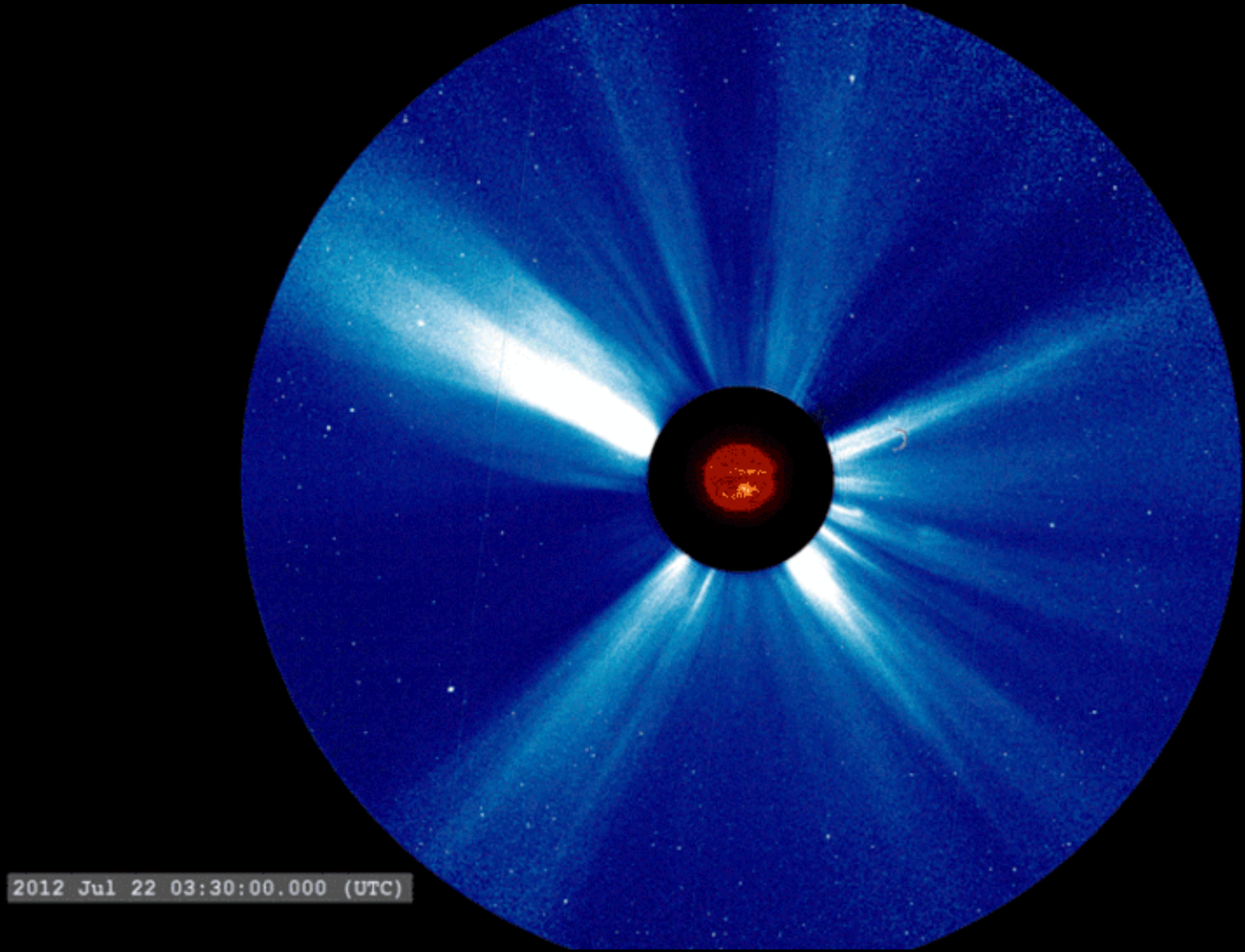
- Magnetic helicity is defined for a system of volume V as the integral $\mathscr{H} = \int_V \left(\overrightarrow{A} \cdot \overrightarrow{B}\right) \mathrm{d}V$, where $\overrightarrow{A}$ is the magnetic vector potential.
- Calculate $\dfrac{\mathrm{d}\mathscr{H}}{\mathrm{d}t}$ in the regime of resistive MHD in terms of $\overrightarrow{B}$. Assume that potentials $\overrightarrow{A}, \phi$ vanish at the system boundaries.

