The Sun: A Star to Study in Our Backyard

for the International Space Weather Camp

Thursday, 10 June 2021

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NASA/Marshall Space Flight Center

Background Image: Joe Matus, NASA/MSFC, August 21, 2017

Outline

- A bit of history of USA astrophysics
- The Sun vs. a couple of stars
  - What is a Star?
  - What is the Sun like?
- Eclipses
- Solar Eruptions
- Jets in Coronal Holes

Astronomy /Astrophysics History in the United States

Maria Mitchell: Educating Future Scientists

- Discovered a comet in 1847 at age 29
- First woman elected to the American
- Academy of Arts and Sciences (1848)
- First woman elected to the American
- Association for the Advancement of Science(1850)
- First professor hired at new Vassar College (1865 – Poughkeepsie, New York)
- Co-founded the Association for the Advancement of Women (1873)

Maria Mitchell, Her Legacy: Her Students

Edward Pickering: Advocate of women's advanced study, Director of Harvard Observatory (1876)

Mary Watson Whitney, 1847-1921, Professor of Astronomy at Vassar College, and first President of the Alumnae Association

Antonia Maury -- Became one of Edward Pickering's "computers" 1897: published a catalogue of stellar spectra -- first observatory publication credited to a woman.

Mary Watson Whitney -- Succeeded M. Mitchell as Chair of Astronomy Department, Director of Observatory, and Educator

Edward Pickering

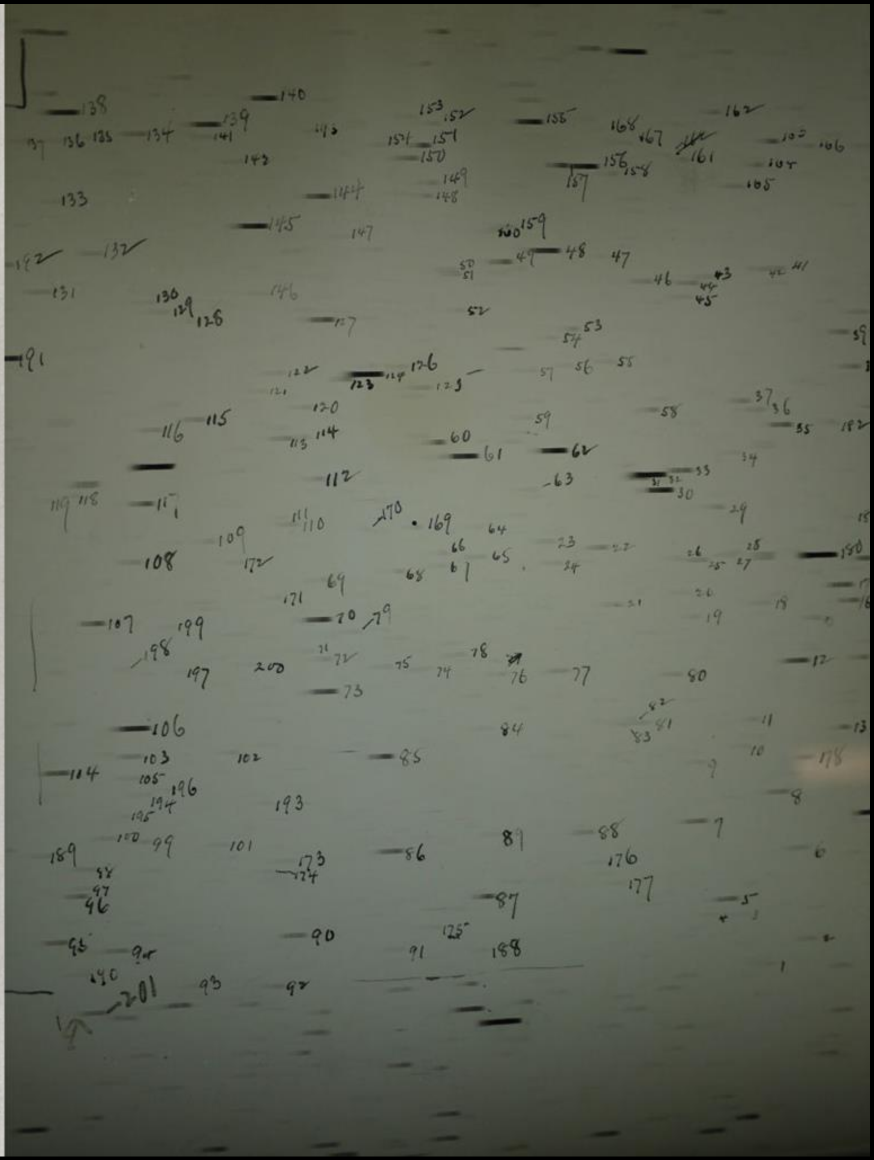
Not satisfied with the math skills of his male assistant,

hired his Scottish housekeeper Williamina Fleming

to help catalogue the spectra of 10,000 stars

Fleming hired 20 other female computers between 1885 and 1900.

Annie Cannon and Spectral Classifications



Edward Pickering and the "Computers" at Harvard Observatory

At Harvard College Observatory, 13 May, 1913

Image Credit: Licenced under Public Domain via Wikipedia Commons - http://commons.wikipedia.org)

William Pickering and his "computers"
Antonia Maury on the far left with back to camera
Annie Cannon on far right

Harvard Computers

Wiliamina Fleming	Office Manager and classifier of stellar spectra
Antonia Maury	Improved classification system
Annie Jump Cannon	Classified spectra of southern stars and redesigned system, developed Harvard Classification System
Cecilia Payne-Gaposhkin	Determined the relationship between stellar classes and stellar temperature and determined that the Sun is mostly hydrogen
Henrietta Swan Leavitt	Intuited that all stars in Small Magellanic Cloud are approximately at the same distance from Earth, leading to her discovery of direct relationship between period and luminosity of Cepheid variables
Anna Winlock	Made the most complete catalog of stars near north and south poles (of her time), and calculated orbits and compiled data on asteroids

The Sun vs. a Couple of Stars

What is a Star?

- Energy Production
- Differences
- H-R Diagram

What is the Sun like?

- Structure
- Surface Features
- Magnetic Fields
- The Solar Cycle
- Solar Eruptions

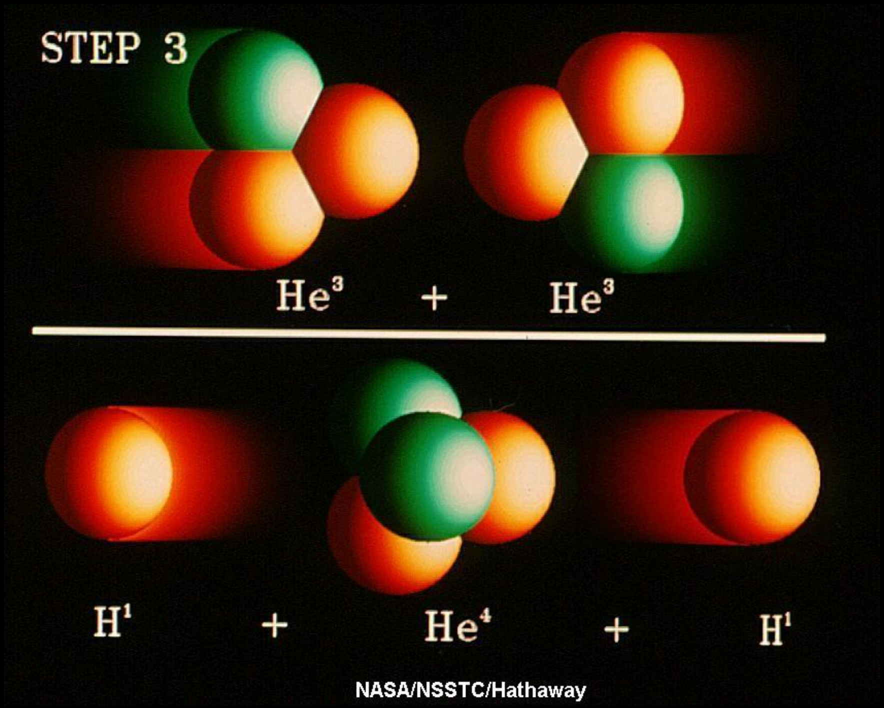
What is a Star?

What is a Star? -- Energy Production

A star is an astrophysical body that produces its own light by thermonuclear reactions in its core.

For solar-type stars, this is the proton-proton chain

1. Two protons collide, form deuterium, a positron, and a neutrino.



2. A proton collides with the deuterium, forming helium-3 and a gamma ray

3. Two He-3s collide to form He-4 plus two protons.

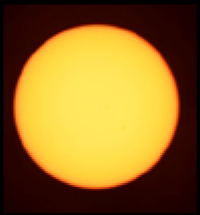
Basically, Hydrogen converts to Helium

(High-mass stars, greater than about 2 solar masses use a different procedure, the CNO cycle.)

What is a Star? -- Differences

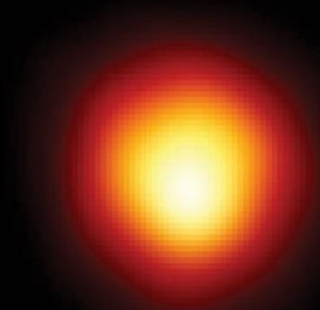
Rigel: A blue-white star, about 860 ly away, 12,000 K, 80 R_O 23 $M_{O,}$ 8 million years old

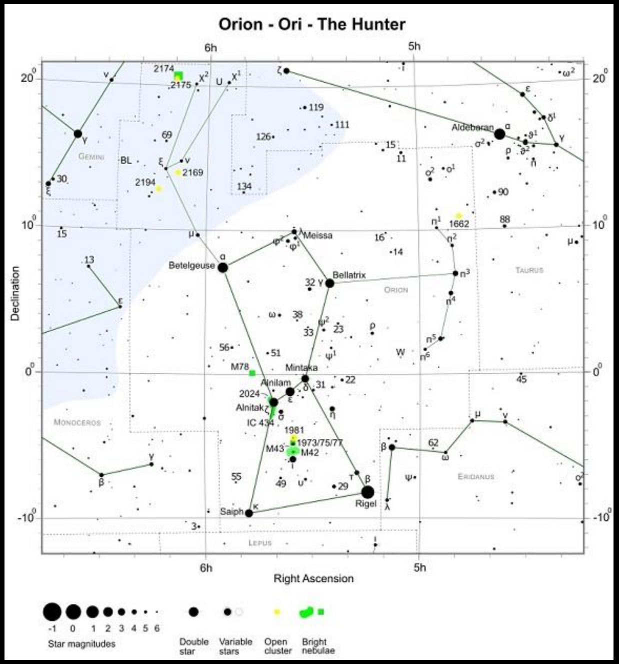
Aging



Our Sun: A yellow star, ~8 lm away, 6000 K, ~700,000 km (432,000 mi, 2 x 10^{30} kg, 4.5 billion years old, ~5 billion yr left

Betelgeuse: A red-giant star, About 650 ly away, 3500 K, 862 $R_{O,}$ 20 $M_{O,}$ 8.5 million years old, ~100,000 years left

