ASTR-6000 Seminar
COLLAGE: Coronal Heating, Solar Wind, & Space Weather

Dr. Steven R. Cranmer
Dr. Thomas E. Berger

Syllabus

COLLAGE: Topics in Coronal Heating, Solar/Stellar Wind Acceleration, and Space Weather

Instructors:
- Dr. Steven R. Cranmer (steven.cranmer@colorado.edu, 303-735-1265)
  Office: Duane Physics D111, LASP/SPSC N218 (east campus)
- Dr. Thomas E. Berger (thomas.berger@colorado.edu, 303-735-8557)
  Office: Smead Aerospace Building, N433 (east campus)

Course Times: Thursdays, 4:00–4:50 pm (Mountain), Duane Physics room E126
Course Web Pages: https://stevencranmer.bitbucket.io/ASTR_6000_2022/
Office Hours: TBD dates, times, & modes (in-person or virtual)

SUMMARY

This hybrid course is the ninth offering of the *George Ellery Hale Collaborative Graduate Education (COLLAGE)* program, a joint effort between CU Boulder, the National Solar Observatory (NSO), New Jersey Institute of Technology (NJIT), University of Hawai'i (UH), New Mexico State University (NMSU), Montana State University (MSU), University of Minnesota (UM), Georgia State University (GSU), and the High Altitude Observatory (HAO). We anticipate that graduate students from outside CU Boulder will take this course by registering for courses at their home institutions that are used for special topics, seminar-type discussions, or independent study. At CU Boulder, this course is a **one-credit seminar** graduate elective. The CU class will meet in person, but we will also hold synchronous Zoom sessions to join together everyone at all of the participating institutions (with additional instructors lined up to facilitate local discussions).

In this course, we will cover the physics of the solar corona, including a survey of proposed solutions to the "coronal heating problem," the extension of the Sun's magnetic field into the heliosphere, the acceleration and evolution of the solar wind and coronal mass ejections (CMEs), an introduction to the impacts of "space weather" on human life and society, and a summary of space weather forecasting.

COLLAGE: brief history

- It's not easy to offer advanced grad-level "specialty" courses in solar physics, since there are often insufficient numbers of both instructors and students.
- At the time when NSO came to Boulder, the **Hale Collaborative Graduate Education (COLLAGE) Program** was inaugurated to meet existing needs, to build up cohorts, and to strengthen our solar physics research community.
- Starting in 2013, these courses were offered online using web-enabled technologies. Eventually, it may become synchronized to a 3-year cycle, but for now, we teach topics as instructors become available…

One way to categorize the topical breakdown:	2013	2014	2016	2017	2018	2019	2020	2021	**2022**
1. Foundations: Solar telescopes and instrumentation			x				x		
2. Foundations: Spectral line formation and spectropolarimetry	x		x			x	x	x	
3. Foundations: Instrumental spectroscopy & spectropolarimetry	x		x			x	x	x	
4. Foundations: Topics in applied solar magnetohydrodynamics				x	x	x		x	
5. Dynamical processes: Photosph. flows, multiscale convection	x				x	x			
6. Dynamical processes: Chromospheric dynamics and waves				x					
7. Dynamical processes: Solar and stellar winds									✓
8. Dynamical processes: Helio and asteroseismology	x				x				
9. Solar activity: The solar dynamo	x				x	x			
10. Solar activity: Solar surface magnetic field			x	x		x	x	x	
11. Solar activity: Flares on the Sun and stars	x			x				x	
12. Solar activity: Solar corona and coronal mass ejections	x	x	x	x		x			✓
13. Influences: In situ space physics measurements							x		
14. Influences: Solar influences on planetary space environments		x							✓
15. Influences: Outer heliosphere and interaction with the ISM		x							
16. Influences: Space weather events and their causes		x							✓

2022 schedule of topics

Draft (subject to change):

1.	Jan. 13	Course overview: survey of data, jargon, & unanswered questions
2.	Jan. 20	Coronal heating: origins & scaling laws
3.	Jan. 27	Coronal heating: physics of wave/turbulence concepts
4.	Feb. 3	Coronal heating: physics of reconnection/nanoflare concepts
5.	Feb. 10	Magnetic field extrapolation: from photosphere to heliosphere
6.	Feb. 17	Solar wind: the Parker (1958) model & observations
7.	Feb. 24	Solar wind: advanced physics; hands-on exercises
8.	Mar. 3	Solar wind: evolution, corotating streams, & the outer heliosphere
9.	Mar. 10	Coronal mass ejections (CMEs): acceleration, heating, & evolution
10.	Mar. 17	Space weather: the interplanetary space environment
11.	Mar. 31	Space weather: terrestrial responses & technological impacts
12.	Apr. 7	Space weather: case studies of historical events
13.	Apr. 14	Space weather: "research to operations" and forecasting
14.	Apr. 21	The solar/stellar connection: scalings & exoplanet impacts
15.	Apr. 28	Course summary & round-table discussion: what did we learn?

Grading

At CU Boulder…

Active participation in paper discussions (5 or 6)	50%
Computation assignments (2 or 3)	50%

Like many other seminars, we will organize a good fraction of our time around reading and discussing **scientific papers.** There will be about 5 or 6 paper-reading assignments, usually with a one-week turnaround and a due-date on the day of class that we will be discussing that particular topic. You'll be graded on the total number of "responses to prompts" that you submit online, and these come in two types:

1. Brief individual responses, seen only by the instructors, to top-level questions like "why did the authors do what they did?" and "why should we care?"
2. Public posts on a class-wide discussion board, in which you can ask questions about things you didn't understand or share details that you found particularly interesting. You're also encouraged to comment on, or respond to, other students' posts, but please be respectful and constructive.

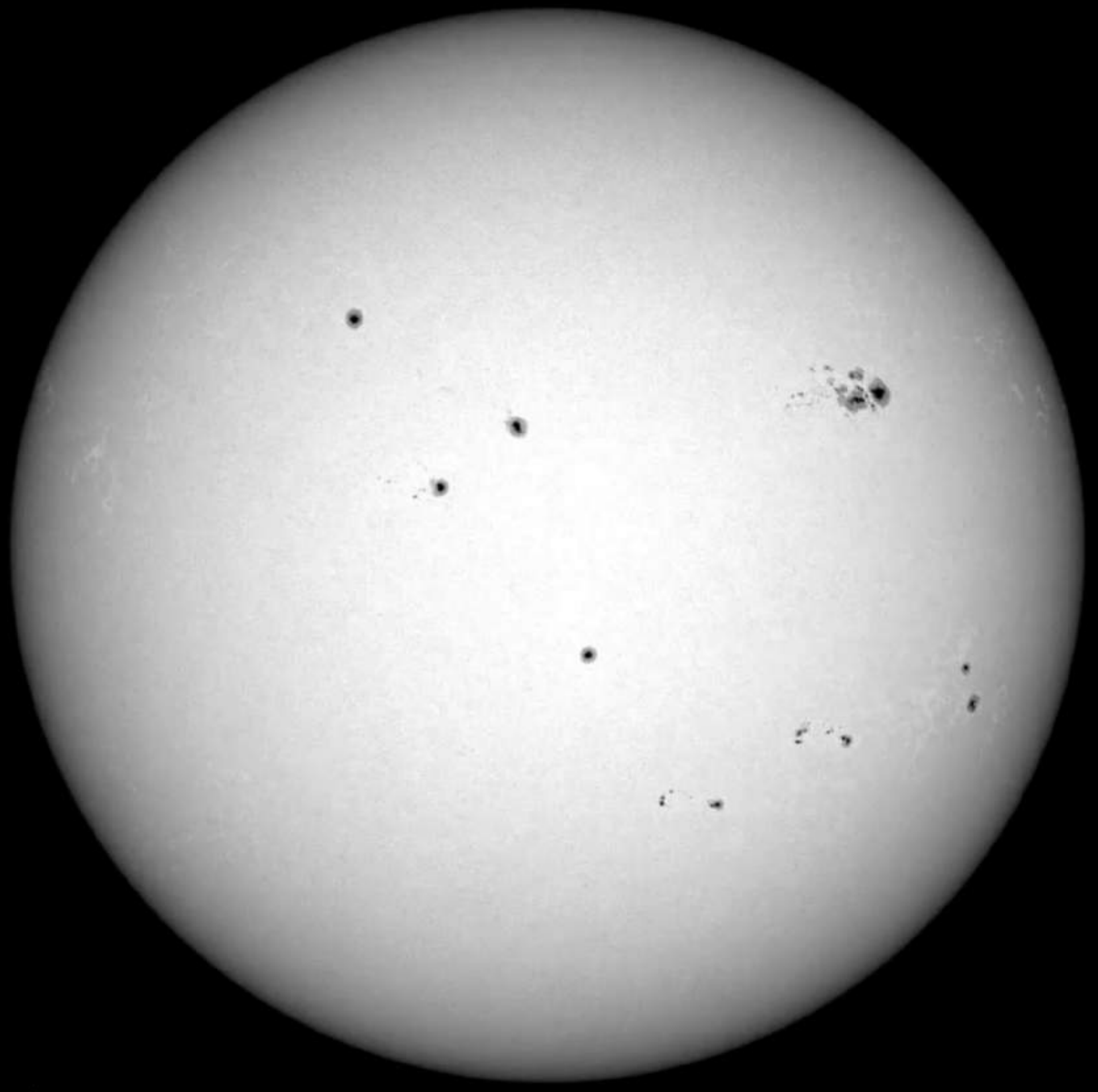
It is still not yet clear how many papers we will read, but if there end up being N papers, you will earn full credit for these assignments by submitting at least $3N$ separate responses of either type. We will devote *a bit* of time in class to discussing and summarizing each online discussion, but we expect a good amount of closure (i.e., questions getting answered) to happen online, too.

We will also explore our topics in more depth by going through a few **hands-on computation exercises.** For those, the assignments for you will usually be to extend them in some way (i.e., add more physics or figure out new ways of visualizing the output) or, if python isn't your game, to re-implement them in some other language or code of your choice (maybe Mathematica or Julia?). There will also be at least one computation exercise that will be more open-ended—almost a mini-project—in which you will choose a topic and do something that goes beyond what we discussed in class. You could analyze some online data, reproduce some results from a paper, or follow up on any of the loose threads that we'll surely leave dangling. More information about these assignments will be made available soon.