This problem is worth 5 points. Solutions should be sent as 1-page PDF files to knalew@camk.edu.pl before the next lecture.

a filament initiating a coronal mass ejection (CME)

Solar Dynamics Observatory (NASA), 171A+304A, 31 Aug 2012

a coronal mass ejection (CME)
followed by solar energetic particles (SEP)
observed by STEREO (NASA, since 2006)

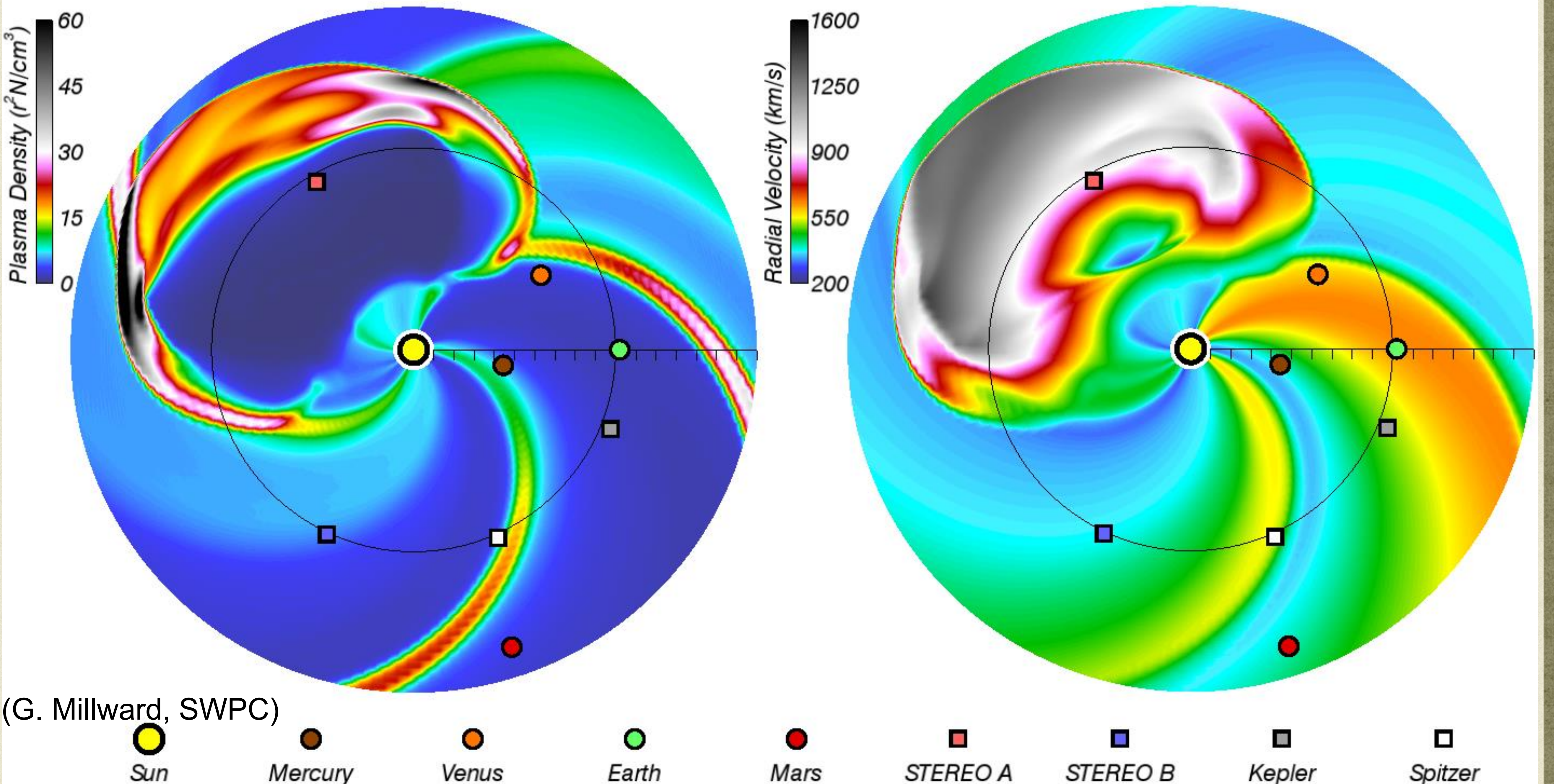


SPACE WEATHER

simulation of a dangerous July 2012 CME

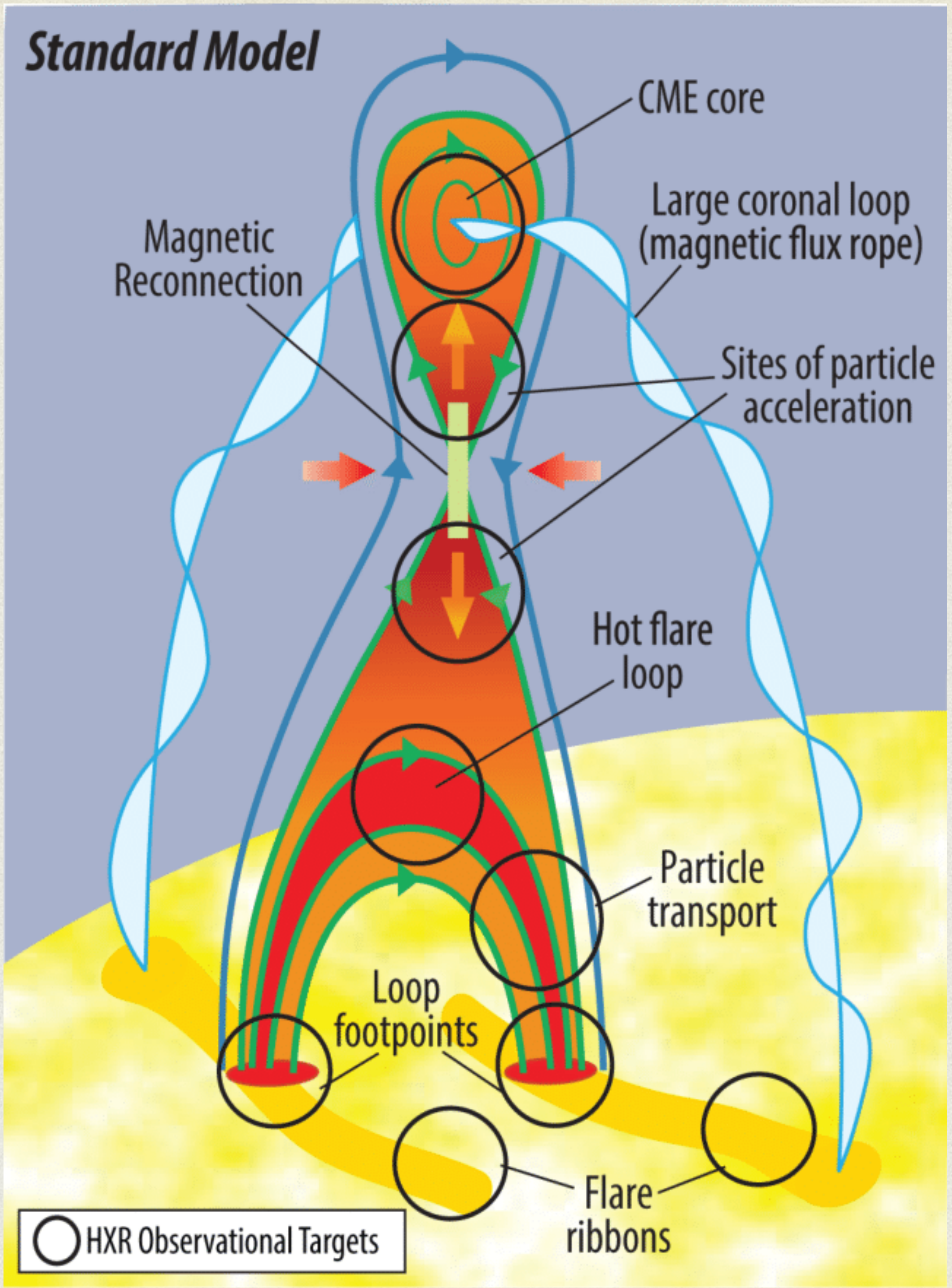
[Baker et al., 2013]