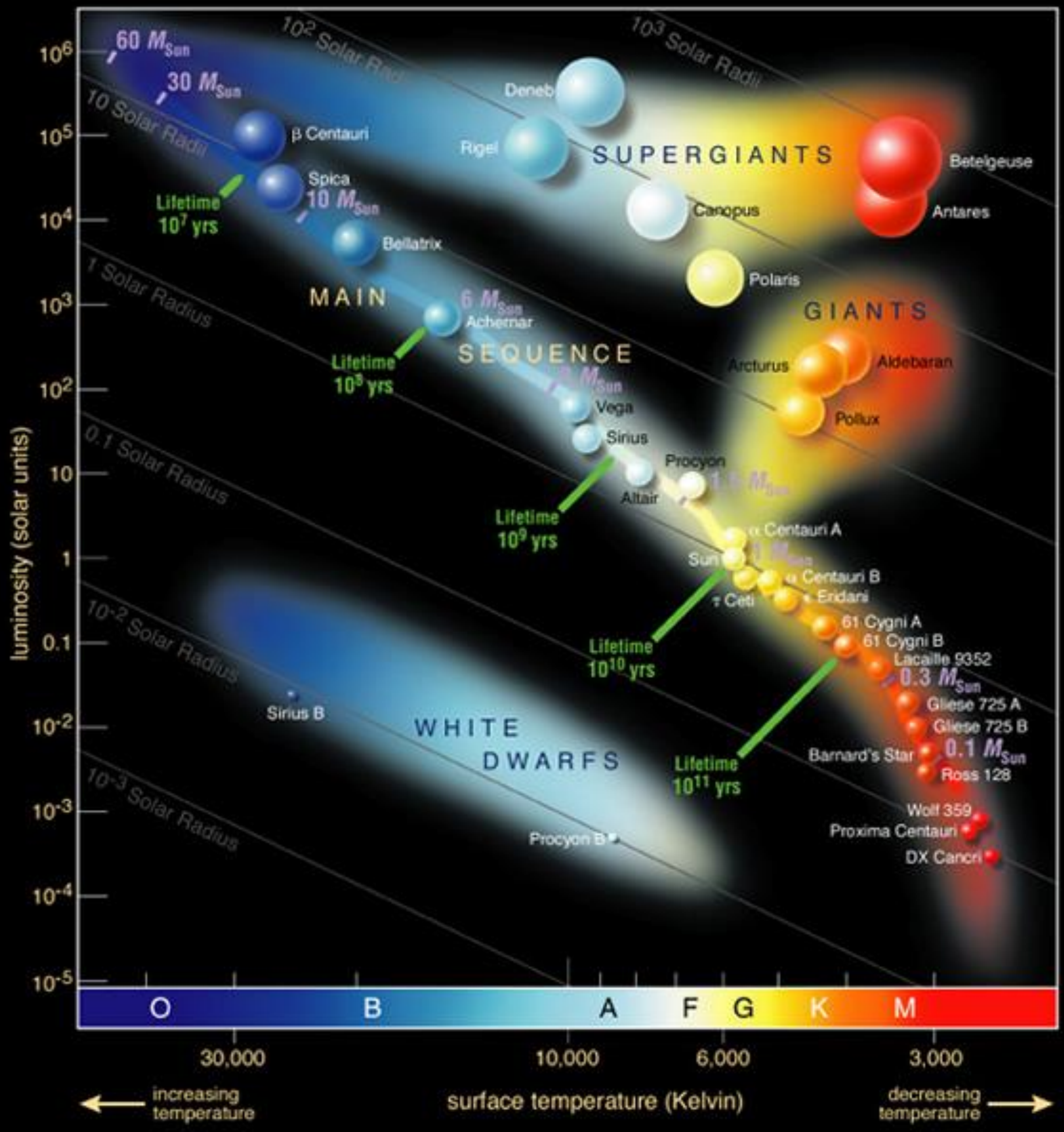




Brightness

Color

Hertzsprung-Russell Diagram



α-Cen-A is G2,
α-Cen-B is K1,
Proxima (α-Cen-C) is M6,
4.2 ly

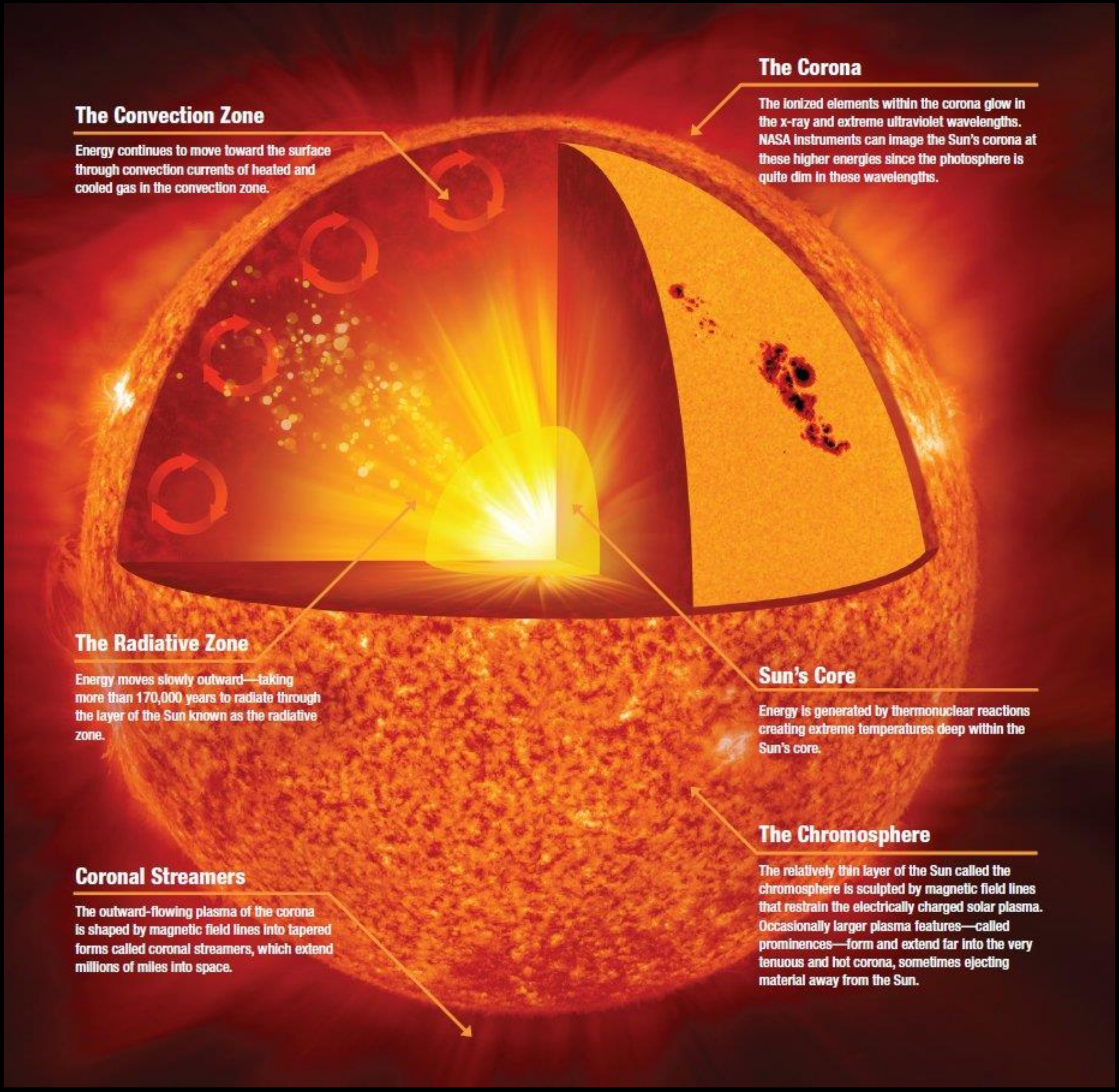
Sun is G2
8.5 light minutes away

Betelgeuse is M2
643 ly

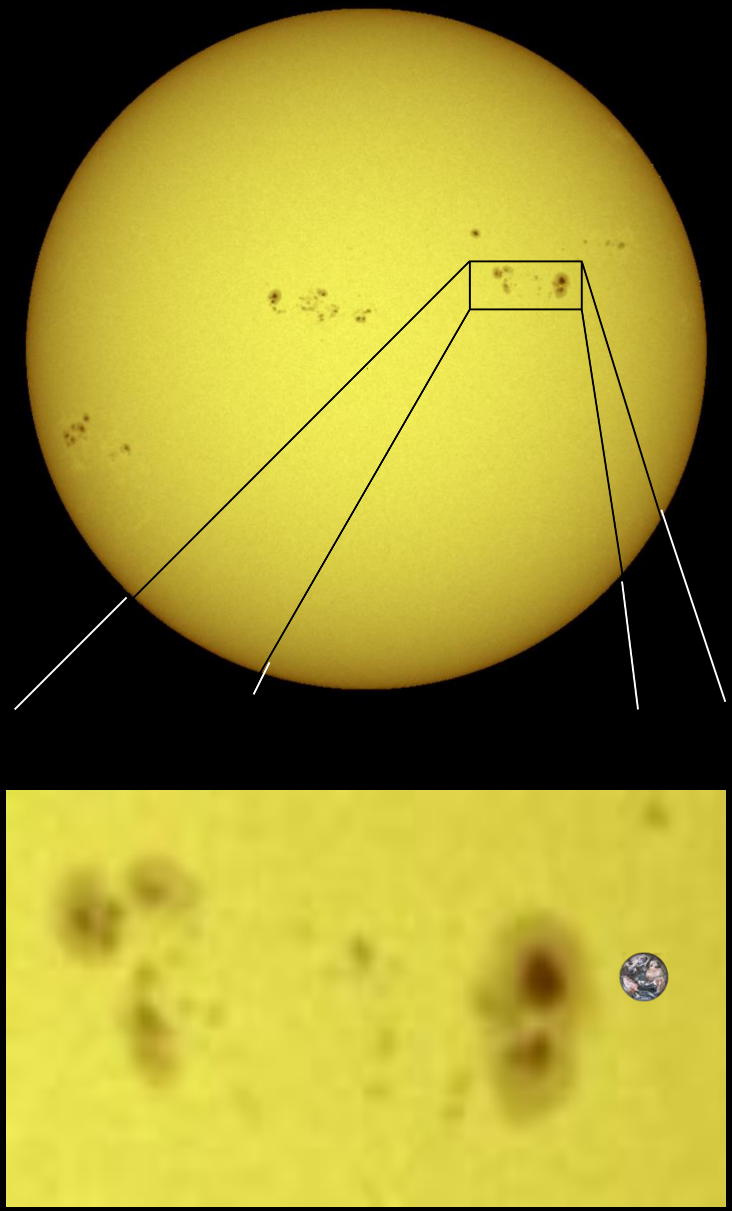
Rigel is B8
860 ly

What is the Sun like?

The Sun: Structure



The Sun: Surface Features - Sunspots

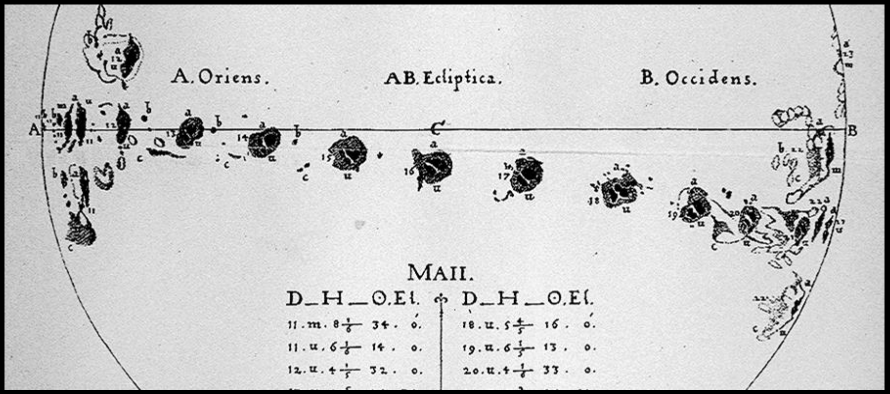


Sunspots are regions that are cooler than their surroundings, produced by strong magnetic fields.

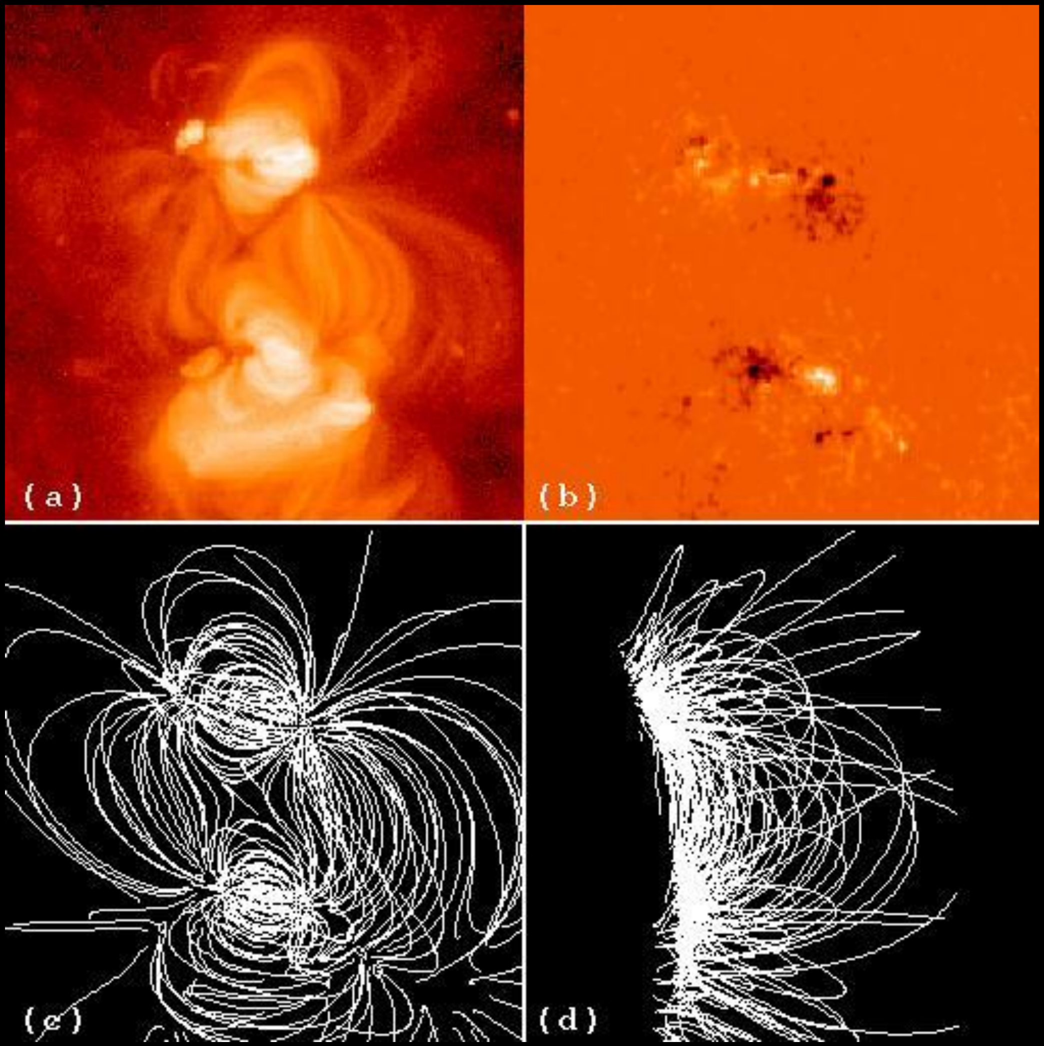
Sunspots have an Umbra surrounded by the lighter Penumbra.

Sunspots usually appear in groups, with lifetimes of days or weeks.

The earliest sunspot observations (c. 1609) indicated that the Sun rotates once in about 27 days.



The Sun: Sunspot - Magnetic Fields



(a) Yohkoh Soft X-ray Telescope,
Corona
4 Jan, 1994 7:35 UT

(b) Line-of-Sight magnetic field
from Kitt Peak National Observatory
at 16:31 UT

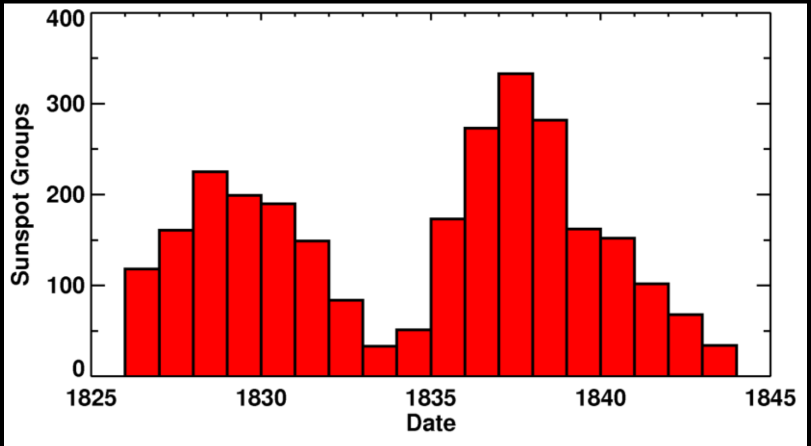
(c), (d) Extrapolated Magnetic Field

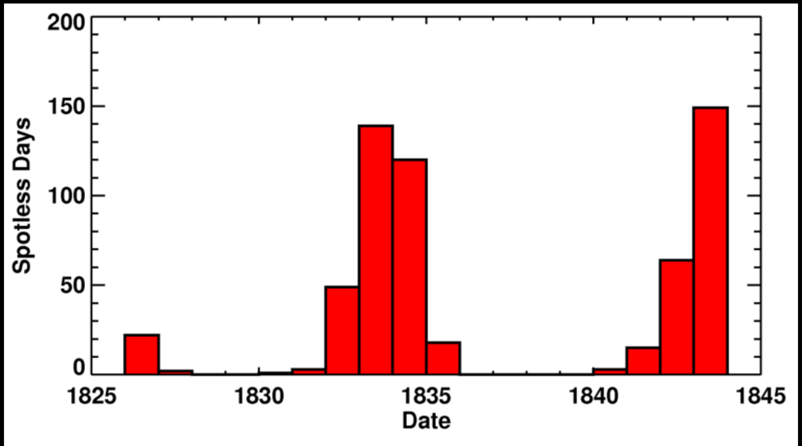
The Sun: Sunspot Cycle Discovery

Sunspots observed > 230 years
1844 Heinrich Schwabe, amateur astronomer, Dessau, Germany