Modes of interaction

- Zoom: weekly class, Thursdays, 4:00-4:50 pm (Mountain Time)
- Slack: https://nsocollage2022.slack.com
  for online discussions about papers, assignments, etc.
- Web page: https://stevencranmer.bitbucket.io/ASTR_6000_2022/
- Office hours (also Zoom): TBD
- Archived videos of past classes (eventually): https://nso.edu/students/collage/
- Canvas: grading-related details for the CU students

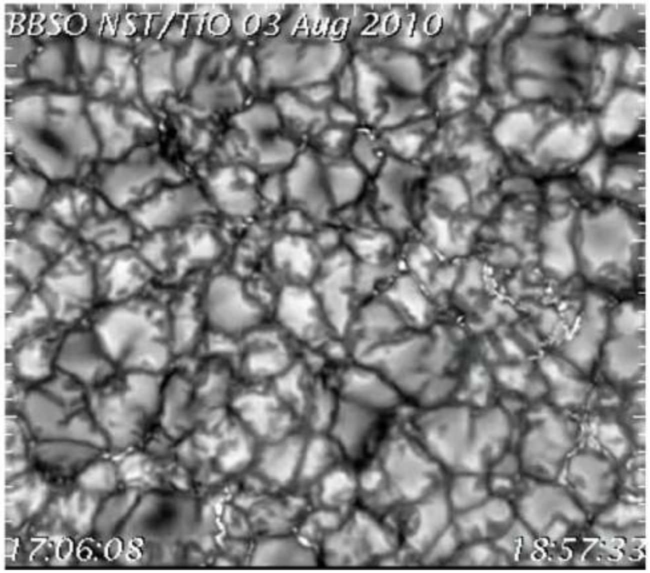
The Sun

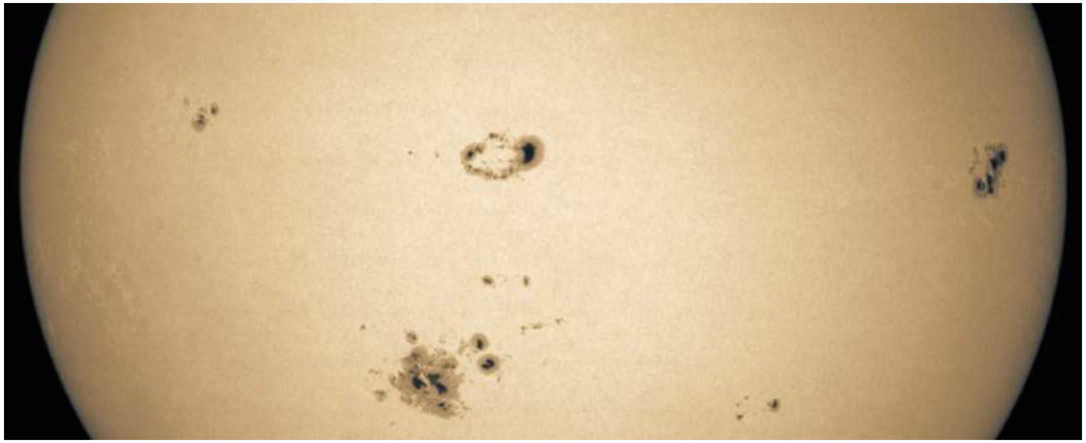


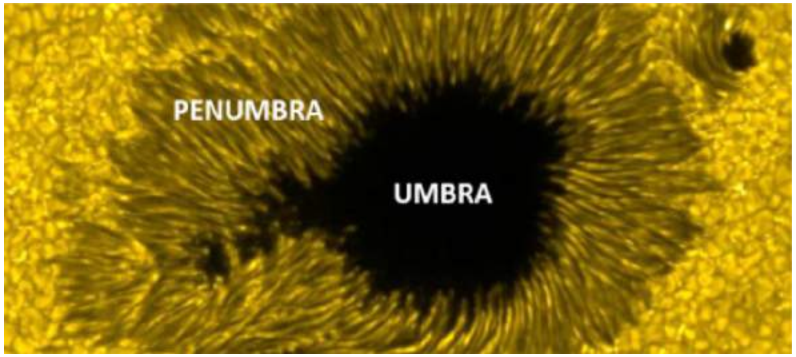
The Sun

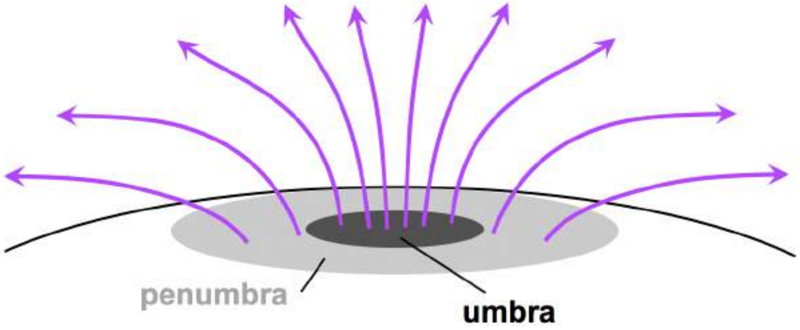
Photosphere

- The visible "surface" of the Sun: a thin boundary, below which photons are trapped… above which, photons escape freely.
- Structured on scales from < 1 Mm (granulation) to ~30 Mm (supergranulation & sunspots) up to the solar radius (700 Mm).





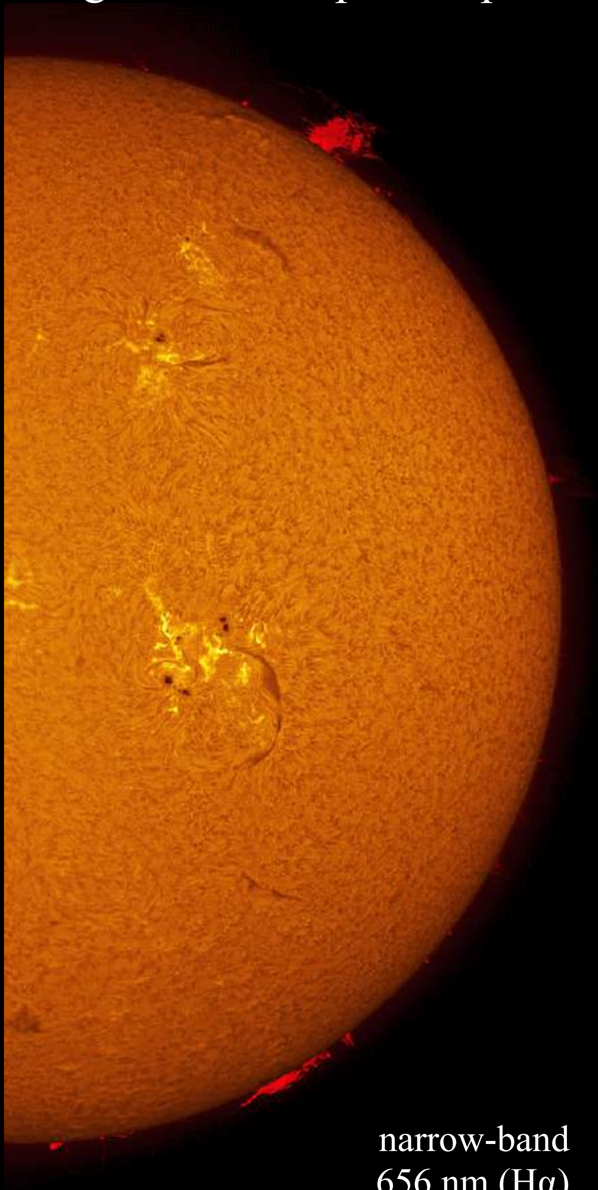




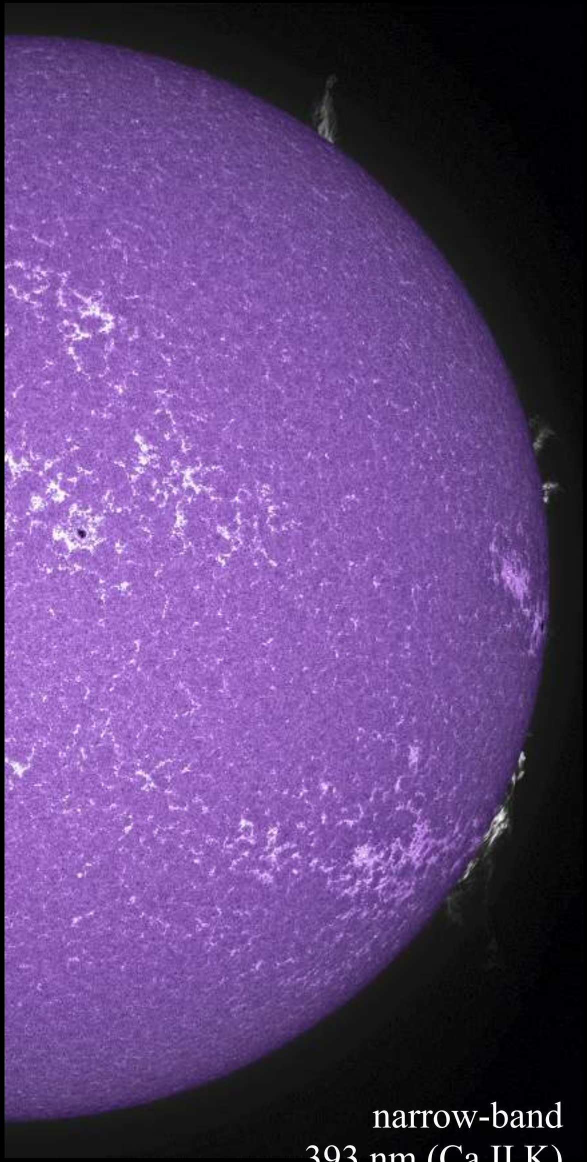
Chromosphere

- Originally seen as a colorful ring in total eclipses. Spectral lines reveal upper layers…