WSA-ENLIL

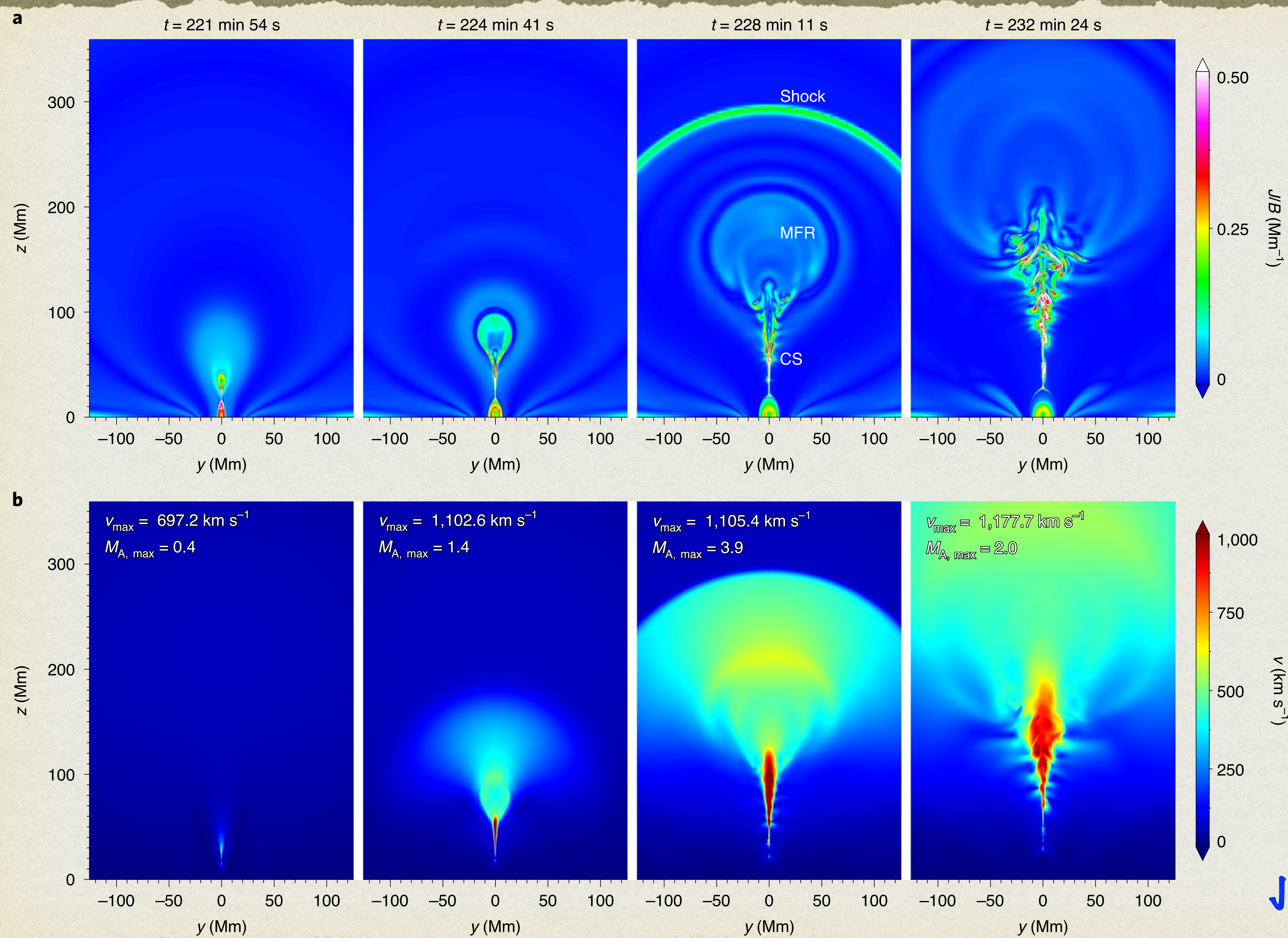


(G. Millward, SWPC)

SOLAR ERUPTION MECHANISM



SOLAR ERUPTION SIMULATIONS



Jiang et al. (2021)

SOLAR CORONA

- First spectroscopic observations during eclipses led to the discoveries of helium (Janssen 1868) and *coronium* (Young, Harkness 1869).
- The 530nm coronium line has been identified only in 1939-40 as Fe XIV (Grotrian, Edlen), implying temperatures of $T \sim 10^6$ K.

- Coronal heating mechanism: waves (AC), reconnection (DC).

Zeitschrift für Astrophysik, Bd. 29, S. 274—286 (1951).

Kometenschweife und solare Korpuskularstrahlung.

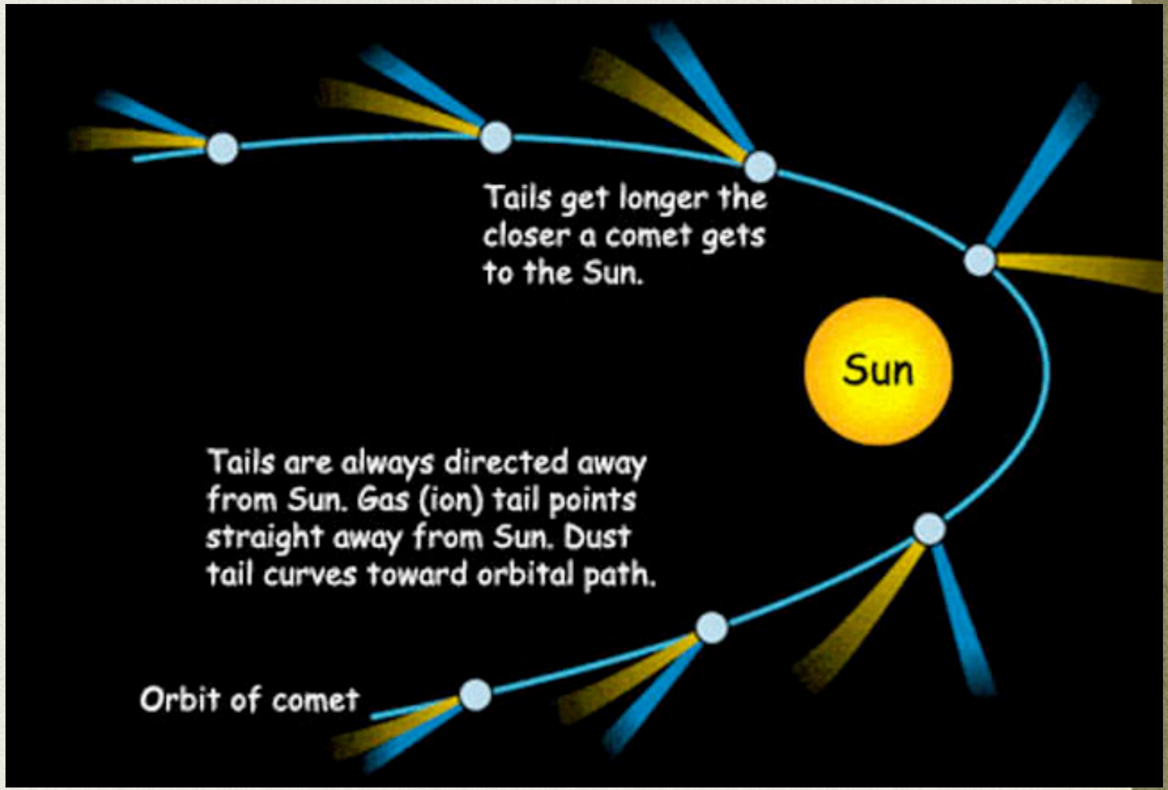
Von

L. BIERMANN.

Max-Planck-Institut für Physik, Göttingen.