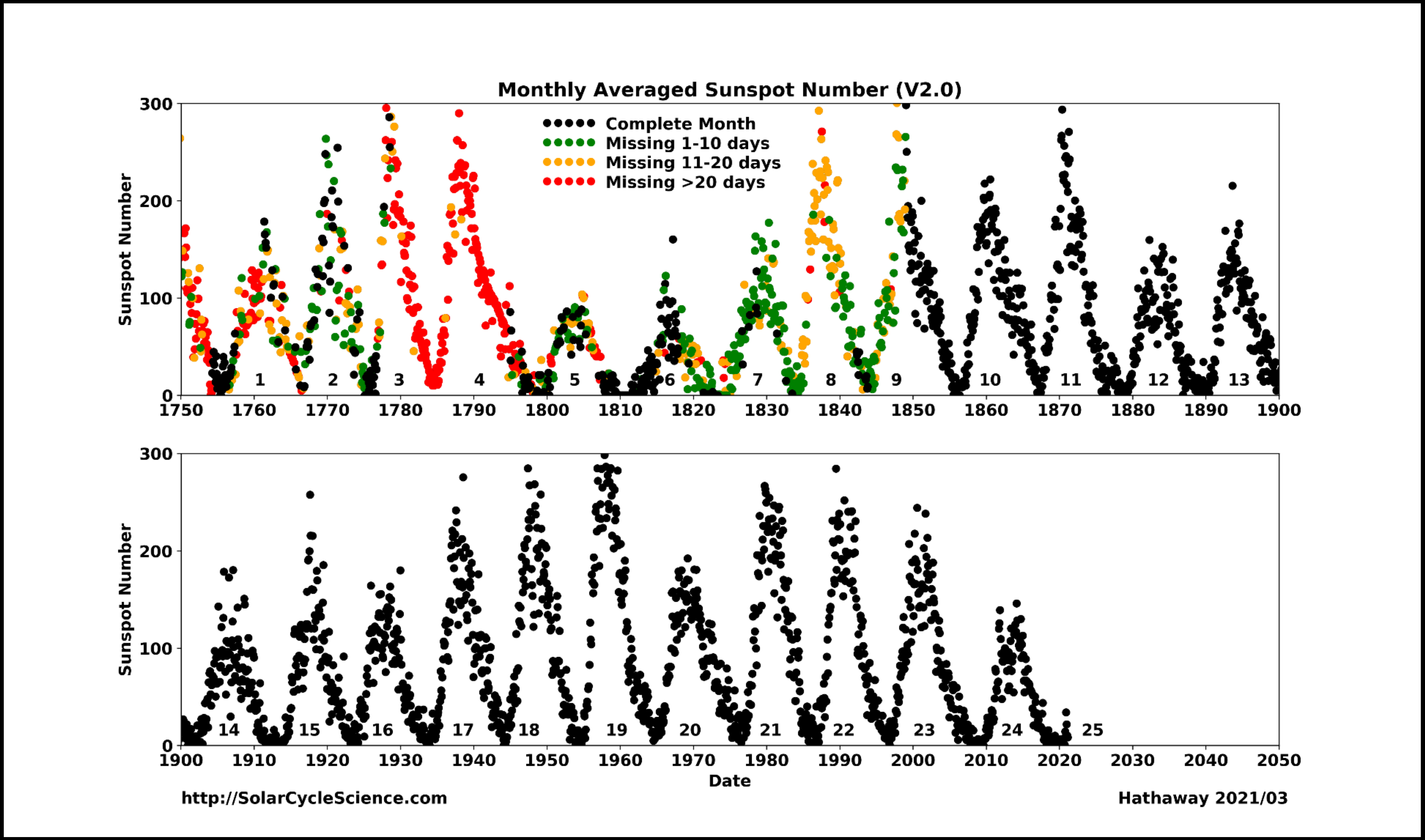
Cycle: increase and decrease over ~10-years
- number of sunspot groups and the
- number of days without sunspots

Schwabe's data for 1826 to 1843





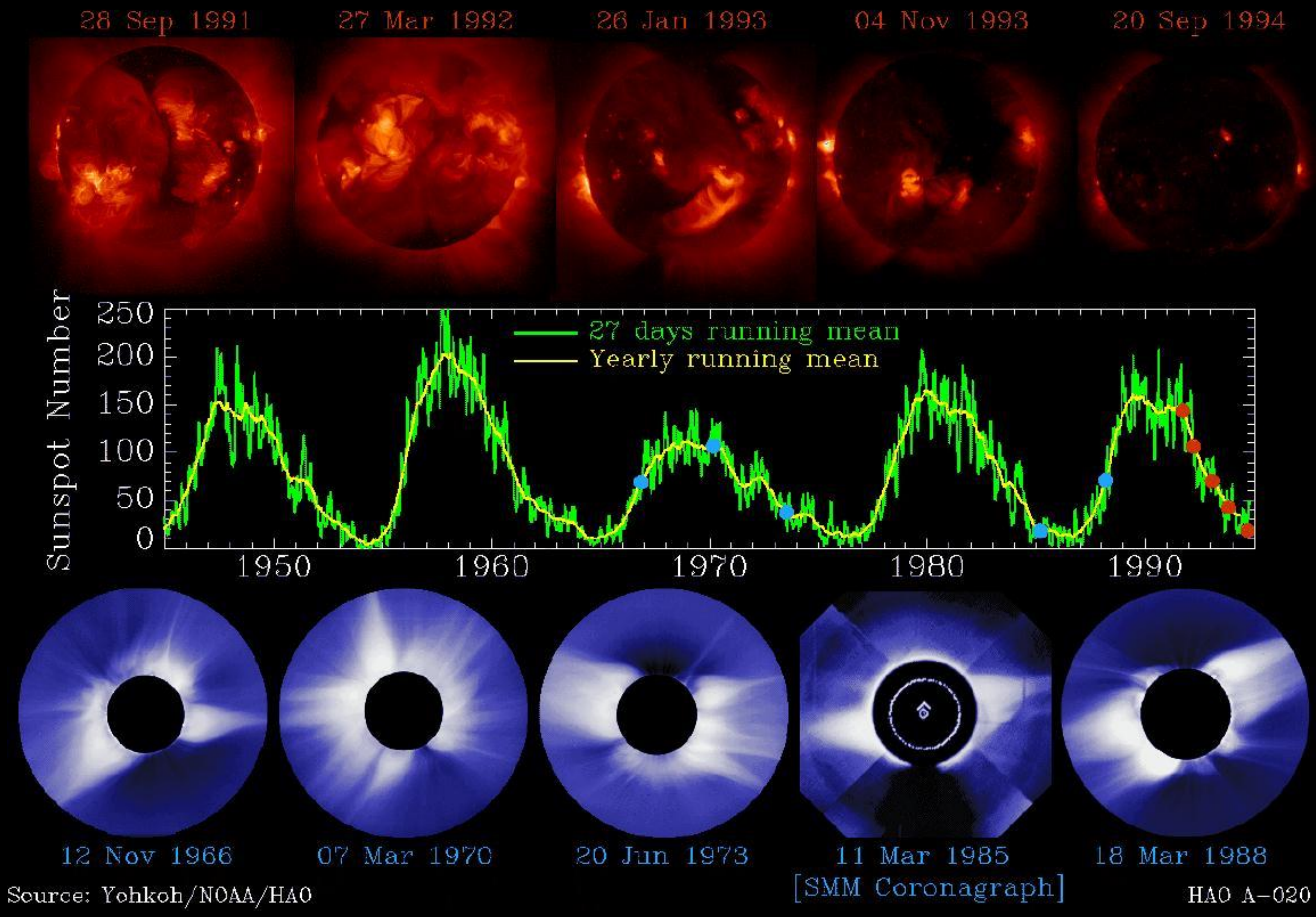
The Sun: 24 Full Cycles Observed



- **Rudolf Wolf 1849 -- “Relative” Sunspot Number = 10 times number sunspot groups + total distinct spots**
- **Average cycle: ~11 years, -2, +3**
- **Average amplitude: ~100, with range from 50 to 200**

(Image used with permission of David Hathaway)

The Corona and the Solar Cycle



The Corona August 21, 2017

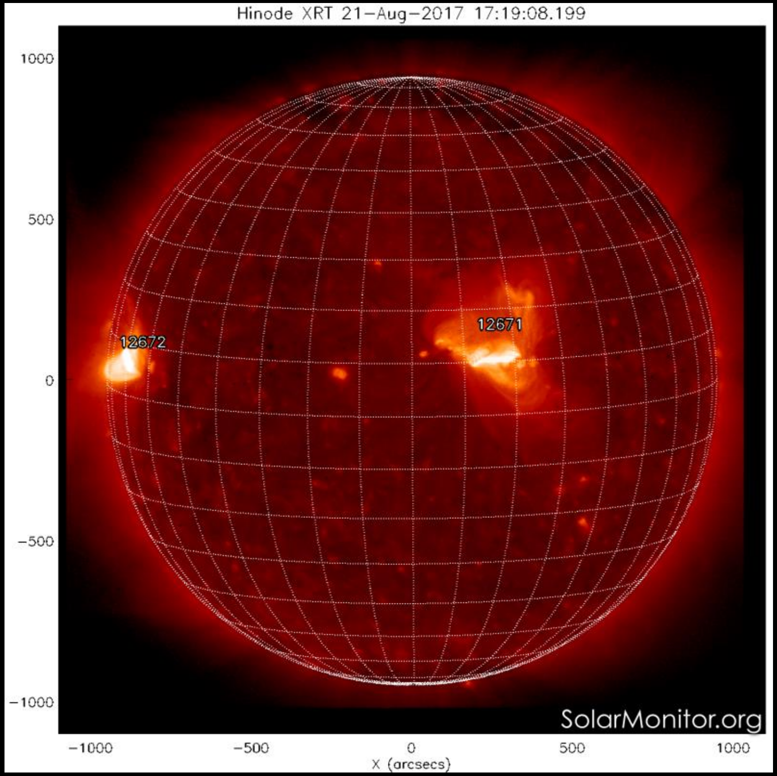


Image by Joe Matus, NASA/MSFC, taken from Hopkinsville, KY

Total Solar EclipseAugust 21, 2017

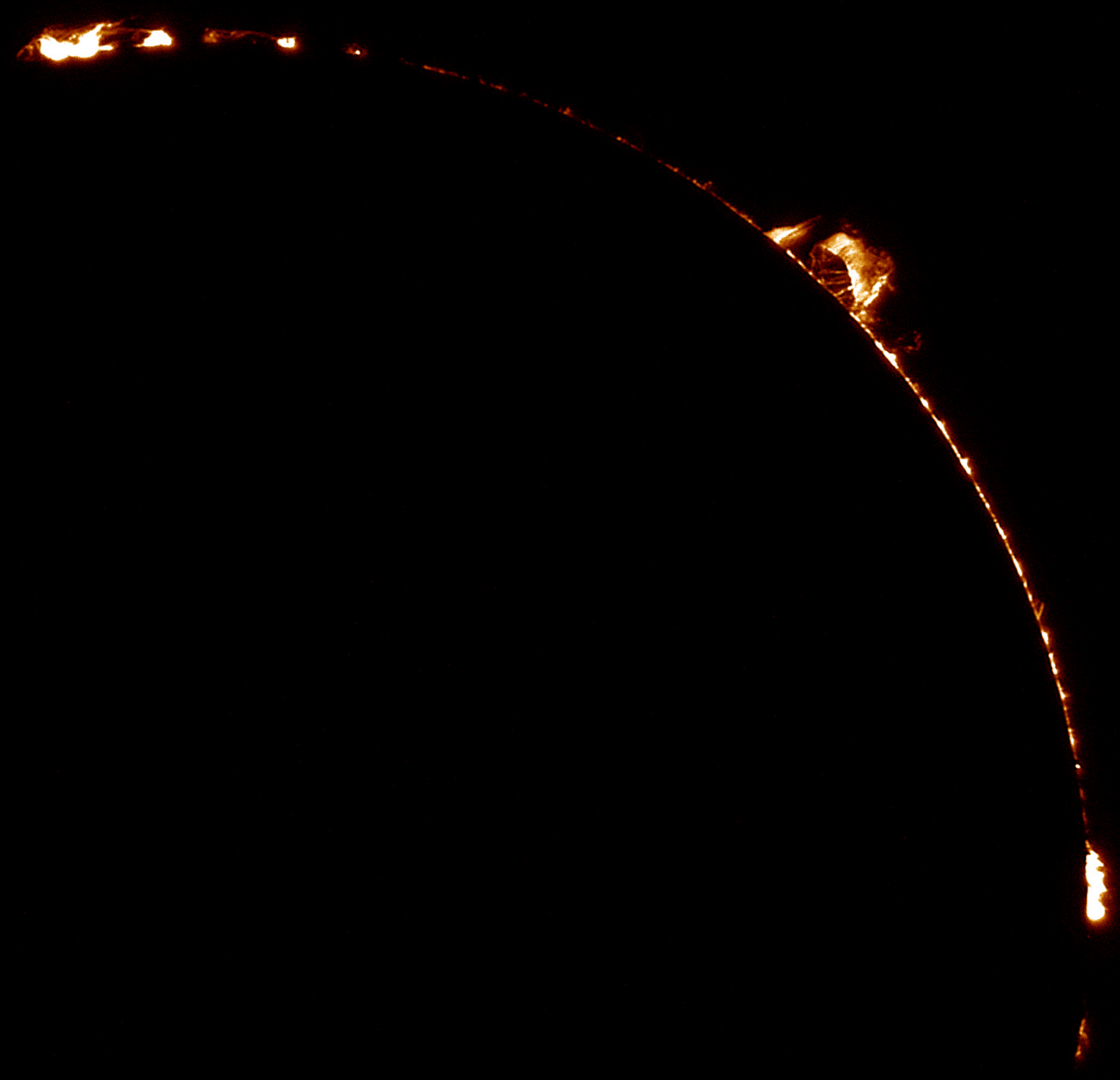


Image Courtesy of Joe Matus, ST 24, NASA/MSFC

Partnerships

- U.S. Space and Rocket Center
- Austin Peay State University
- University of Alabama in Huntsville
- The Inspire Project
- Christian County Schools
- The City of Hopkinsville, KY
- Citizen CATE
- Tennessee Tech

Animal Behavior Observations: Cows, Bees, Crickets, Turtles

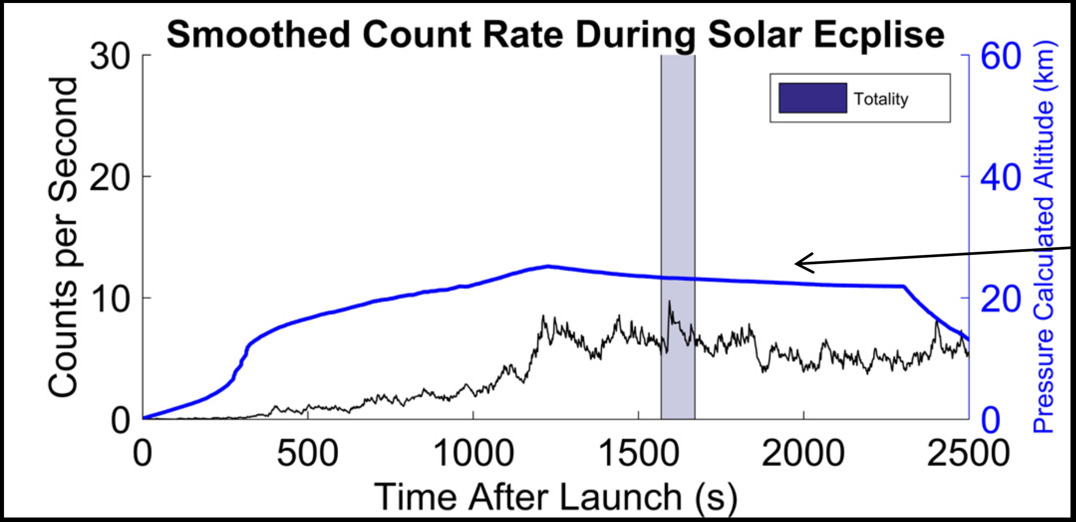
Totality (~13:30 CDT) Behavior

- 1 of 8 cows moved from shade tree
- 97% bees returned to hive, takeoffs 0.5 hr after totality
- 50% of crickets were active/chirping
- 40 turtles on pond bank, only 7 by 15:00 CDT