broad-band
400-800 nm

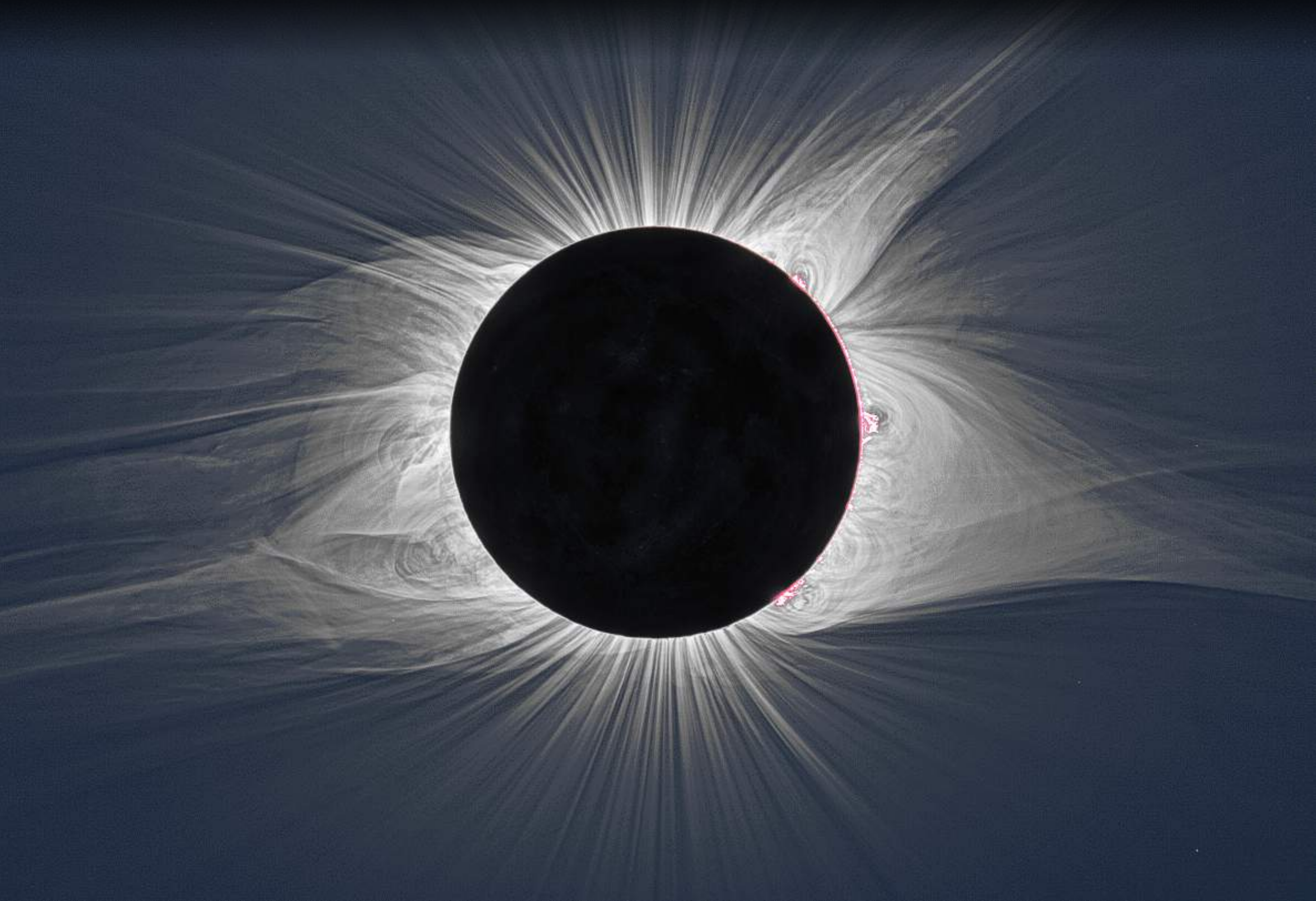


narrow-band
656 nm (Hα)



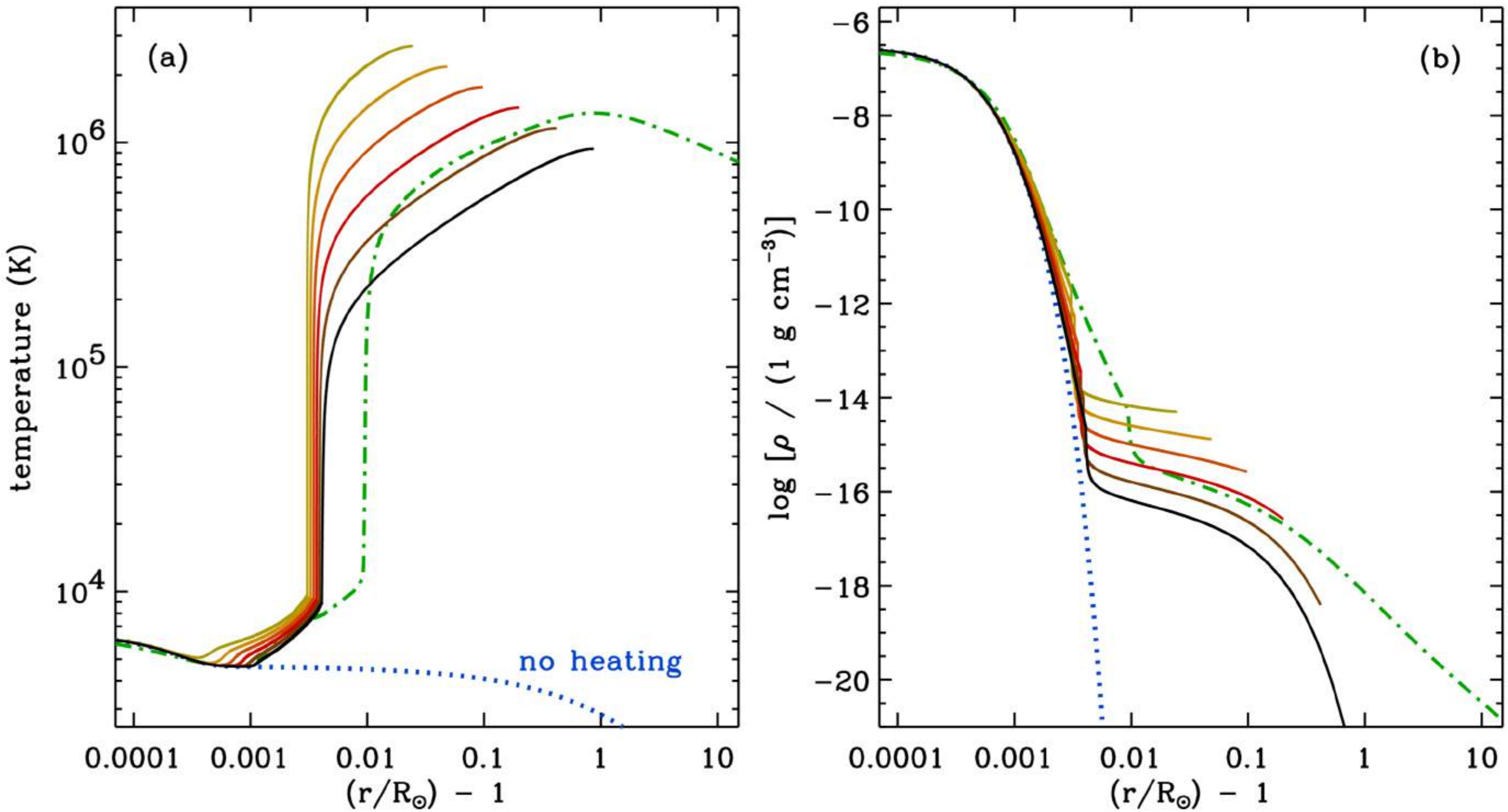
narrow-band
393 nm (Ca II K)

Corona



The chromospheric & coronal heating problems

- As one goes up from the photosphere, temperature drops, then it starts going up again, despite getting further away from the ultimate source of energy… Why?



Multiple ways to observe

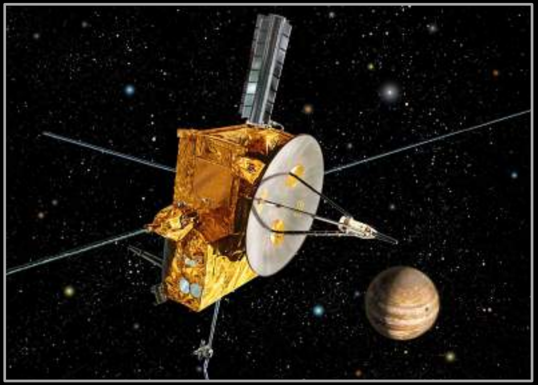
Ground-based telescopes

- Visible & infrared wavelengths only
- Big mirrors: great spatial resolution
- Straightforward for human maintenance

Space-based telescopes

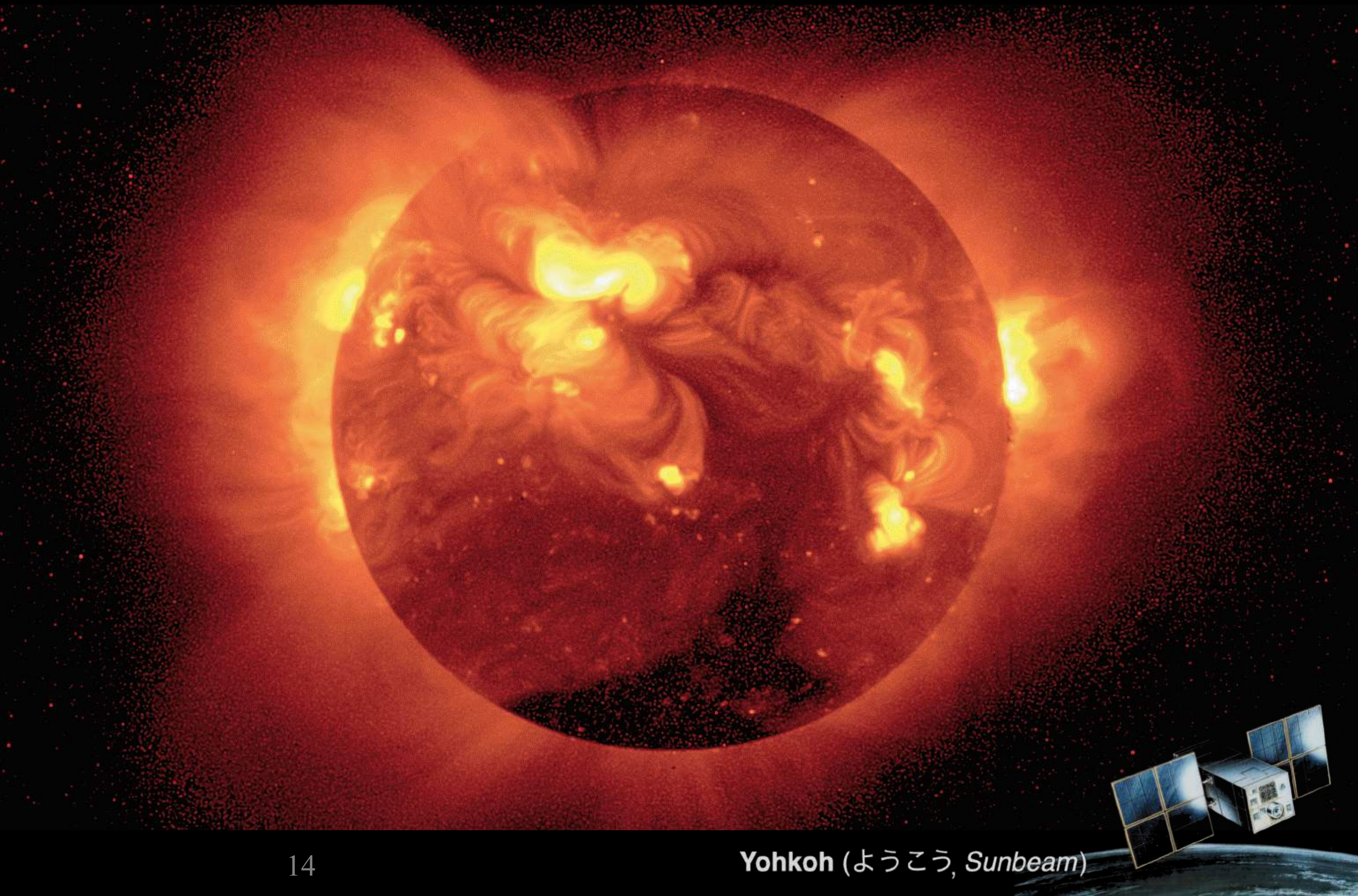
- Images & spectra in X-ray, UV, etc.
- Stable platform
- No weather issues (except maybe space weather!)