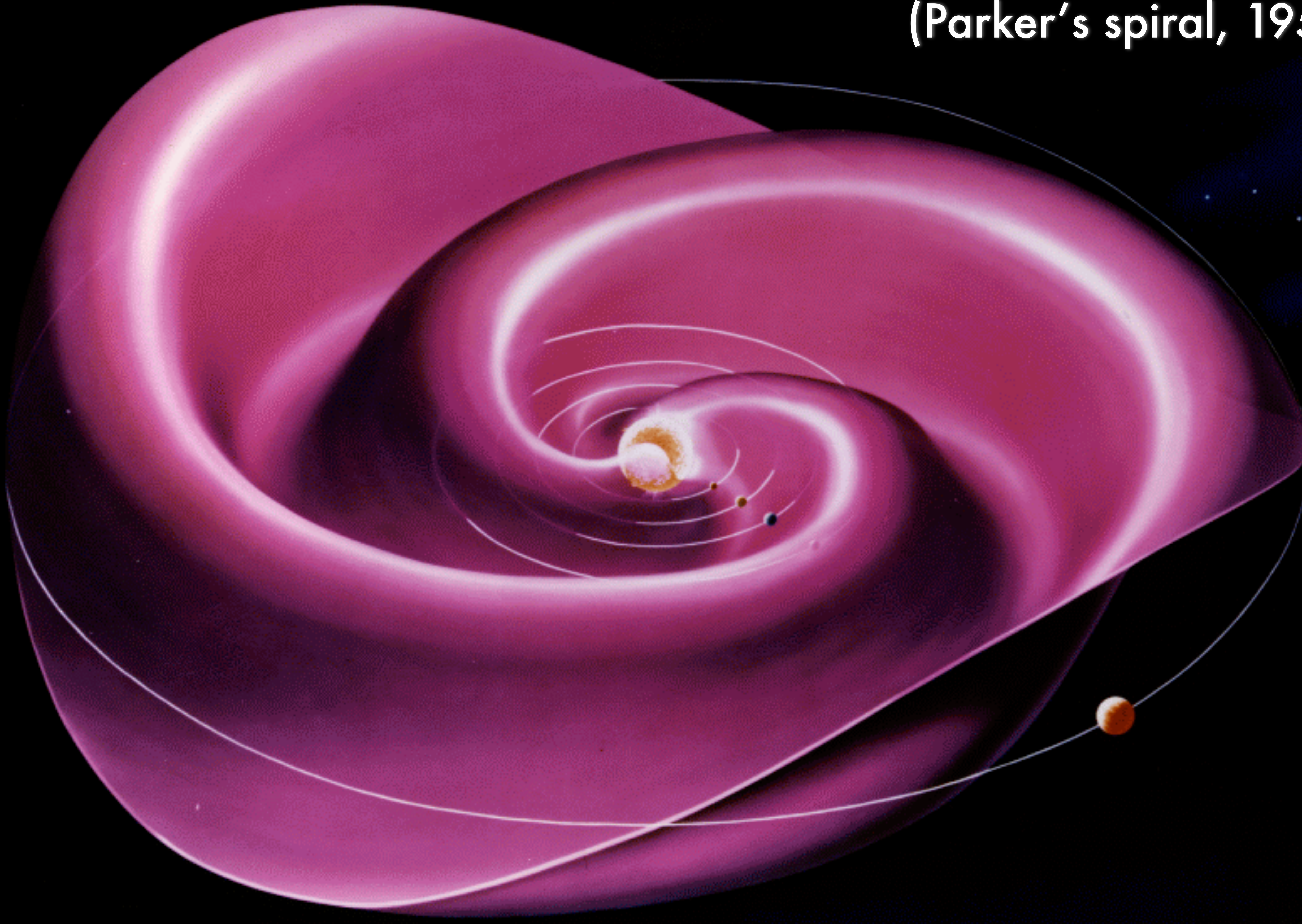
(Eingegangen am 10. Mai 1951.)