Montana State Balloon Project

50 Teams from across the nation flew payloads

Three teams at APSU:
APSU, Arkansas State, and UAH

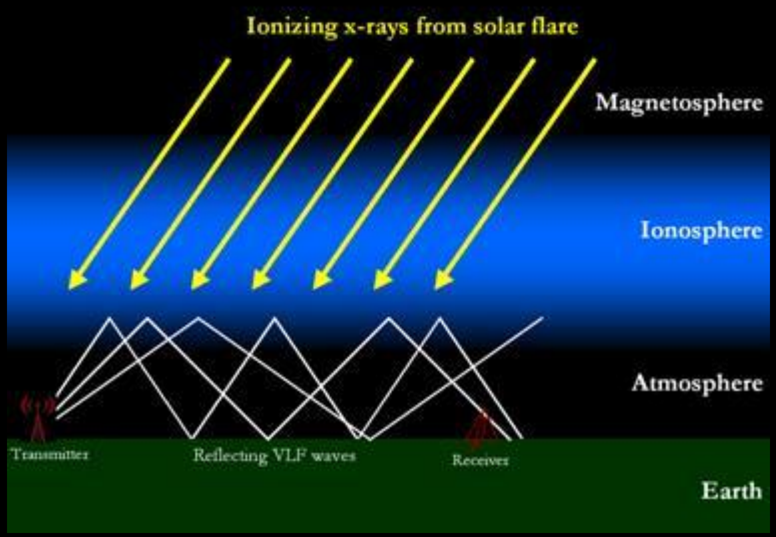


Note plateau in altitude

Payloads:
- Video-streaming camera
- Two pounds of hops for Straight to Ale Eclipse Brew
- Geiger counter, temperature, pressure

Impact of Reduced Solar Irradiance on the Ionosphere

Character of the lower ionosphere not well understood



Physical Processes:

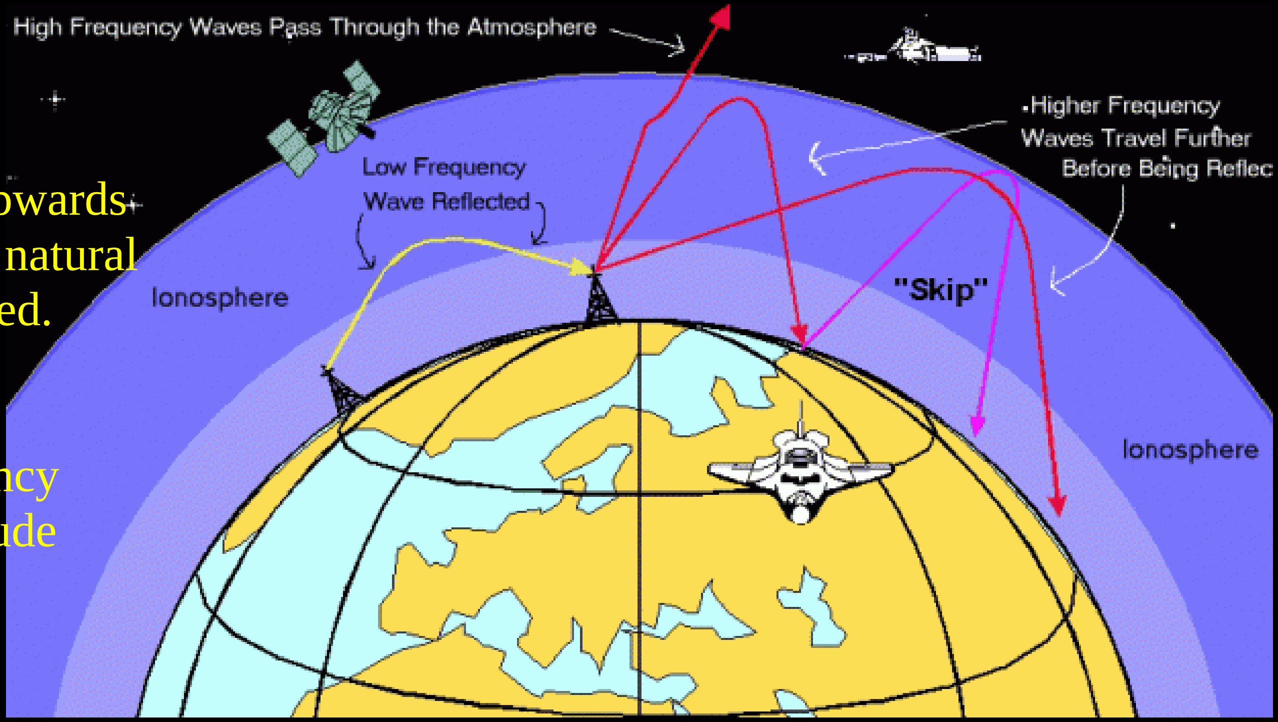
Solar radiation reduced

Ionosphere responds--ions recombine

How quickly does the ionosphere recover?

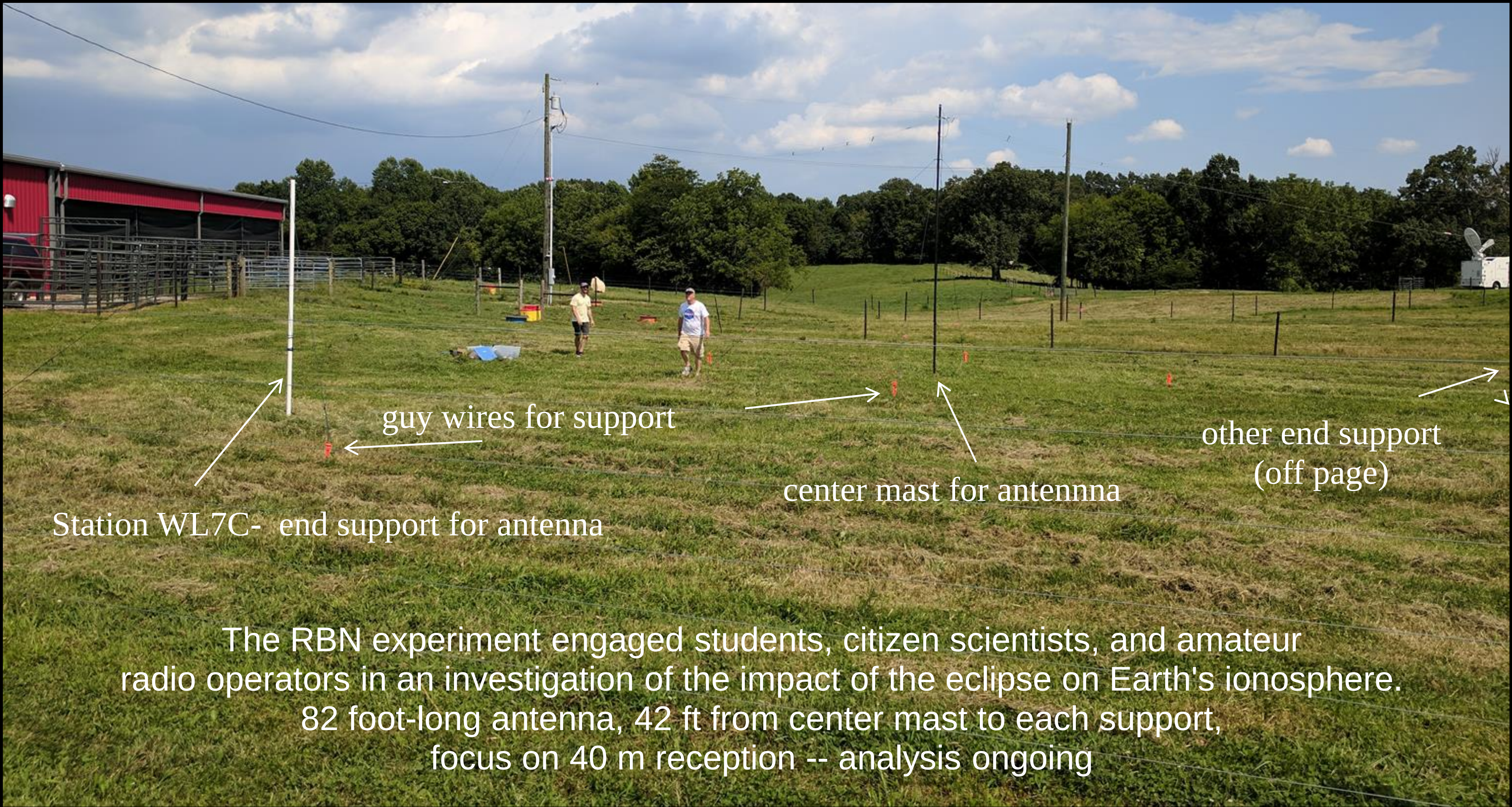
Measurements: Radio signal transmitted upwards
A layer of electrons reflect, when plasma's natural oscillation frequency equals that transmitted.

Time-of-flight measured
-> Height of reflection
Plasma density proportional to frequency
-> Plasma Density as function of altitude

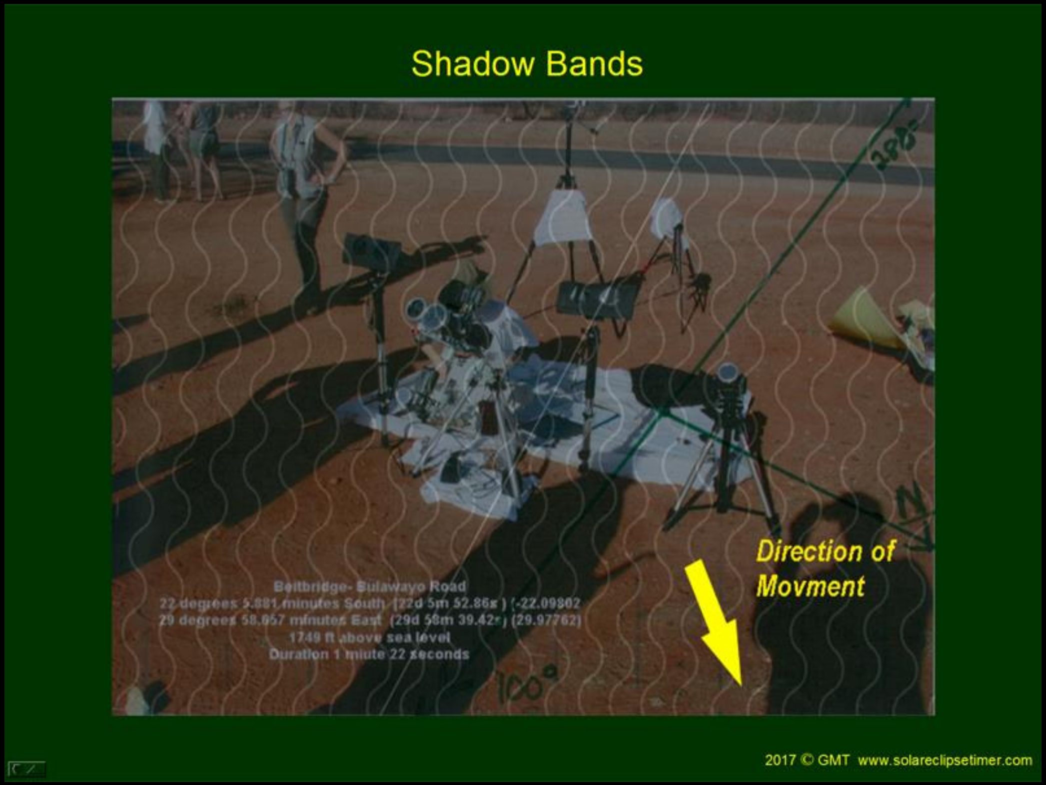


Reverse Beacon Network (RBN)

The RBN: an array of passive receivers that record radio links of amateur (ham) operators (Frissell et al., 2014)