"In situ" particle & field detection



- Goes right where the plasma is
- Direct measurement of electromagnetic fields & plasma density, speed, temperature, etc.

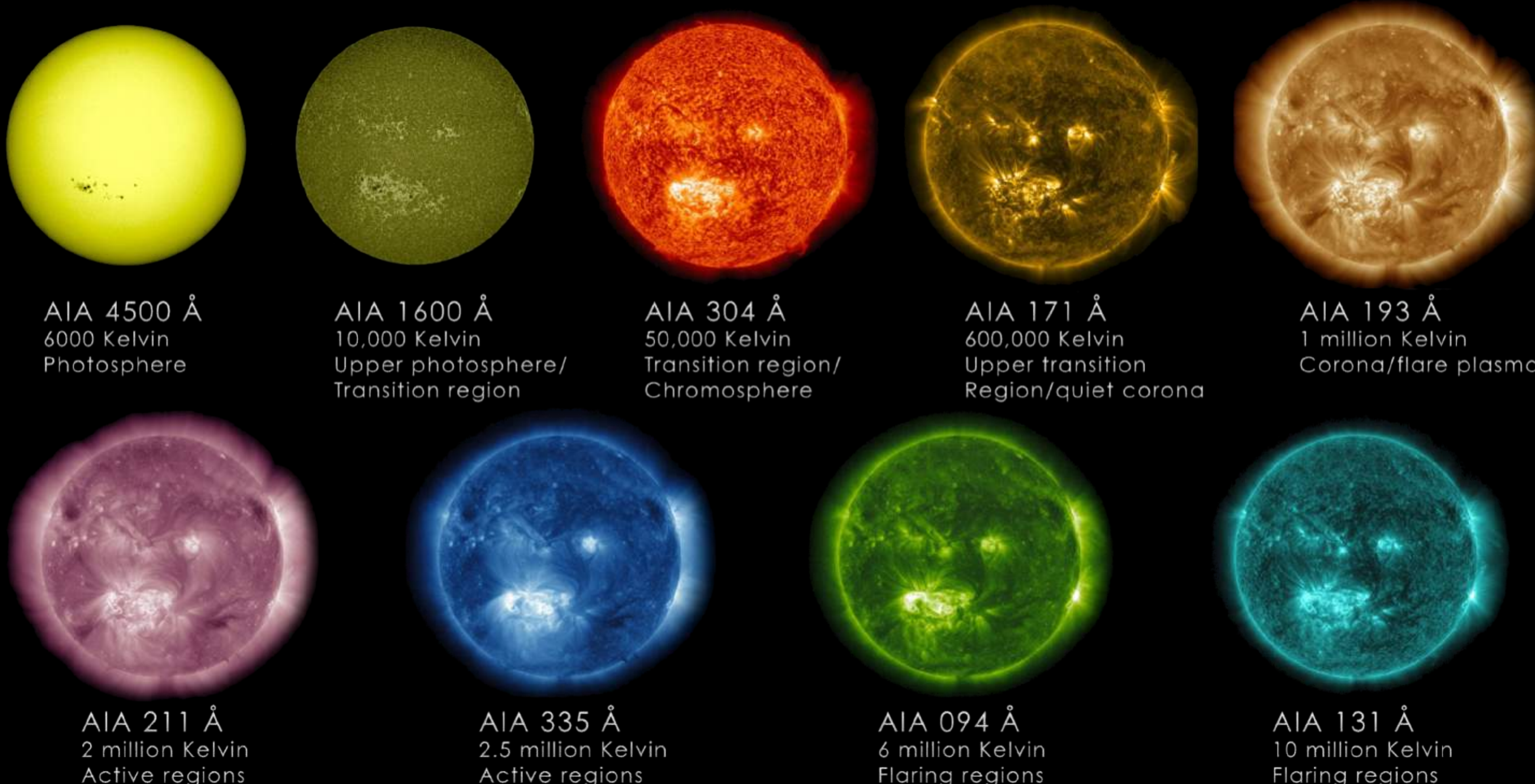
The corona is bright in X-rays



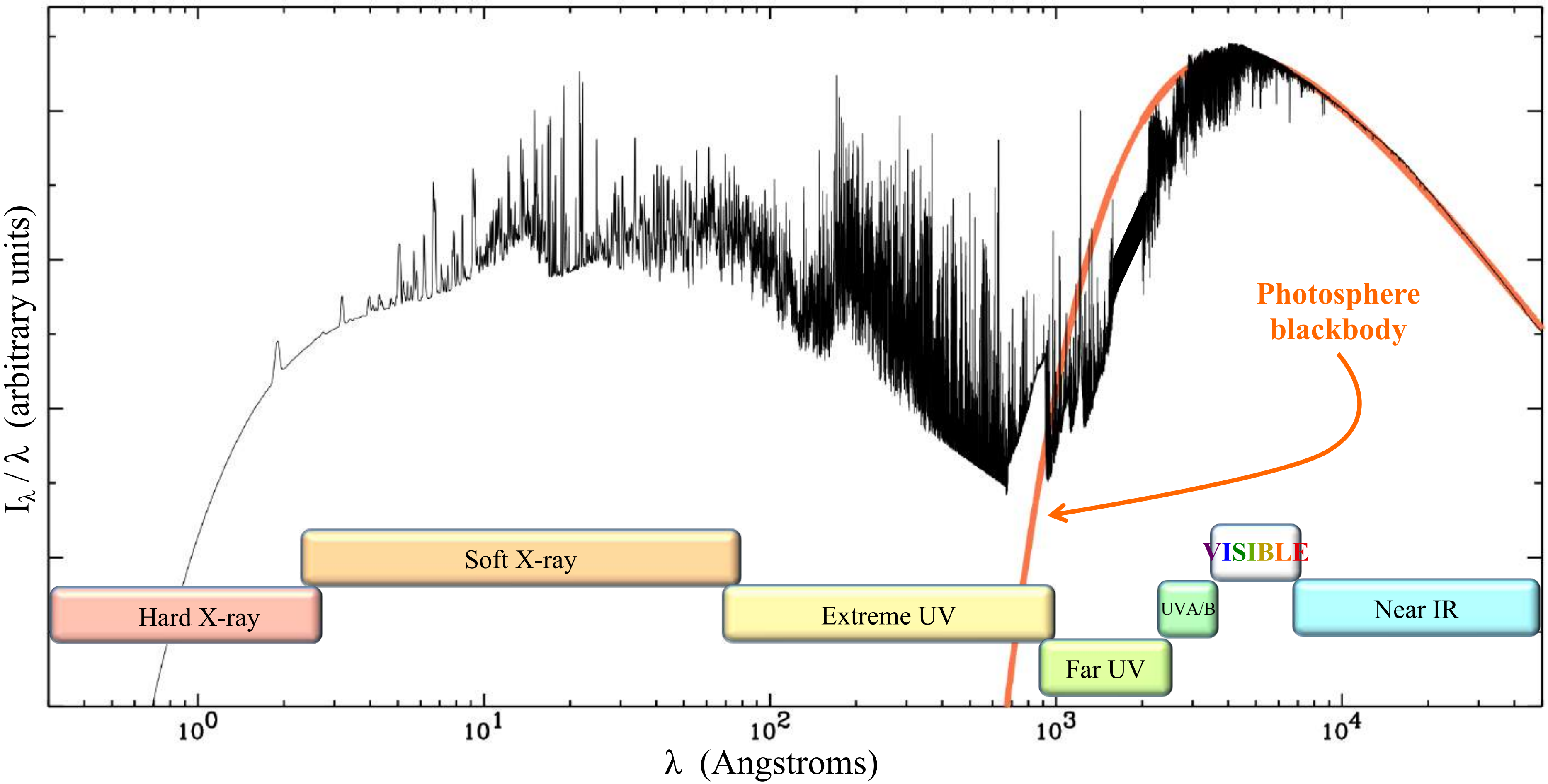
Yohkoh (ようこう, *Sunbeam*)

Solar Dynamics Observatory: 2010 to present

4096 x 4096 pixel images (in multiple EUV bands) every ~10 s (~1.5 TB/day)



Corona dominates Sun's spectrum in UV & X-ray

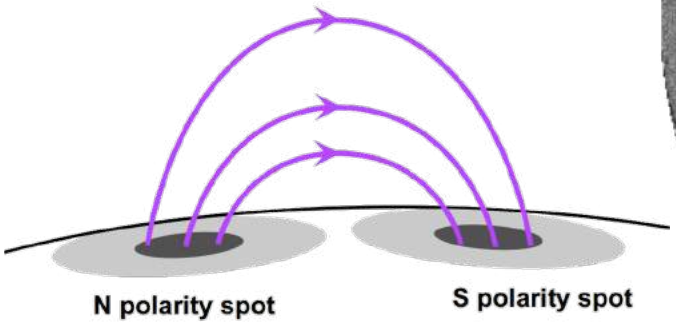


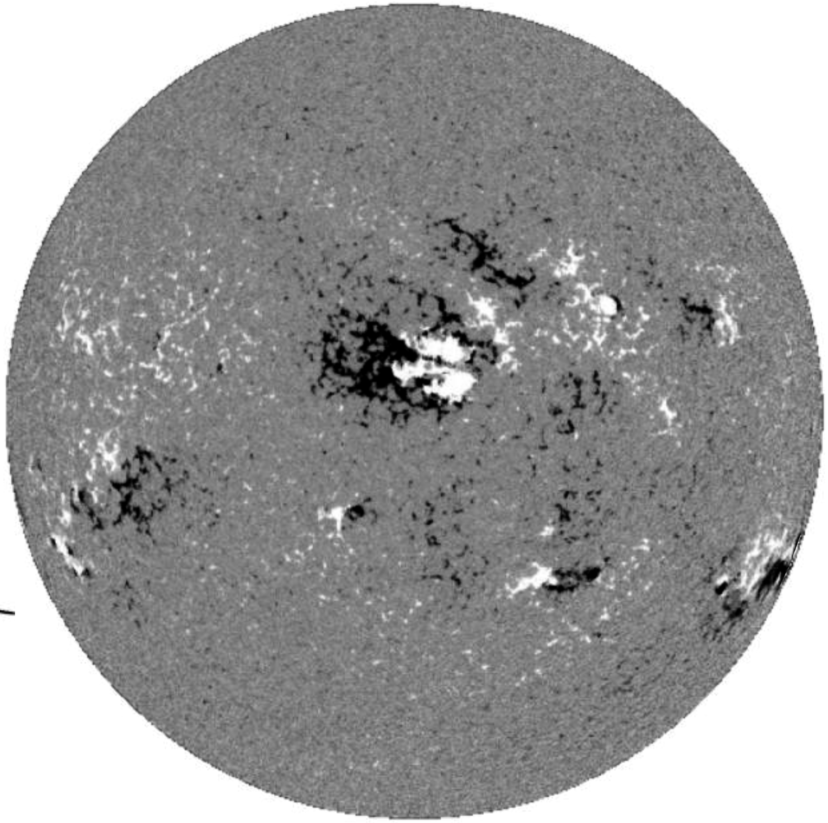
Measuring the magnetic field

- Images of the Sun's surface in Zeeman-sensitive lines give us maps of the magnetic field:

  White: pointing out, black: pointing in, gray: 0

- Sunspots are pairs: actually "loops"





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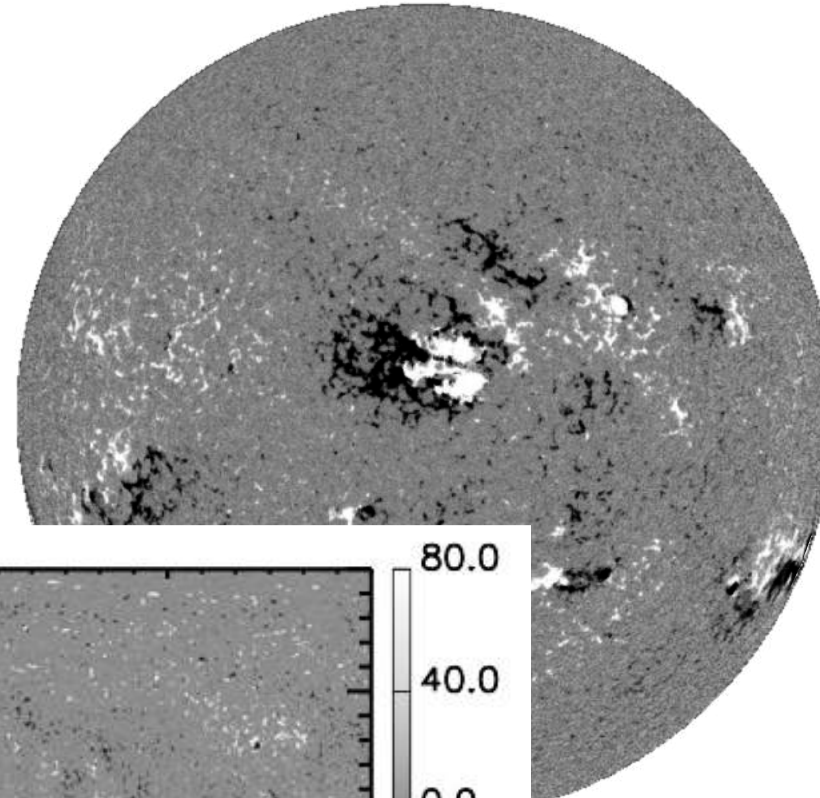
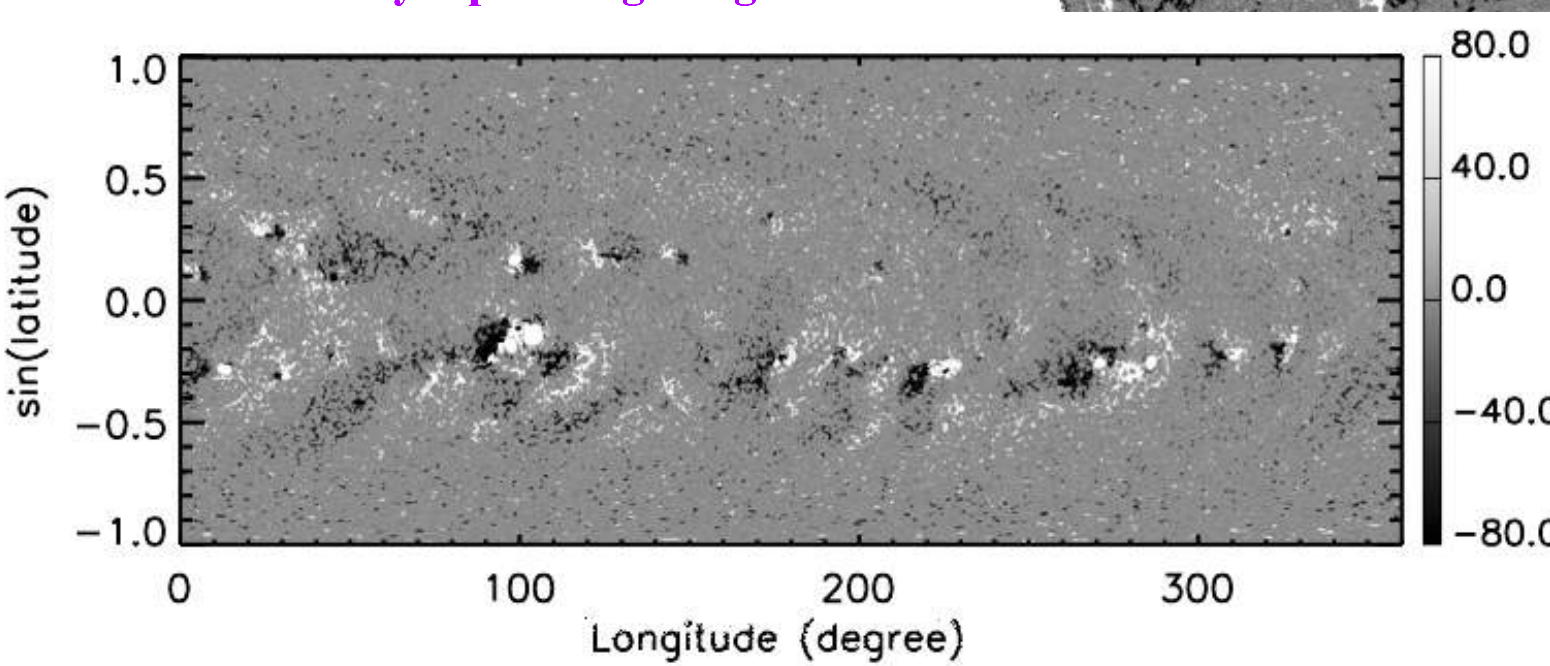


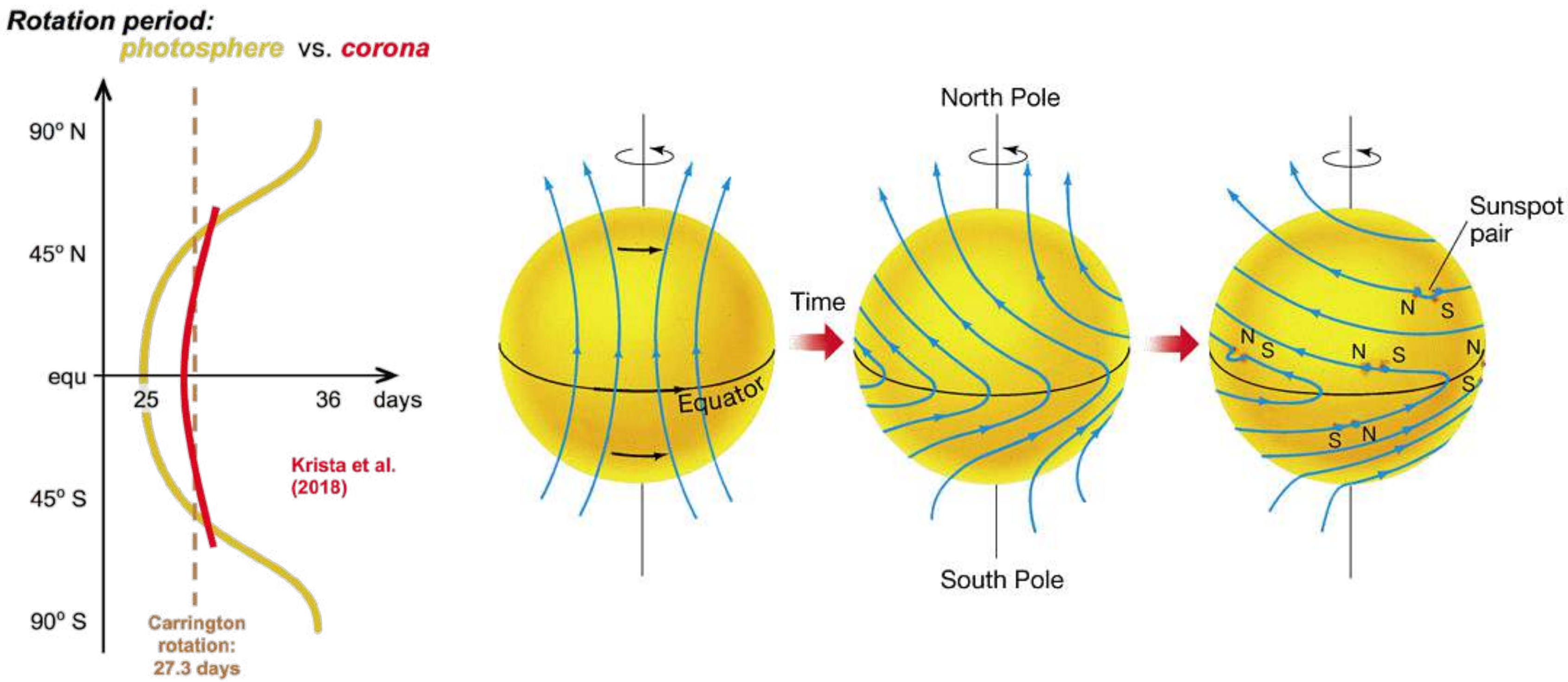
- Sunspots are pairs: actually "loops"

- Collect strips along central meridian, & assemble 1 rotation into a **synoptic magnetogram:**