In langgestreckten Kometenschweifen, die aus Ionen (CO^+ u. a. m.) bestehen, werden oft Beschleunigungen der Schweifelemente beobachtet, welche ihrem Betrage nach die Schwerebeschleunigung der Sonne (0,6 cm sec^{-2} in Erdnähe) um Faktoren der Ordnung 10^1 bis einige 10^3 übertreffen. Derart hohe Beschleunigungen lassen sich nicht auf den Druck der Sonnenstrahlung auf die Moleküle zurückführen. Es wird die Auffassung begründet, daß diese Beschleunigungen durch die Korpuskularstrahlung der Sonne hervorgerufen werden. Die solare Korpuskularstrahlung, deren Eigenschaften von den erdmagnetischen Beobachtungen her bekannt sind, besteht aus Ionen und freien Elektronen in gleicher Anzahl (10^3 bis 10^5 cm^{-3}), die mit geordneten Geschwindigkeiten von 10^3 km/sec von der Sonne emittiert werden; die Temperatur der Teilchen wird zu 10^4 angenommen. Unter diesen Umständen erfahren die in der Kometenhülle entstandenen CO^+ Ionen Beschleunigungen bis zu 10^4 cm/sec^2. Der Impuls wird praktisch nur durch die freien Elektronen übertragen, deren effektiver Stoßquerschnitt den gaskinetischen Querschnitt um mehrere Zehnerpotenzen übertrifft. An Hand der Plasmagleichungen lassen sich die entstehenden elektrischen Felder abschätzen; diese stellen sich so ein, daß die freien Elektronen die mittlere Bewegung der solaren Ionen und der kometarischen Molekülionen gerade fast genau mitmachen; die Ionen werden durch das elektrische Feld nicht nennenswert beschleunigt oder verzögert. An Hand dieser Vorstellung über den Beschleunigungsmechanismus lassen sich die Beobachtungen HOFFMEISTERs über die Lage des primären Schweifstrahls verstehen. — Falls die Partikelstrahlung Magnetfelder mit sich führt, ergibt sich eine u. U. noch stärkere Impulsübertragung auf die Molekülionen. — Das gewonnene Bild wird am Beispiel des Kometen Whipple-Fedtke (1942 g) kontrolliert. Die Beobachtungen zeigen einen sehr deutlichen Einfluß des magnetischen Sturms vom 29. III. 1943 und einen ähnlichen Effekt fast genau eine Sonnenrotation früher, der wahrscheinlich durch von dem gleichen Herd auf der Sonne ausgehende Partikelstrahlung verursacht wurde.



Universe Today / NASA

heliospheric current sheet
(Parker's spiral, 1958)