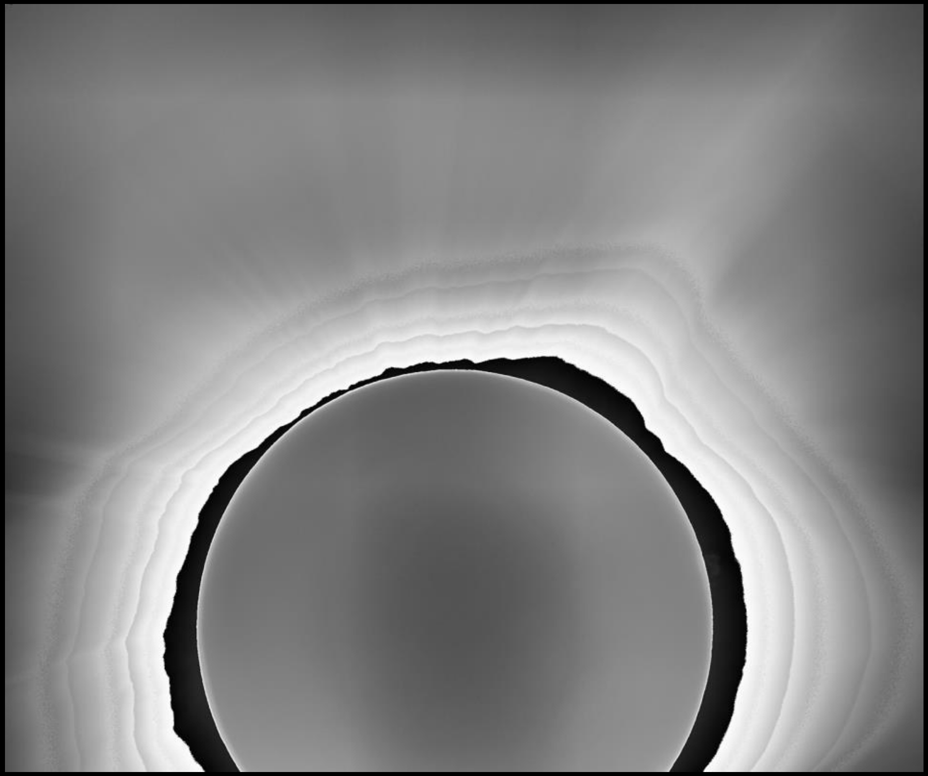


Shadow Bands

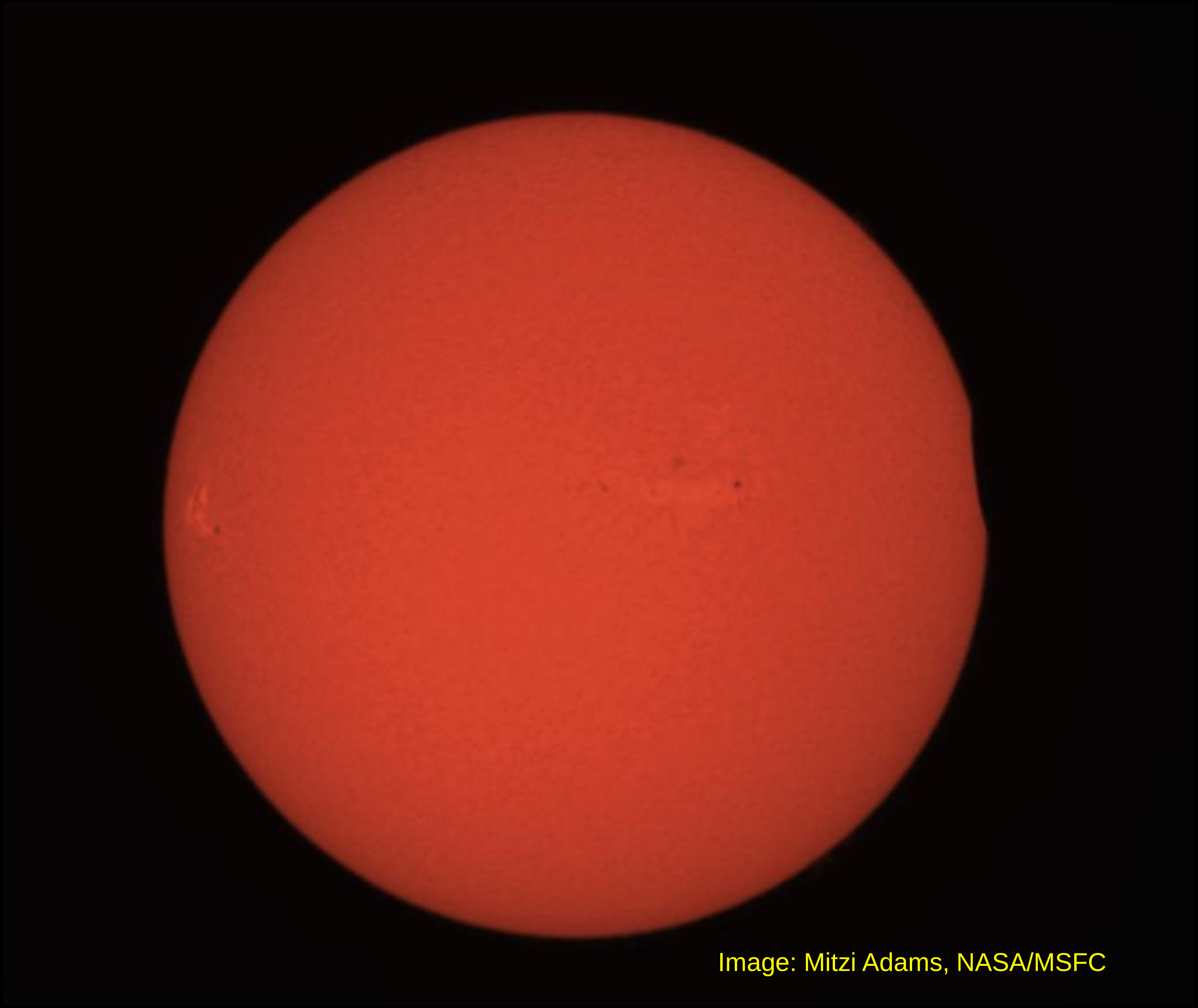


Citizen Continental-America Telescopic Eclipse Experiment (CATE)