Jargon alert 1: Carrington Rotations

- The Sun undergoes differential rotation: faster at equator…



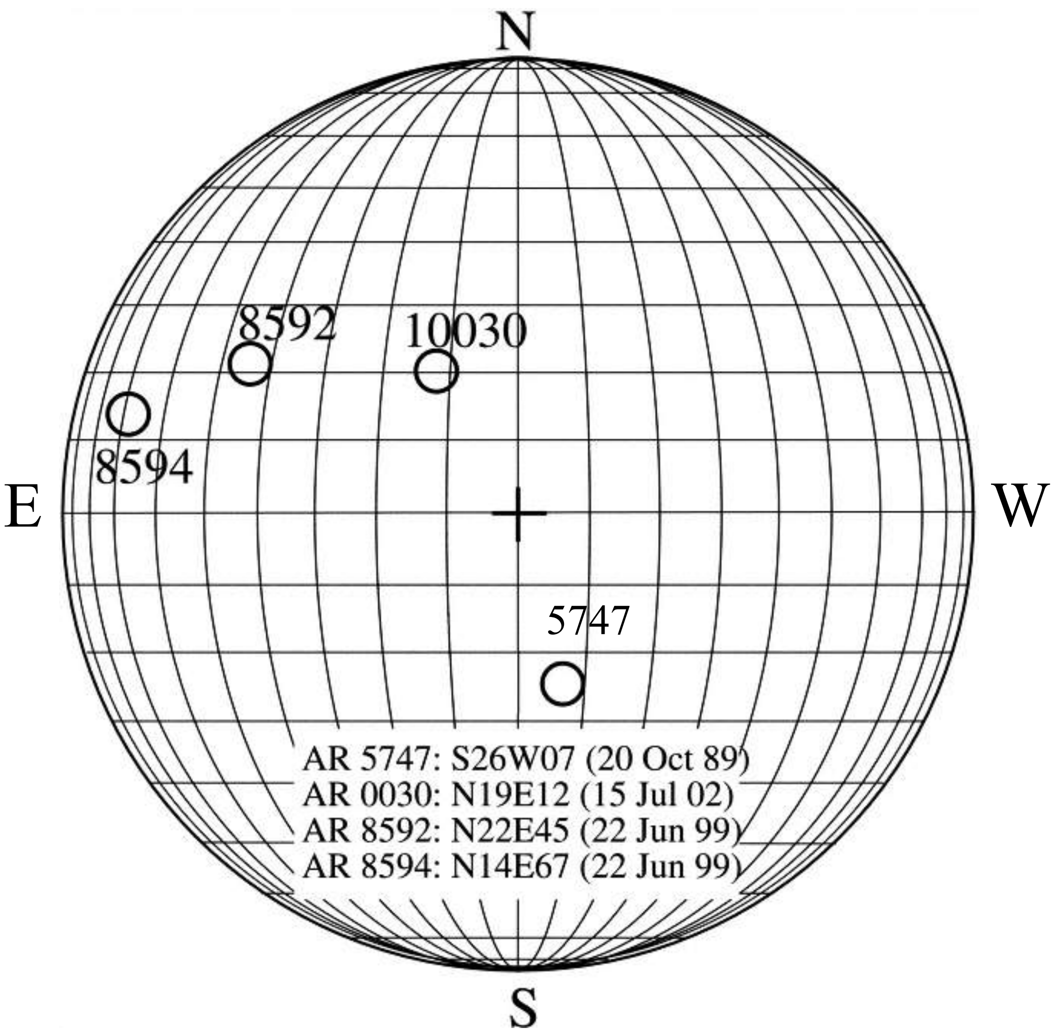
- However, the corona/heliosphere rotates more rigidly… many features relevant to space weather recur every **27.2753 days** = 1 Carrington Rotation (CR) period.

- They're numbered sequentially: CR 1 started Nov. 9, 1853. We're now up to the ~2250's.

- **Synoptic** (latitude-longitude) maps are constructed (after the fact) for each CR.

Jargon alert 2: Heliographic coordinates

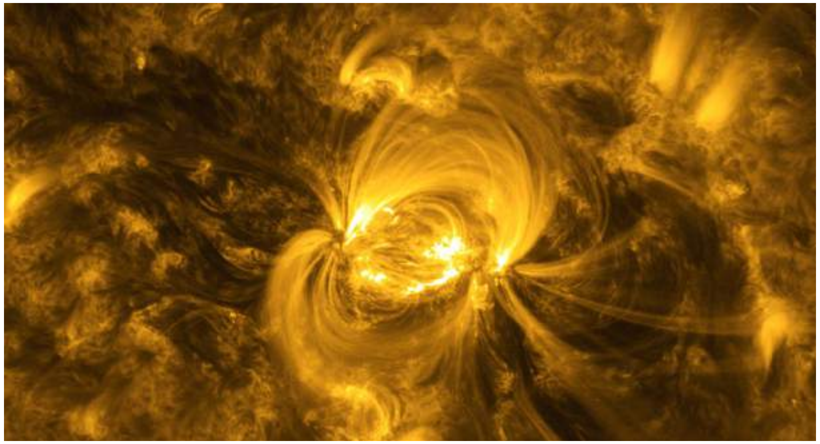
- How do we label feature locations on the Sun? There are multiple conventions…



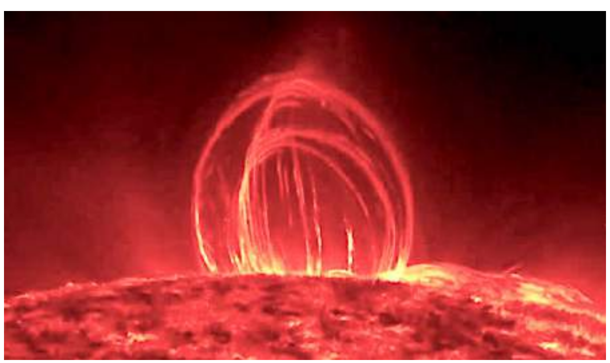
North ***East*** ***South***

Large-scale coronal structure

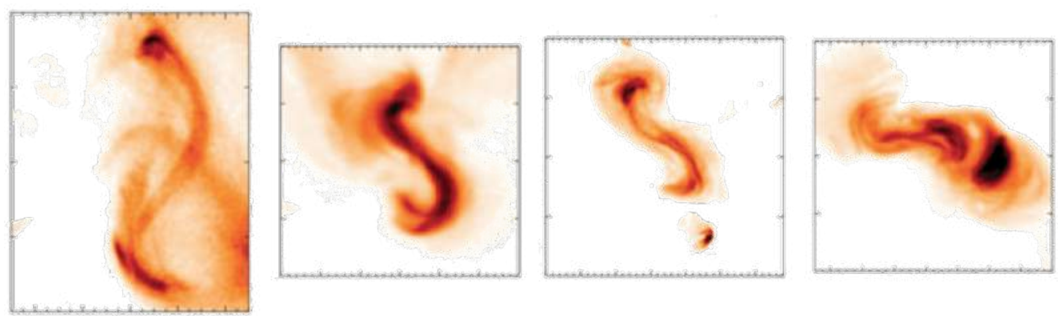
Active regions (brightest in UV & X-ray) tend to coincide with **sunspots** (dark in visible):



Some isolated **coronal loops** aren't associated with active regions…

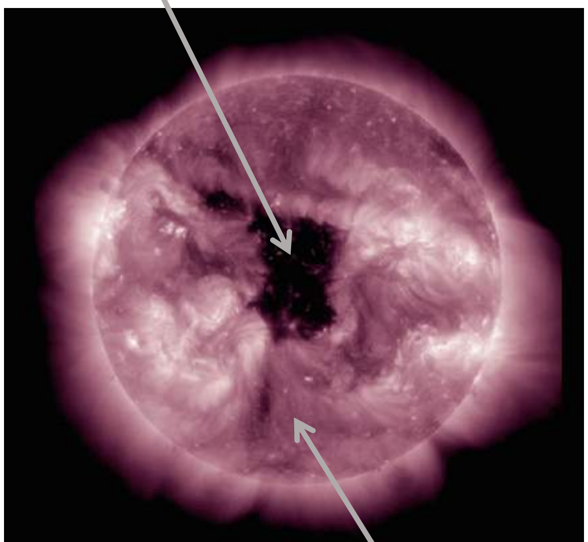


When active regions get ready to flare, the underlying B-field twist is observable as **"sigmoid"** X-ray loops:

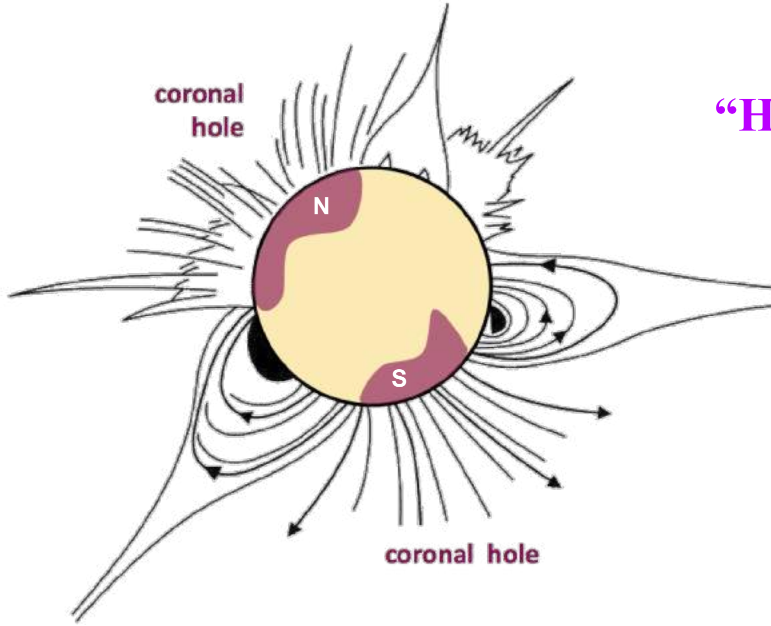


Large-scale coronal structure

Coronal holes have low density (dark in UV/X-ray) & coincide with solar wind footpoints

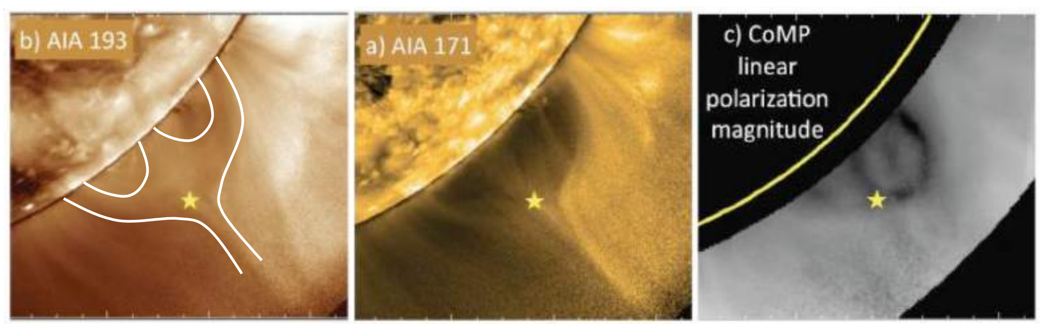


Fuzzy regions with intermediate intensity are often called **Quiet Sun**



"Helmet" streamers are high-density extensions of the largest loops

Some **"pseudostreamers"** are associated with more complex polarities & dark prominence cavities…



The extended solar atmosphere

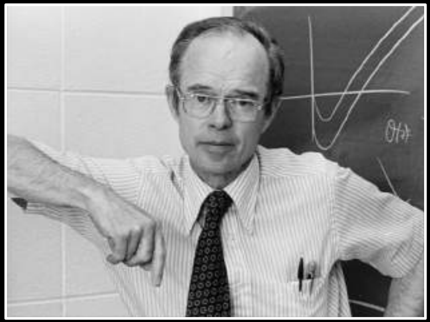
Where will you be on April 8, 2024?