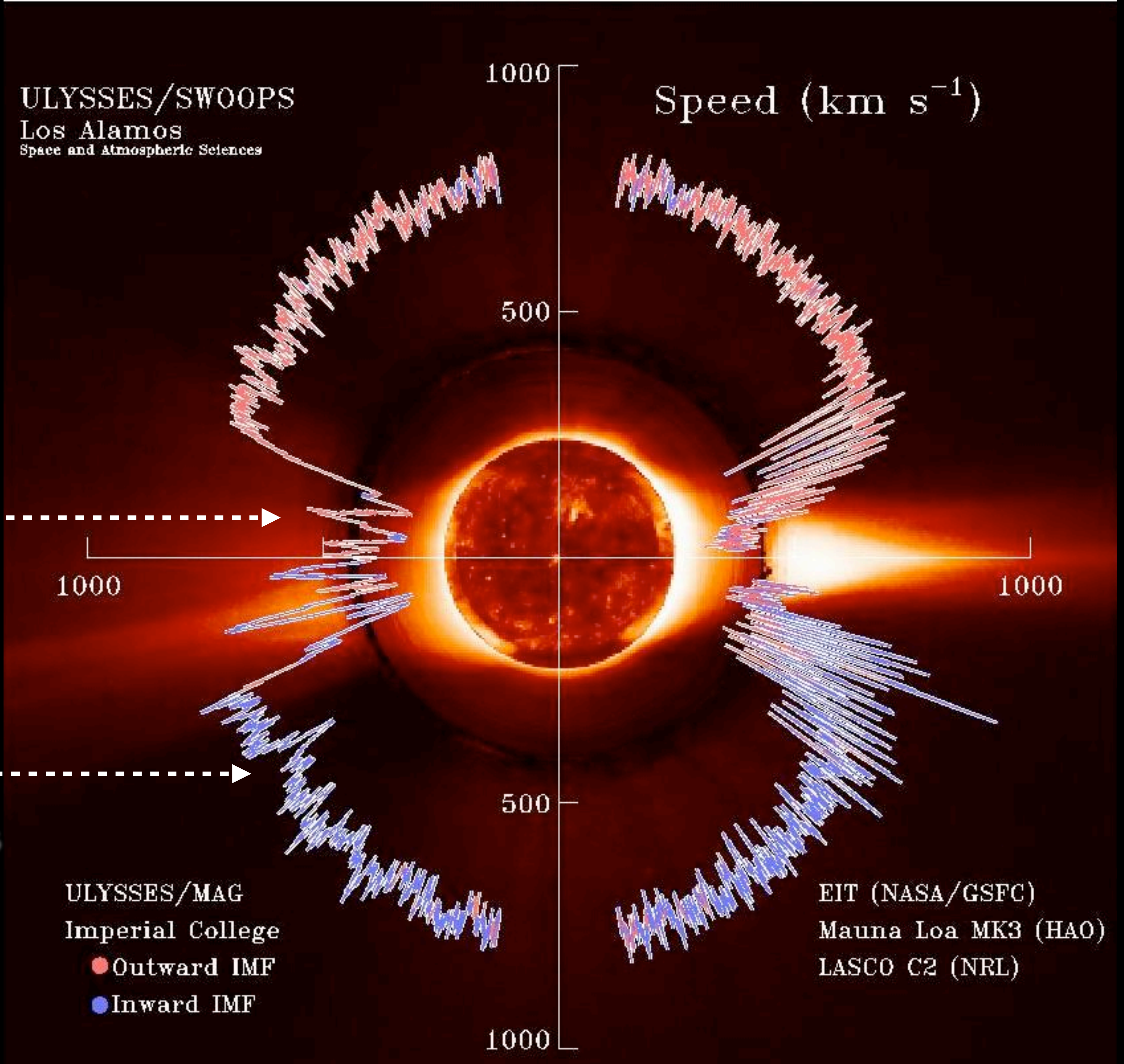


Werner Heil, Public domain, Wikimedia Commons

solar wind at solar minimum

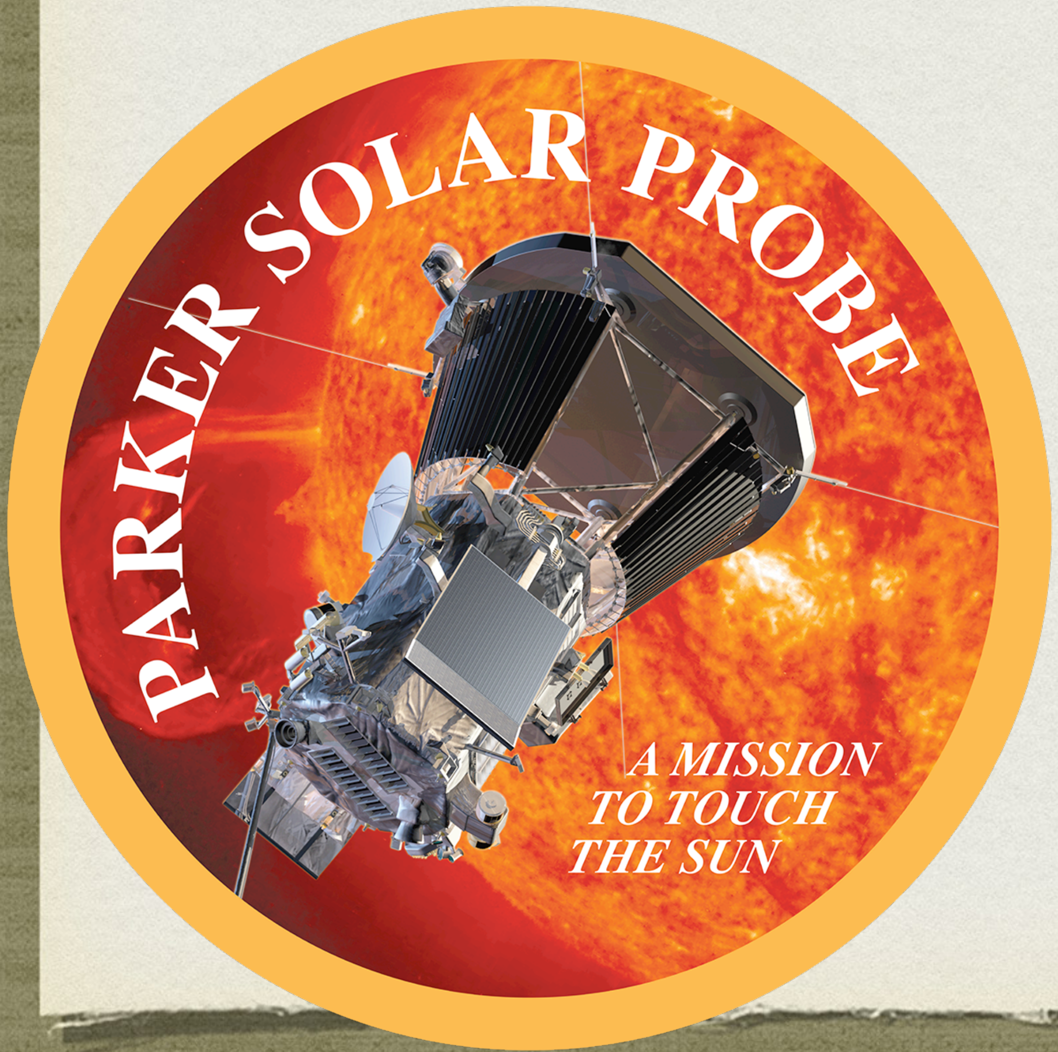
slow solar wind from streamers

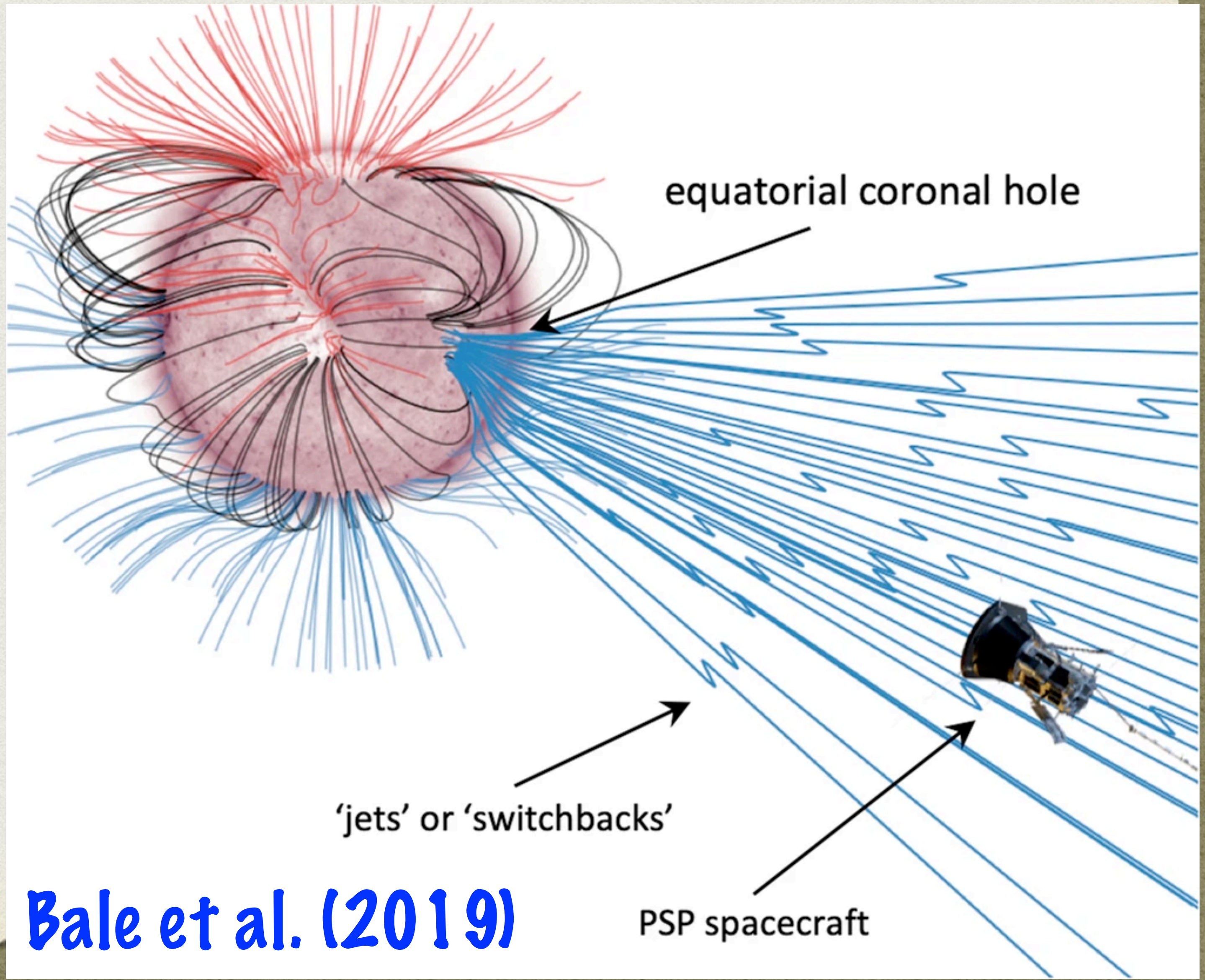
fast solar wind from coronal holes



PARKER SOLAR PROBE MAGNETIC SWITCHBACKS

- Parker Solar Probe, NASA mission launched in Aug 2018, closest approach 0.046 AU ($9.9R_{\odot}$).
- Magnetic switchbacks are localized magnetic field reversals detected in slow solar wind at ~0.2 AU, suggesting impulsive energization at equatorial coronal holes.





SUN: SUMMARY

- Dark sunspots on the surface of the Sun are magnetic flux tubes with $B \sim 3$ kG (quiet Sun: ~ 1 G), usually in pairs of opposite polarity.
- The sunspots statistics show an 11-year cycle, in fact a 22-year cycle of magnetic dynamo with alternating polarity.
- The Sun has an extended tenuous corona of $\sim$ MK temperature with unknown heating mechanism, it is also a source of structured solar wind extending as the heliosphere far beyond the planets.
- Active Sun produces solar flares that may be associated with coronal mass ejections that may impact Earth's magnetosphere (space weather), inducing potentially dangerous geomagnetic storms.