62 Sites Across Country Using
Identical Equipment
Obtained Data



First Contact at APSU



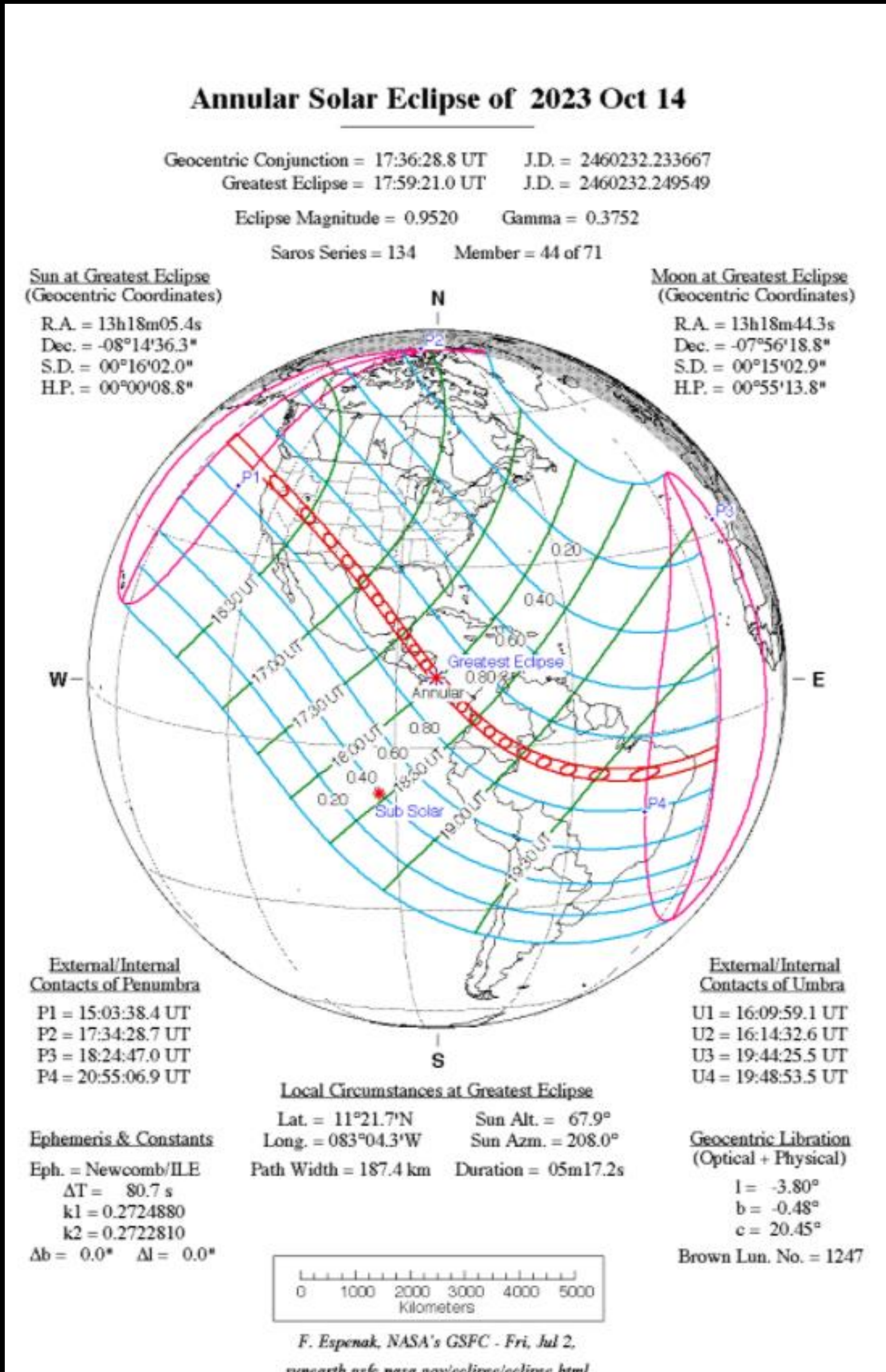
Totality at APSU

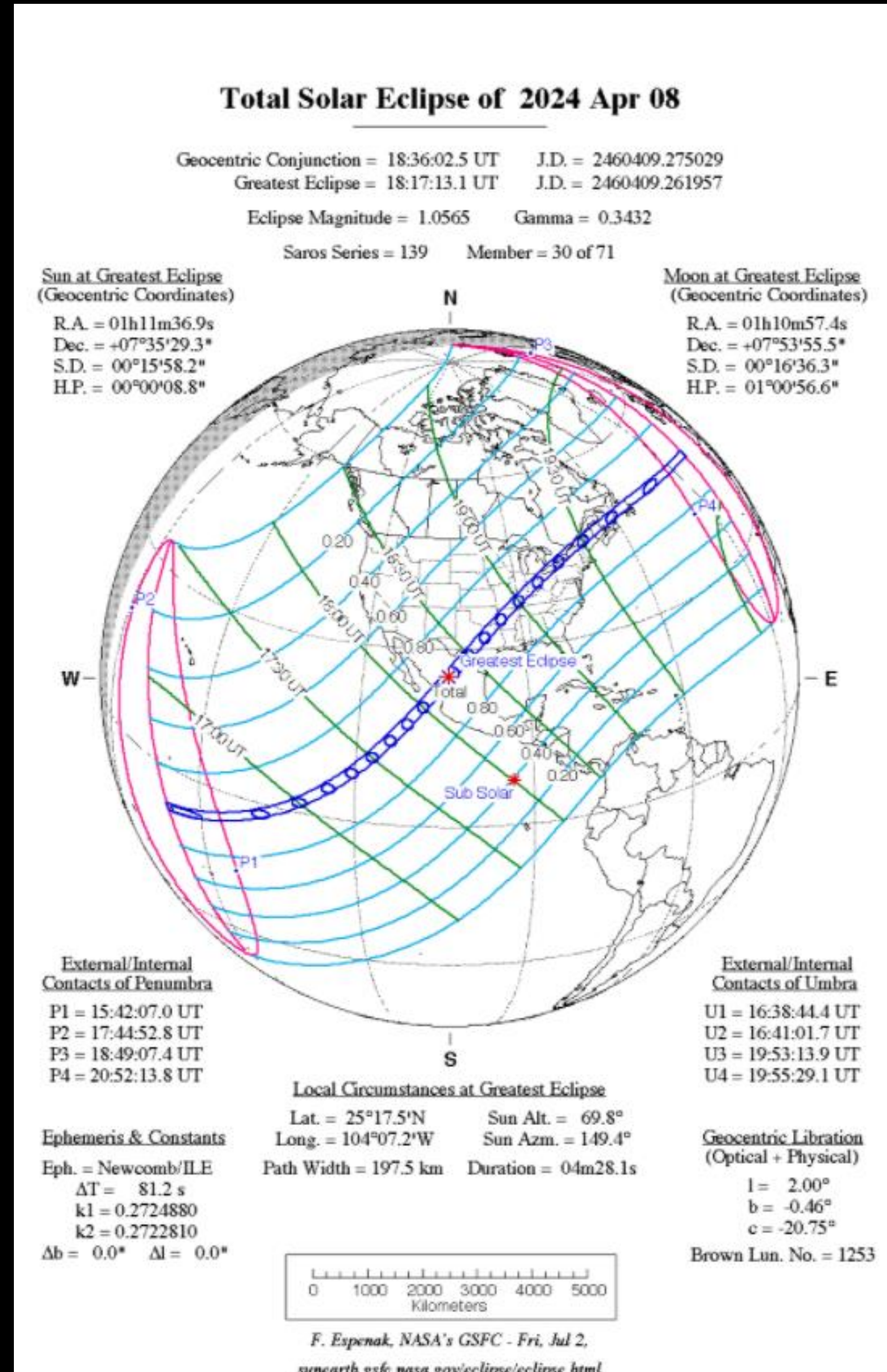
Totality at Hopkinsville, KY

Image from Dr. Jesse-Lee Dimech,
NASA NPP

Image from Joe Matus,
NASA/MSFC/ST24

Next “Big” U.S. Eclipses





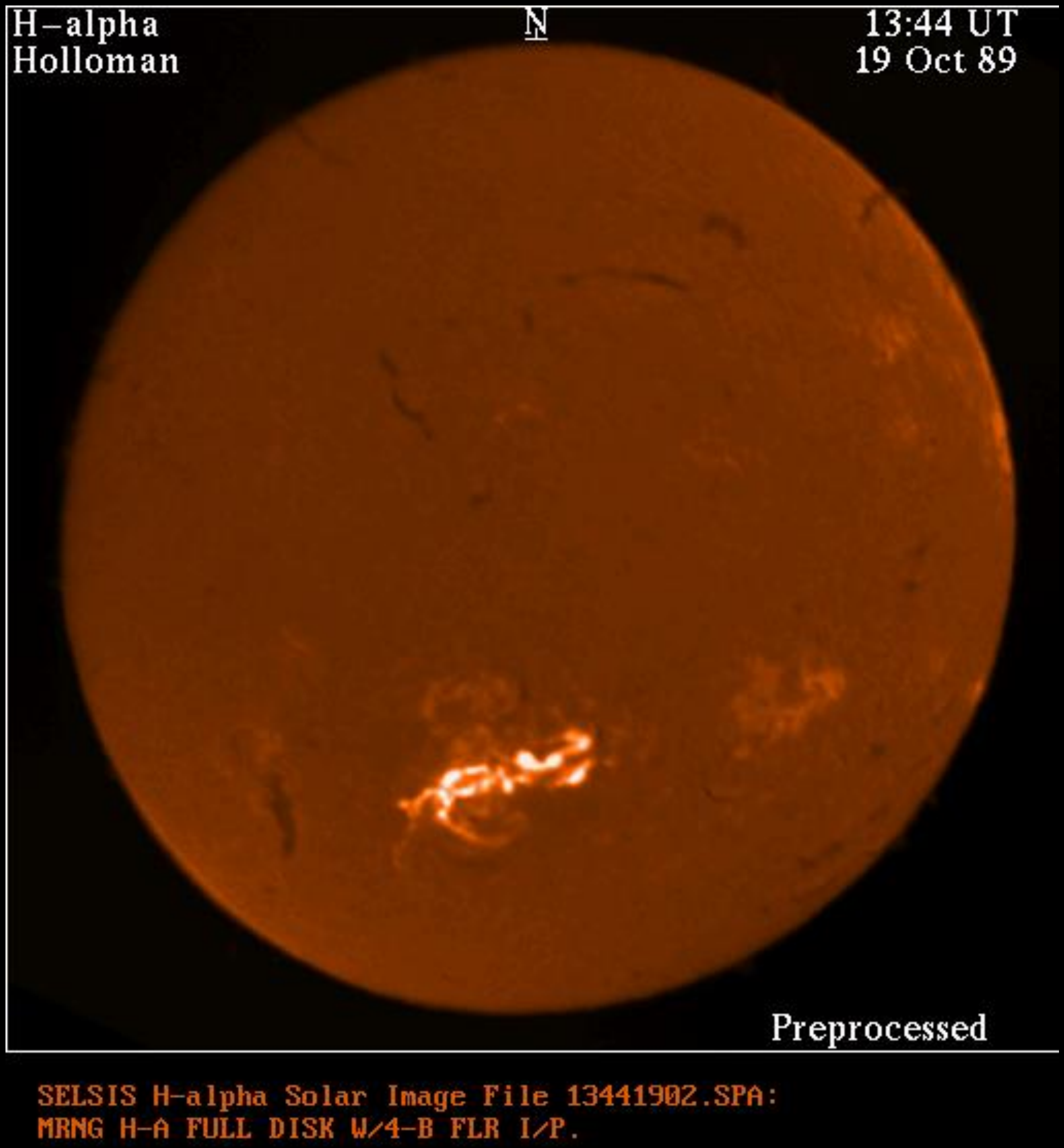
Solar Eruptions

Flares

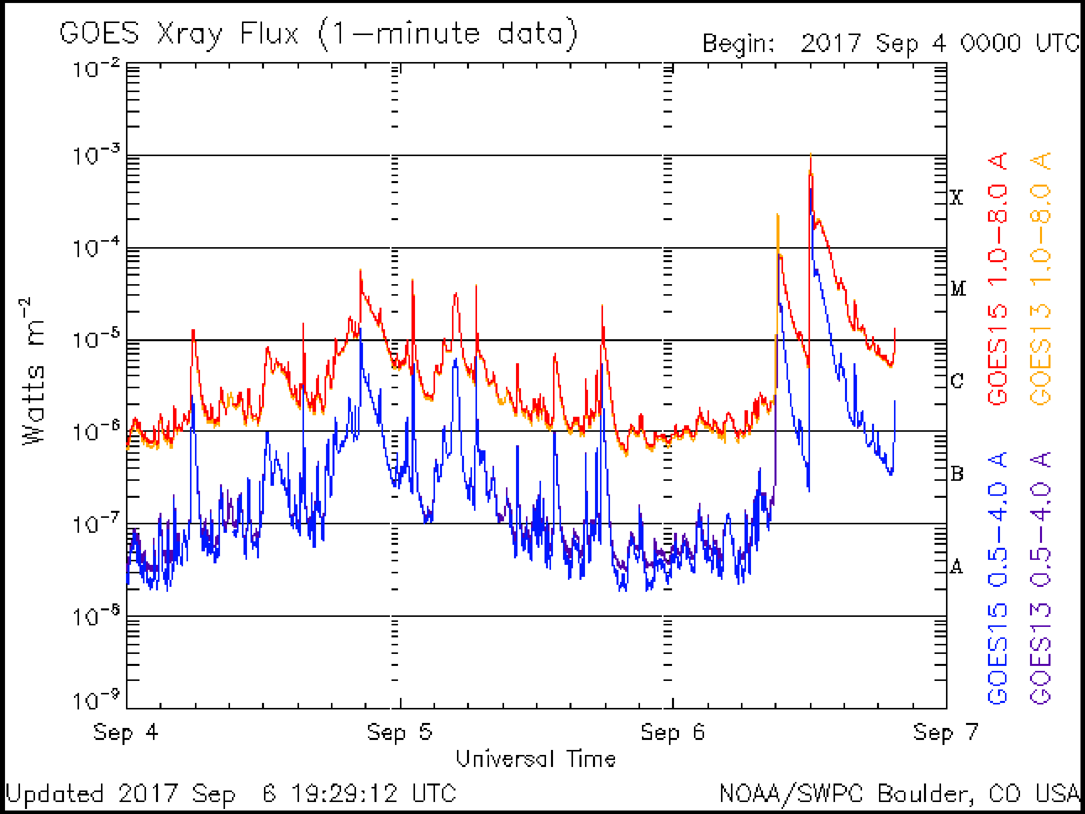
Coronal Mass Ejections

Jets

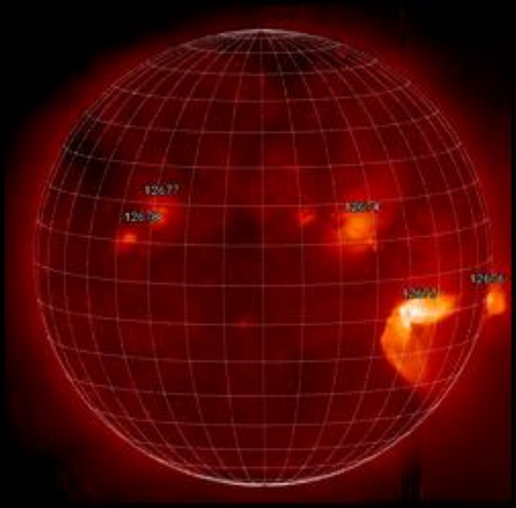
Solar Flares

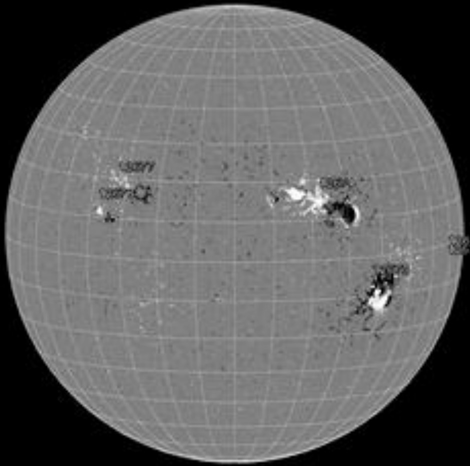


Solar Flare Classification



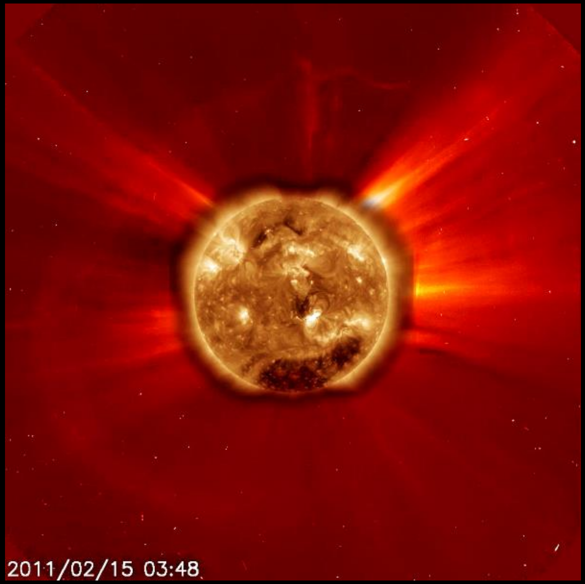
Sept. 6, 17:59 UT
Hinode X-Ray Telescope
(XRT) X9 flare



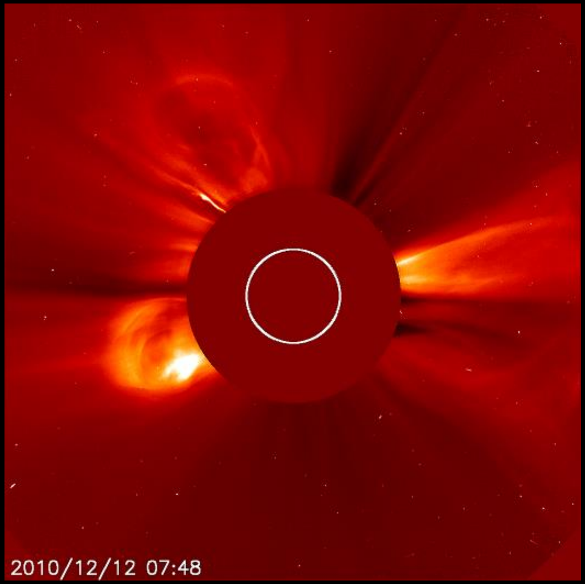


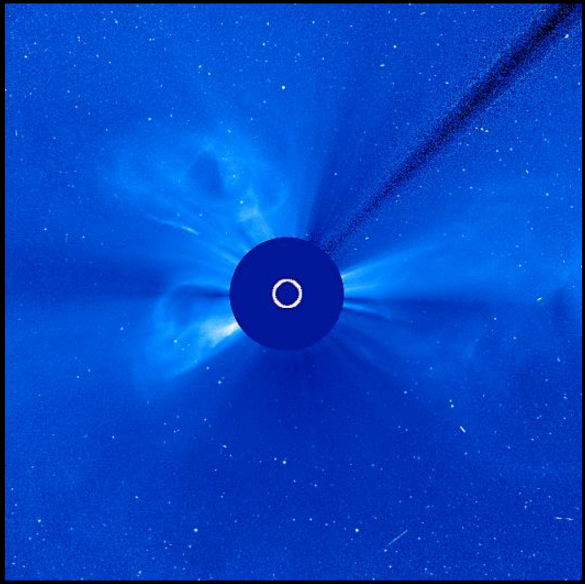
Sept. 6, 18:46 UT
SDO/Helioseismic
and Magnetic Imager
(HMI)

Solar Eruptions
Coronal Mass Ejections



SDO plus SOHO C2
X2-flare and halo CME





Three distinct CMEs
1. To right in both images, from a filament eruption,
2. From North Pole,
3. From far side of Sun.

All three eruptions happened within hours of each other.

Jets in Coronal Holes

Coronal Jets

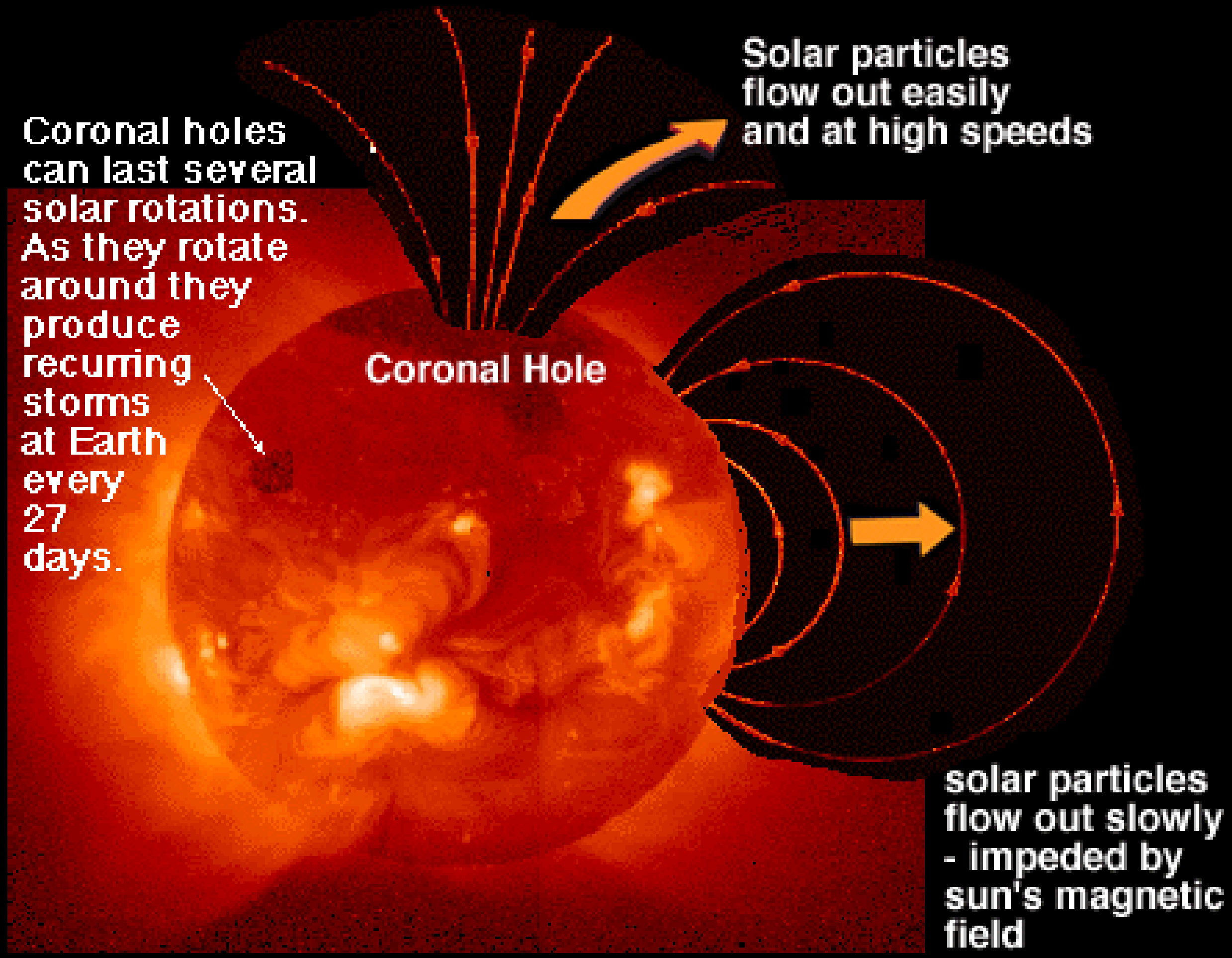
What is a Jet?

JET / noun – plural noun: jets

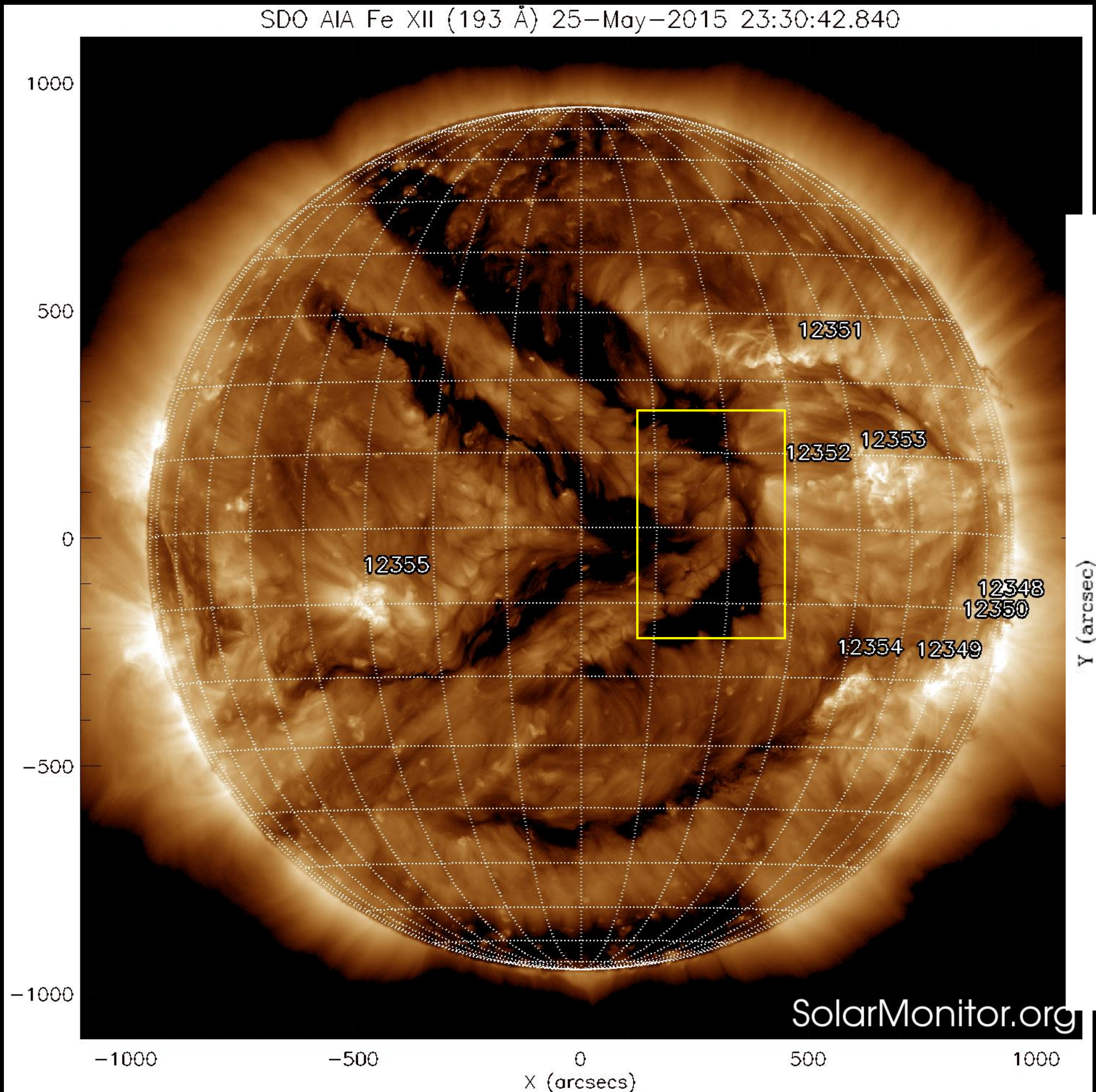
1. a rapid stream of liquid or gas forced out of a small opening."a high-pressure shower with pulsating jets", a nozzle or narrow opening for sending out a jet of liquid or gas. "Agnes turned up the gas jet"