The extended solar atmosphere… keeps going!

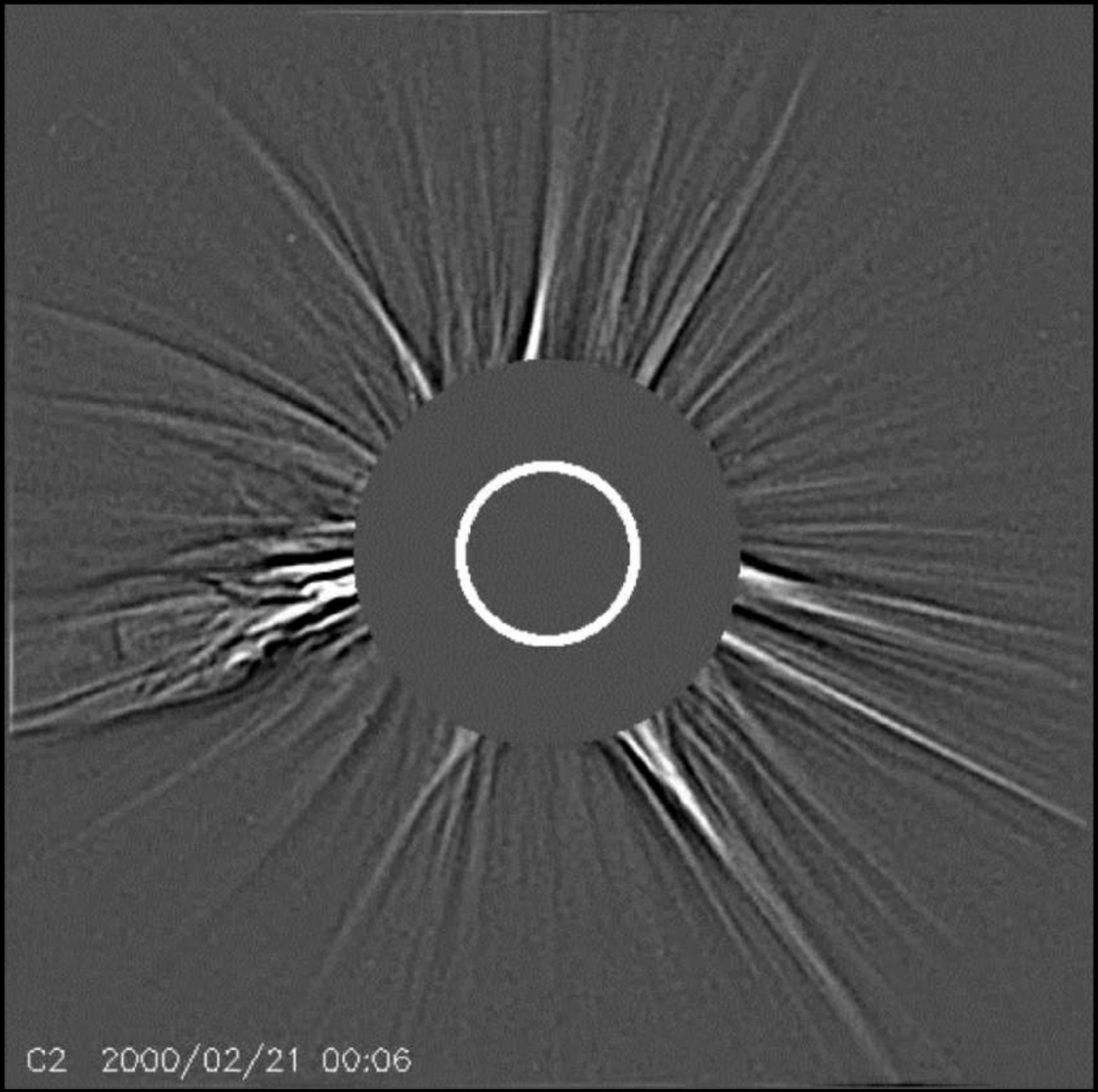
Image credits: Miloslav Drückmuller

The solar wind

- Parker (1958) showed that if the corona is **hot,** it must expand.



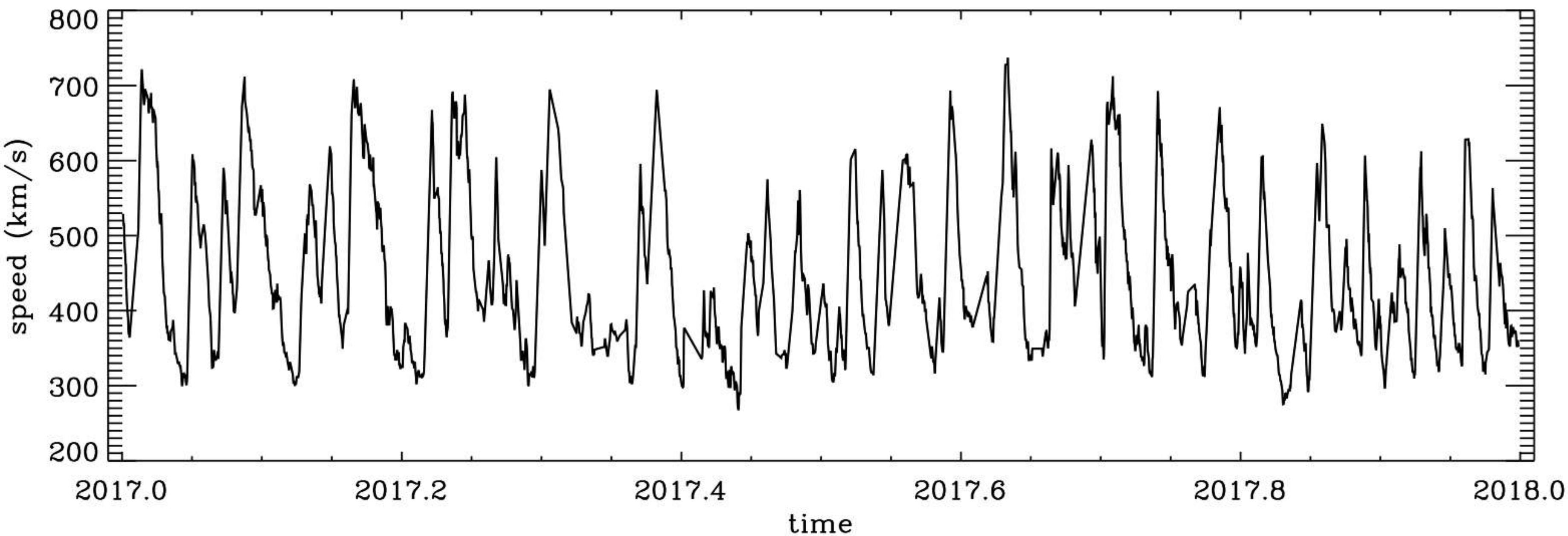
- After ~4 years of controversy, Neugebauer et al. (1962) used in-situ space probe data to confirm the existence of a continuously outflowing **solar wind!**



Wavelet-processed LASCO coronagraph movie

Solar wind speed at 1 AU

- It varies! There are "slow" streams (250 km/s), "fast" streams (800 km/s), and everything in between...
- Here's what spacecraft saw in the vicinity of Earth throughout the year 2017...



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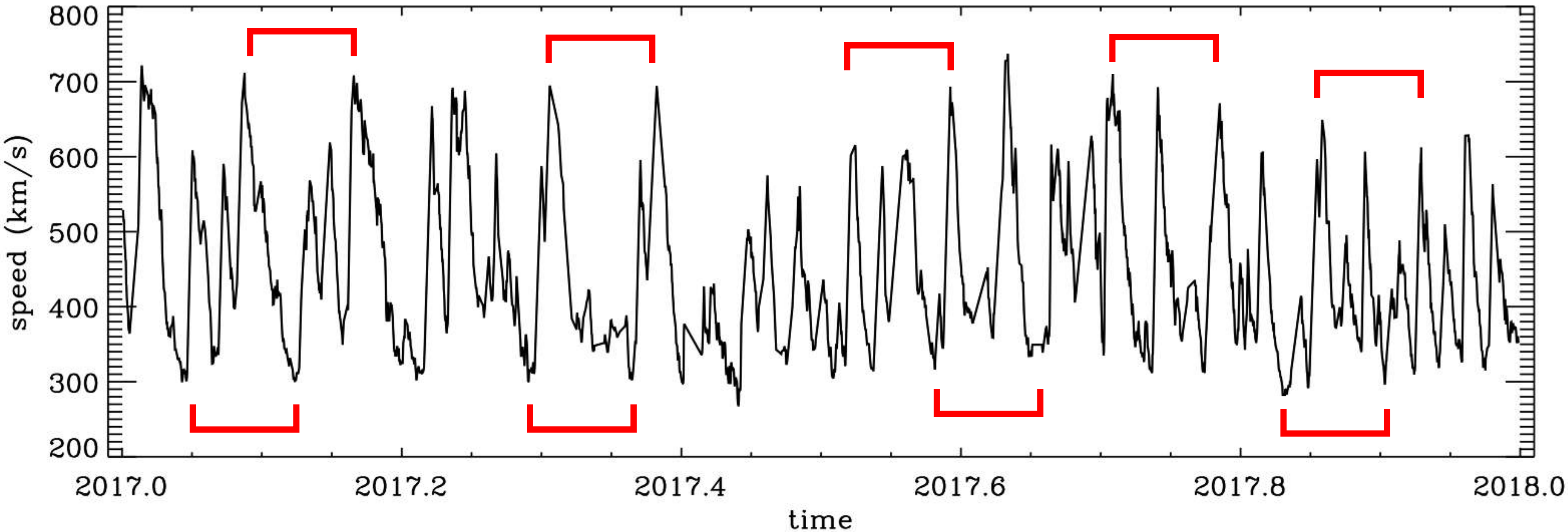
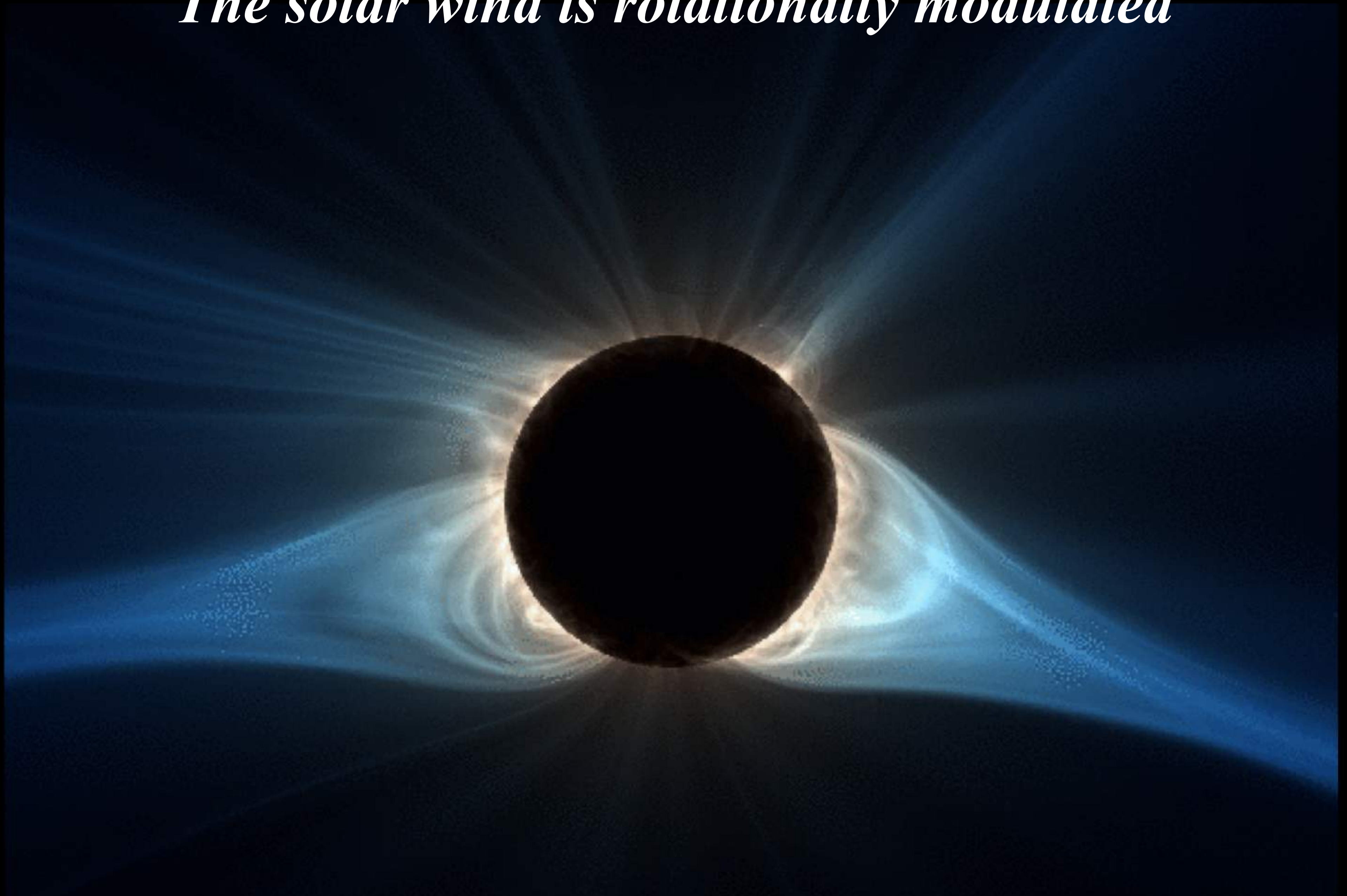