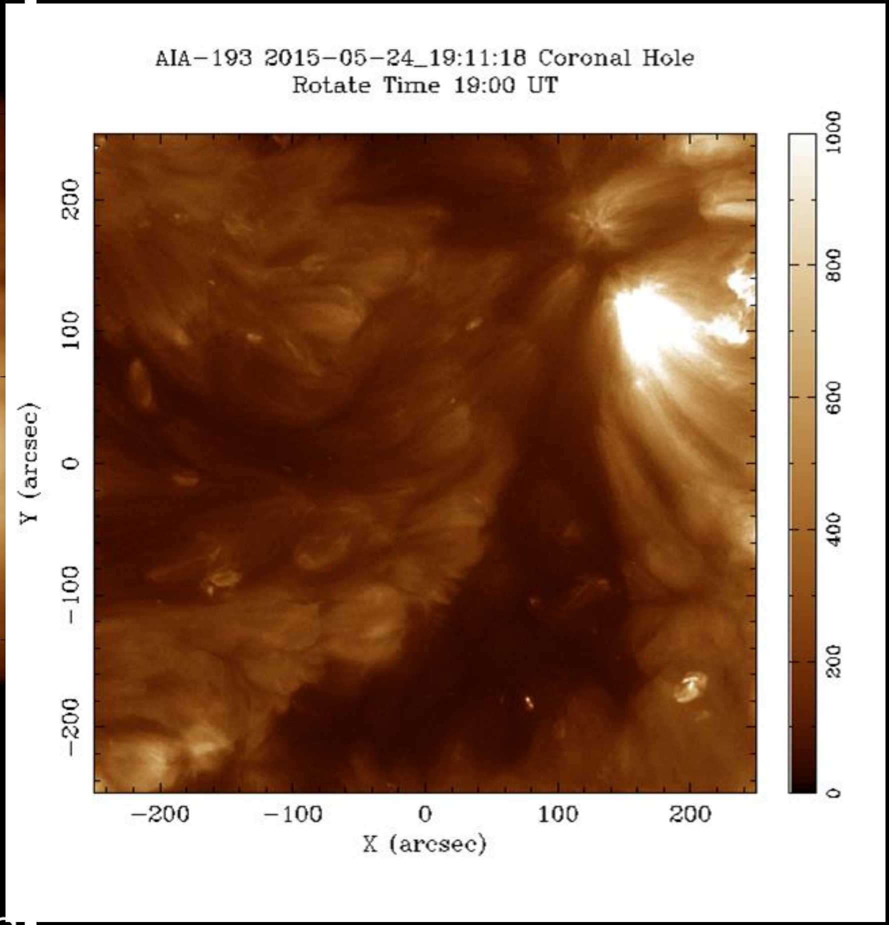
2. an aircraft powered by one or more jet engines."a private jet“. “Astronauts fly T-38 jets.”

Coronal Holes in General (in X rays)

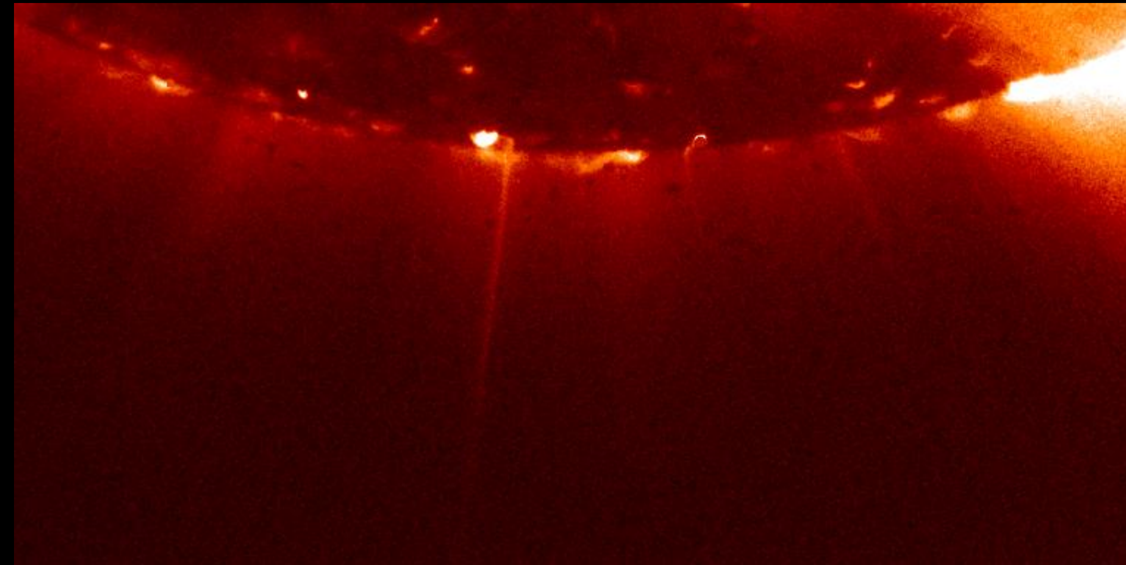


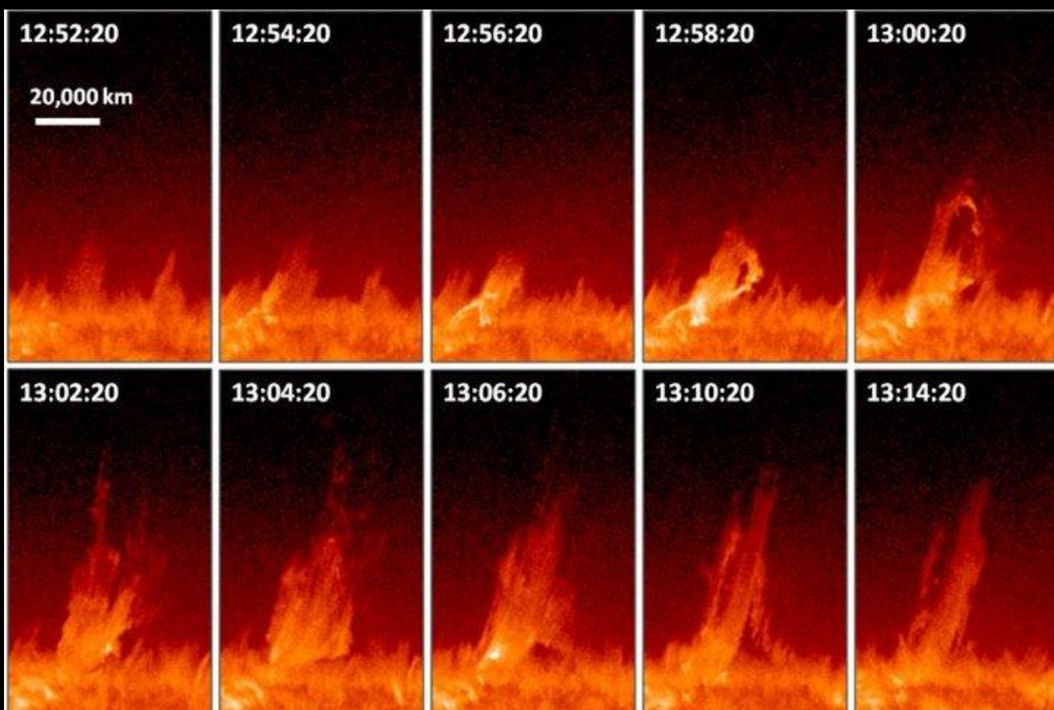
Corona Holes in General (in EUV)

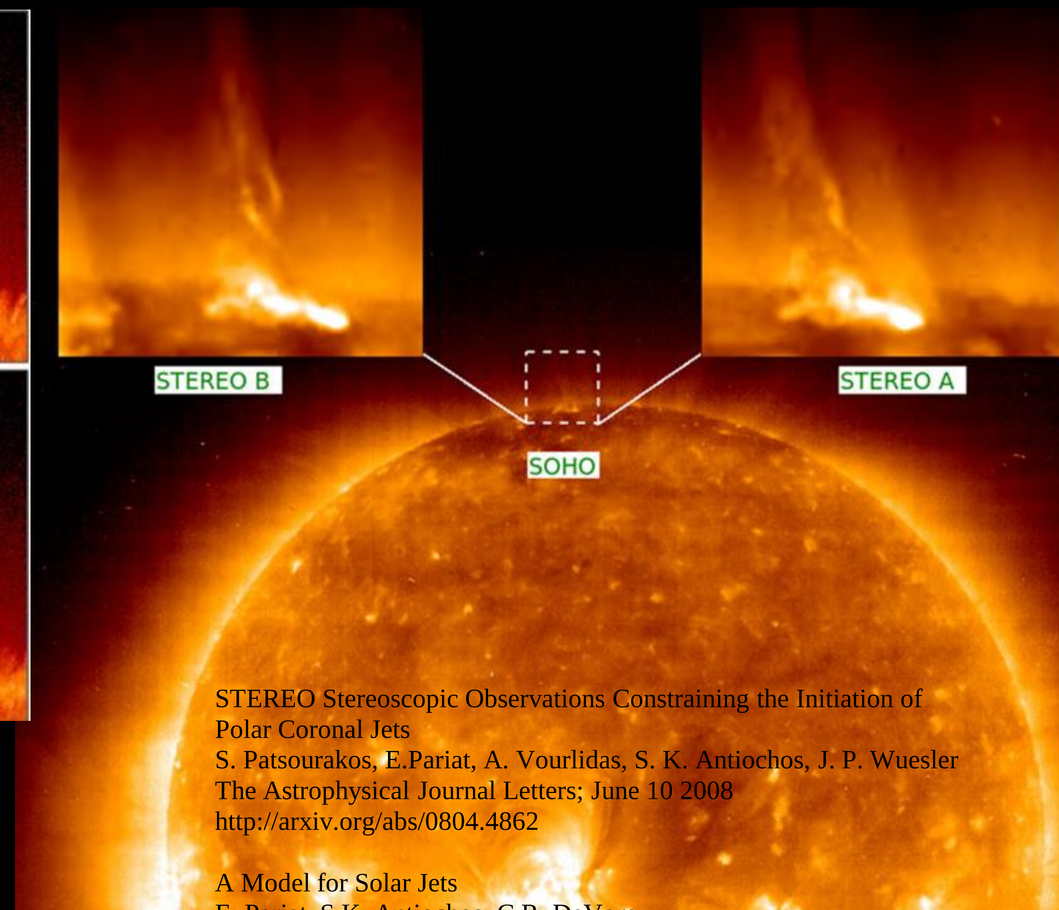




Solar jets can eject a million tons of matter at a speed of a million miles per hour (~45,000 km/s) in just a few minutes.







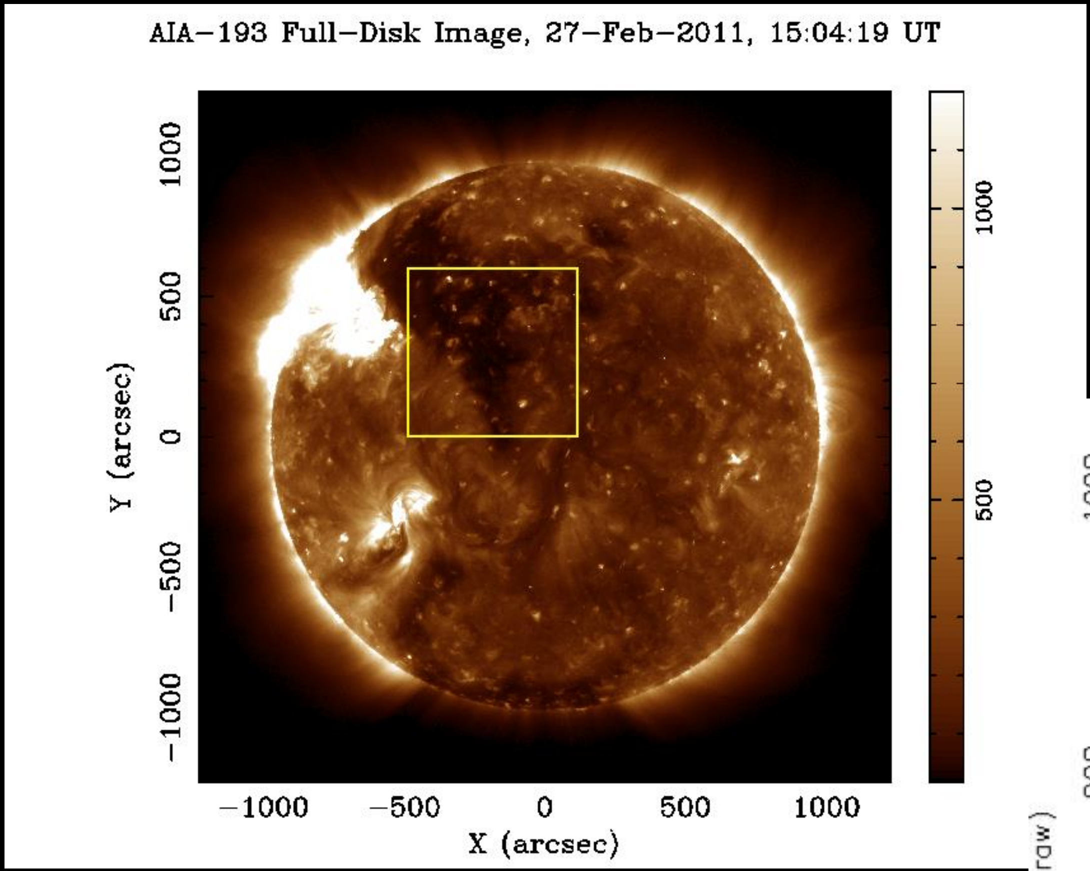
STEREO Stereoscopic Observations Constraining the Initiation of Polar Coronal Jets
S. Patsourakos, E.Pariat, A. Vourlidas, S. K. Antiochos, J. P. Wuesler
The Astrophysical Journal Letters; June 10 2008
http://arxiv.org/abs/0804.4862

A Model for Solar Jets
E. Pariat, S.K. Antiochos, C.R. DeVore

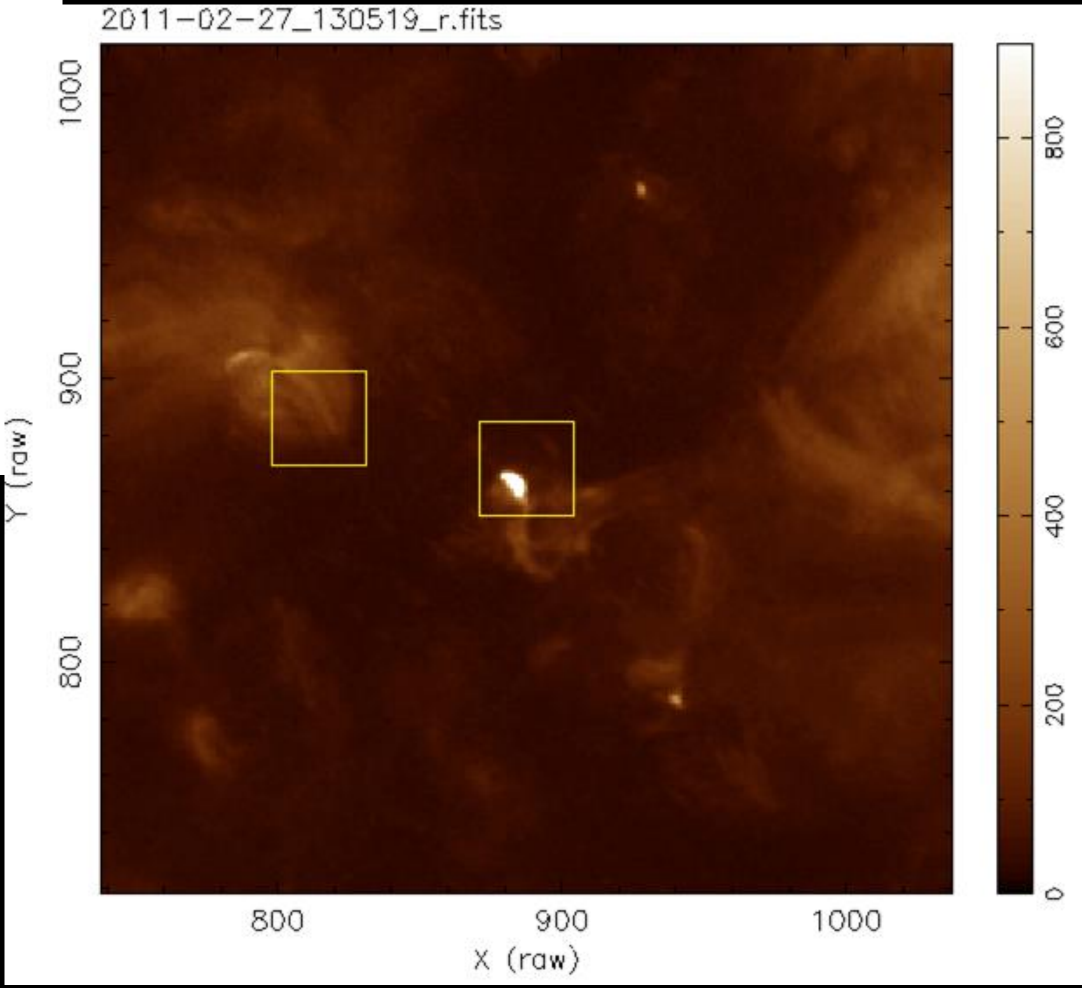
Above is an example of a “blowout” jet, from a northern polar coronal hole on 2010 October 2. The images are from SDO's AIA in 304 Å.

From: The Cool Component and the Dichotomy, Lateral Expansion, and Axial Rotation of Solar X-Ray Jets, R.L. Moore, *et al.*, **ApJ,** 768:134 2013 June 1

Jets in Coronal Holes

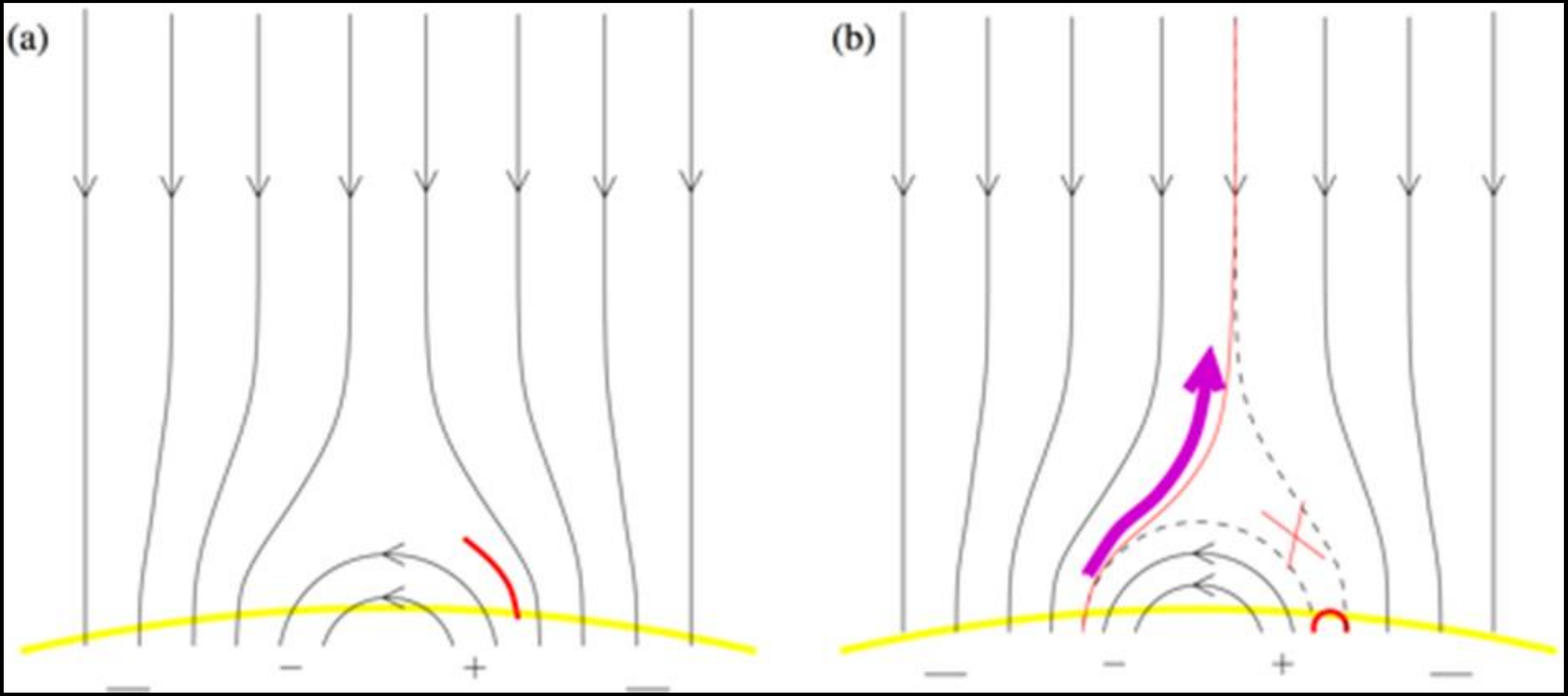


This jet has a component with speeds > 200 km/s (1 min).
In 304 Å, speeds are ~ 80 km/s (4 min.)



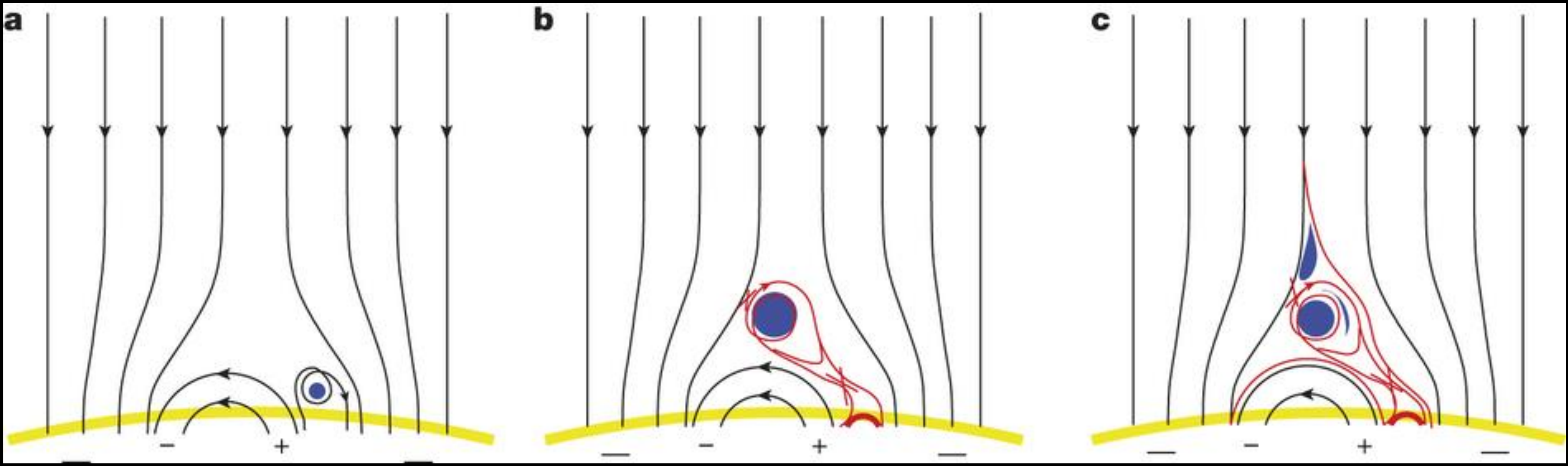
Coronal Mass Ejections have typical speeds of about 300 km/s, but can range from 100 - 3000 km/s

Jet Formation (Cartoon) Solar X-ray Jets



The commonly accepted mechanism for jet formation: Black lines represent magnetic field, with arrows indicating polarity; the yellow curve is the solar limb; the thick red curve in a represents a plasma current sheet; the red cross in b shows the location of field reconnection. a, Initial state. b, Jet formation: flux emergence purportedly forces reconnection at the current sheet (red cross), resulting in new closed-loop field (red loop), and new connections to the open coronal field (thin red line), along which the X-ray jet (purple) flows. According to this model, the new reconnection loops appear as the Jet Bright Point (JBP).

Jet Formation (Cartoon) Solar X-ray Jets (Revised)



Representation of the minifilament-eruption process that drives the formation of solar X-ray jets, as inferred from our observations. Black lines represent magnetic field, with arrows indicating polarities; red curves are newly reconnected field lines; blue features are minifilament material; yellow curve is the solar limb (the apparent edge of the Sun). From the initial state (a), the jet forms as the minifilament erupts (b, c), with reconnection locations indicated by red crosses (b, c). The JBP (bold red arc) forms at the location of filament lift-off (b, c). See Methods for more details.

Summary

Our Sun is a single star with a system of planets

The Sun is a stable star, happily converting hydrogen to helium

The Sun will remain on the Main Sequence of ~ 4.5 billion years more

The Sun is an active star, which produces spots, flares, and coronal mass ejections

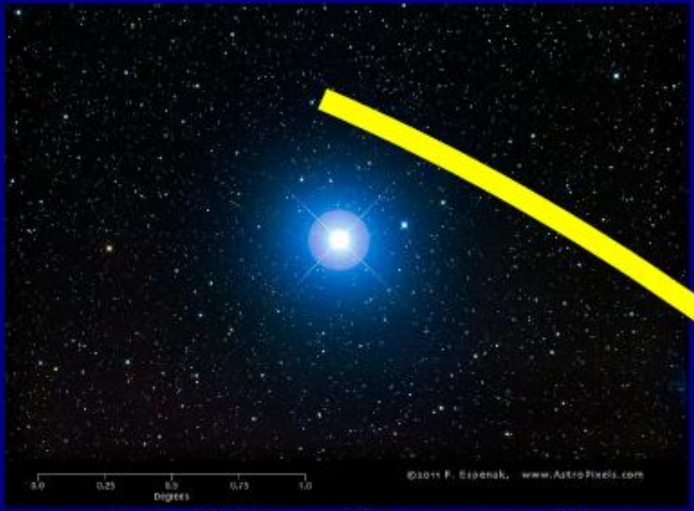
Jets of all sizes occur on the Sun.

The mechanism for producing the jets seems to be similar at all scales.

Because chromospheric jets can trigger flares and CMEs, which can affect Earth, it is important to understand all jets.

Will the Sun end its life with a bang or a whimper?

What is a Star? -- Differences



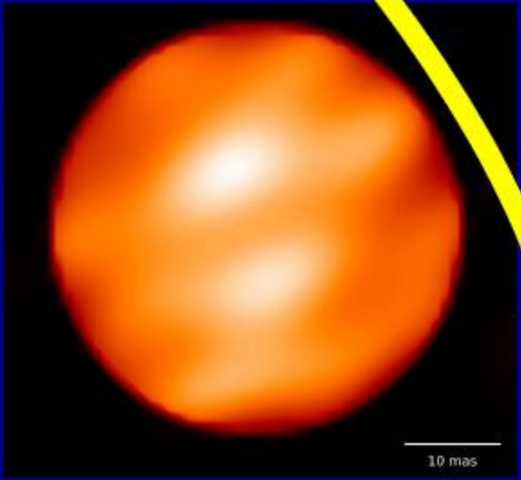
Rigel: A blue-white star, about 8600 ly away, 12,000 K, 80 $R_{\odot}$, 23 $M_{\odot}$, 8 million years old.

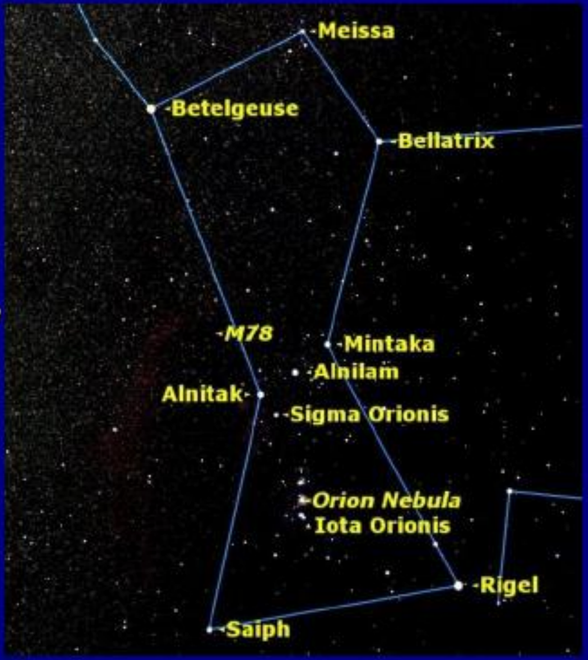
Aging

Our Sun: A yellow star, ~8 lm away, 6,000 K, ~700,000 km (432,000 mi), 2 x 10^{30} kg, 4.5 billion years old, ~ 5M yr left.

Brightness

Betelgeuse: A red-giant star, about 650 ly away, 3500 K, 862 $R_{\odot}$, 20 $M_{\odot}$, 8.5 million years old, ~100,000 years left .





Color