- What's special about this time period... about 0.075 of a year?
- It's about 27 days: roughly the **Carrington rotation rate.**

The solar wind is rotationally modulated

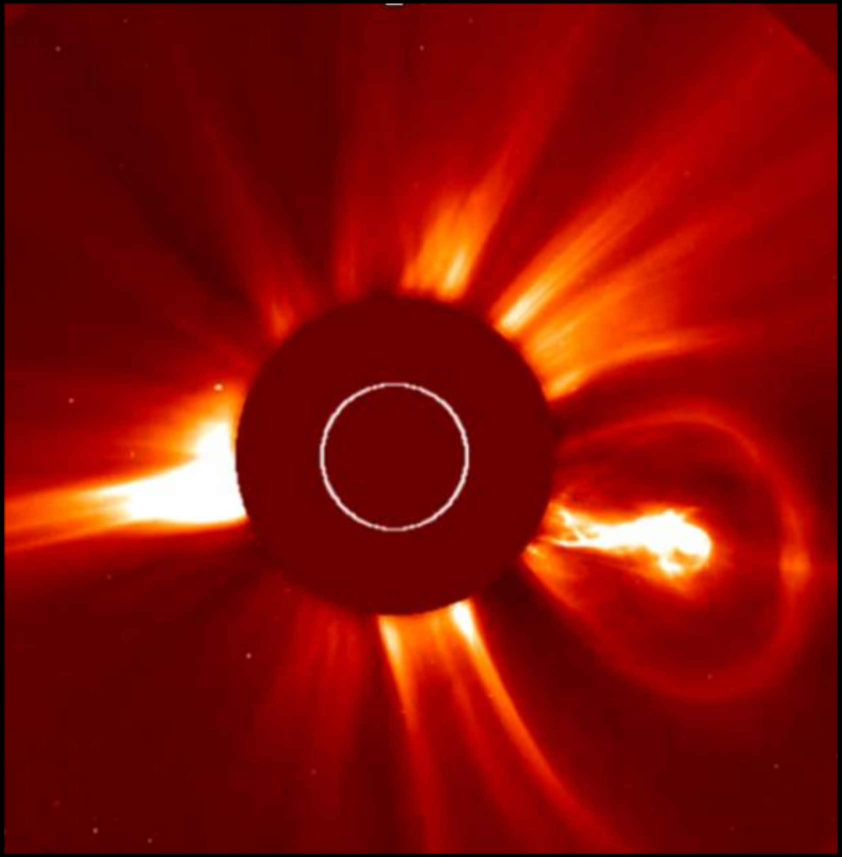


Simulation credit: Predictive Science, Inc.

Solar eruptions

Solar flares produce electromagnetic radiation:

- Travel time to Earth: 8 min
- From gamma-ray to radio



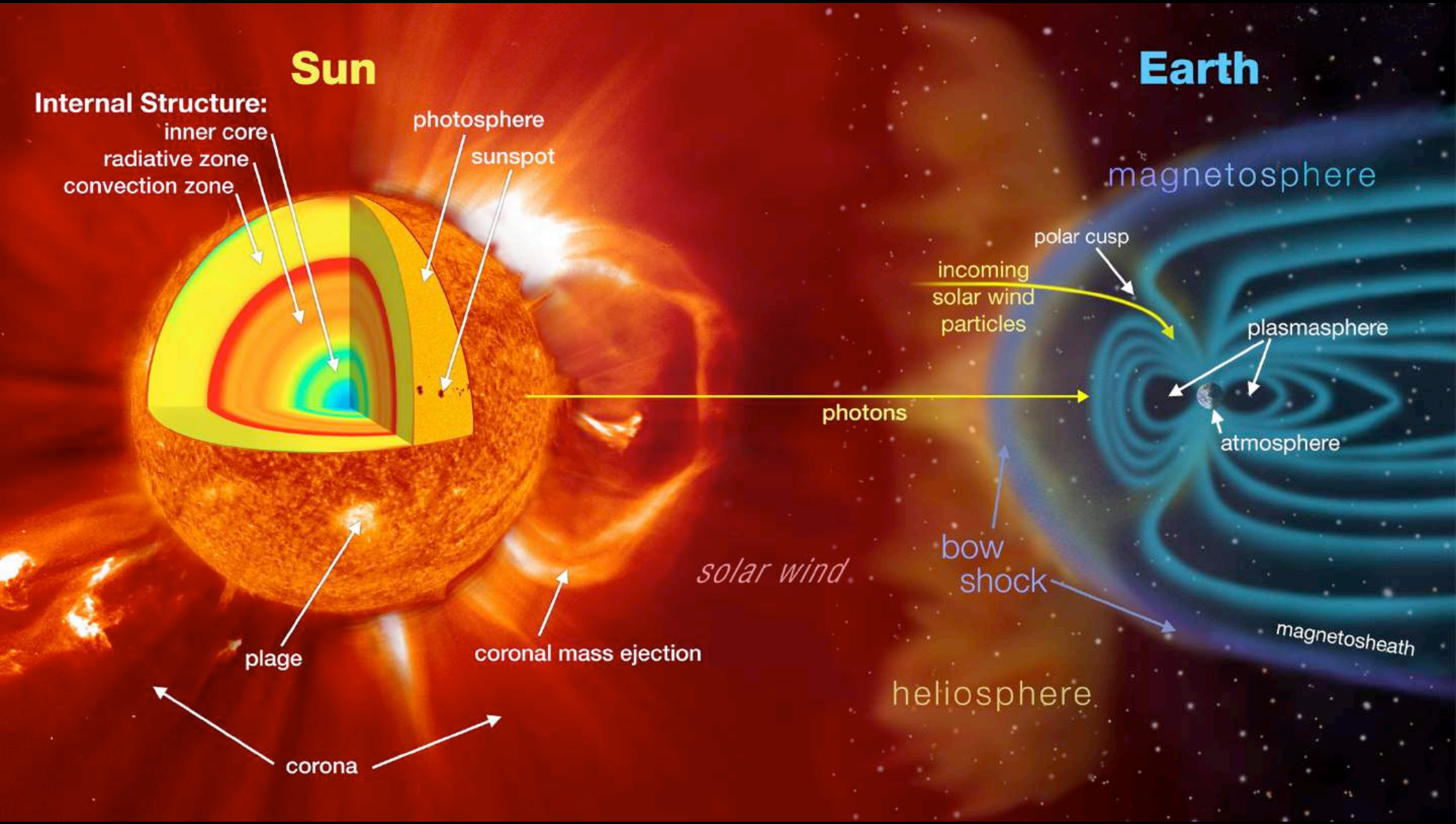
Flares & coronal mass ejections (CMEs) also produce solar energetic particles (SEPs)

- Travel time to Earth: 15 min to hours

CMEs and variable wind streams eventually can disrupt the Earth's magnetic field

- Travel time to Earth: 2 to 4 days

We are "living with a star"

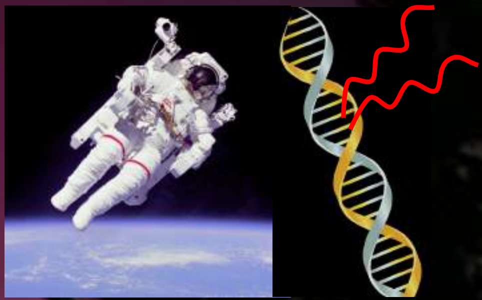


Space weather impacts

Impacts from space weather are wide-ranging, with potentially significant consequences

Satellite Operations

GPS



Human Safety

Power Grid Operations

Aircraft Operations

Communications

For next week

- Read the "How to read a scientific paper" guidelines (optional)
- Read paper 1: Chapter 1 of Aschwanden's *Physics of the Solar Corona* (2005)

  CU students have access to the full book on SpringerLink
  Google Drive link for the chapter is here
- If pressed for time… sections to **read** vs. **skip:**

  1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 1.10, 1.11
- Engage with the Slack discussion