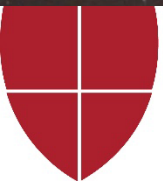


SOAR: Lives of Stars

Lives & Deaths of Small Stars

Aileen A. O'Donoghue
Henry Priest Professor of Physics



ST. LAWRENCE UNIVERSITY

The Lives of Stars

☆ Star Birth: 9/10/26

🌍 Nuclear Explosions Contained by Gravity

☆ Lives & Deaths of Small Stars: 9/17/26

🌍 Planetary Nebulae and White Dwarfs

☆ Deaths of Large Stars: 9/24/26

🌍 Supernovae, Neutron Stars and Black Holes

☆ Black Holes: 10/1/26

🌍 Spaghettification

Outline

- ☆ Review Star Birth

- ☆ Star life on the Main Sequence

 - 🌍 Fusion & Thermodynamic Balance

 - 🌍 The Sun

 - › Sunspots, Solar Wind, Solar Storms, Aurorae

- ☆ Death Throes: Red Giant Stages

- ☆ Planetary Nebulae & White Dwarf Stars

Outline

☆ Review Star Birth

☆ Star life on the Main Sequence

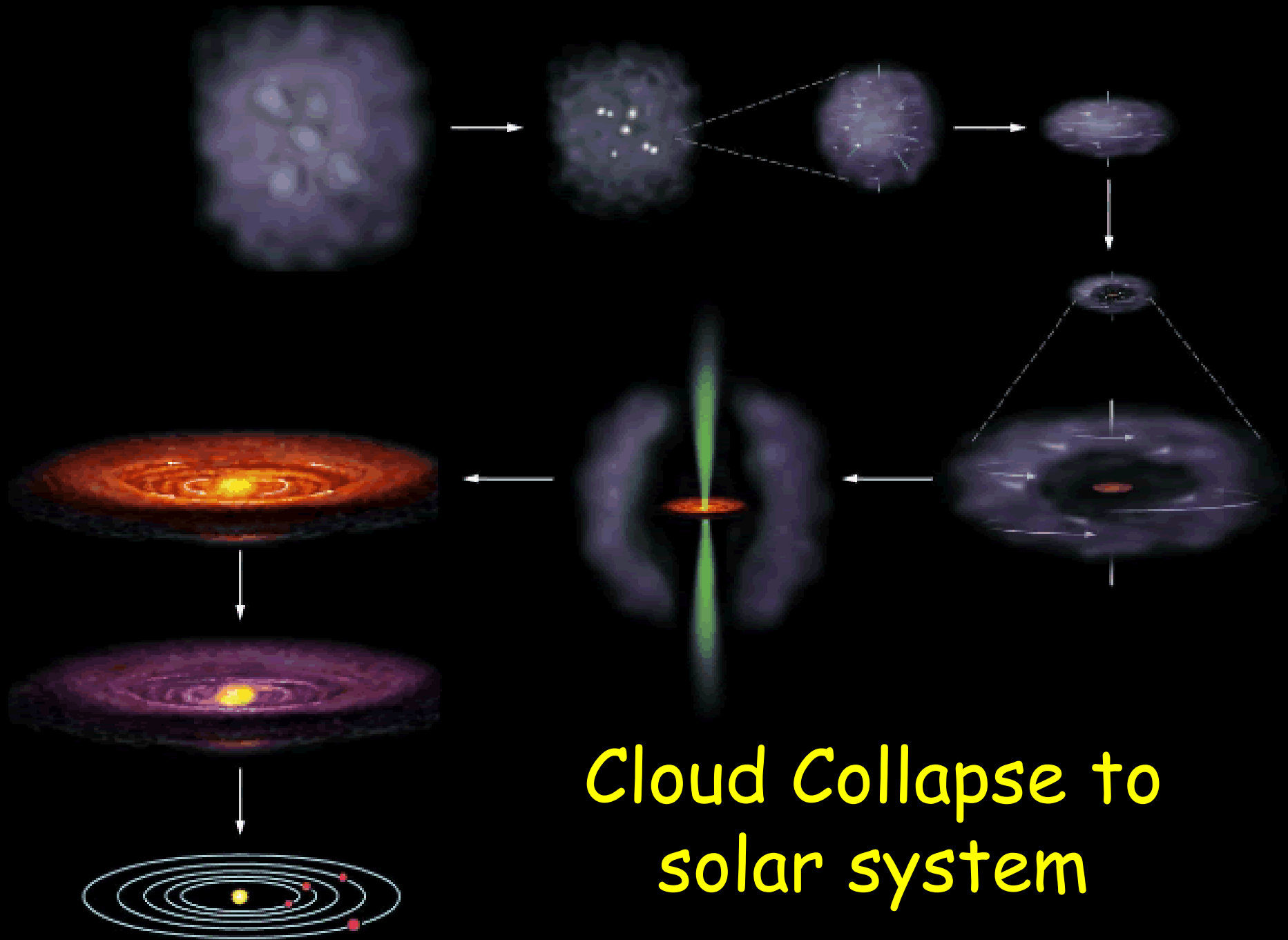
- 🌍 Fusion & Thermodynamic Balance

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 - › Sunspots, Solar Wind, Solar Storms, Aurorae

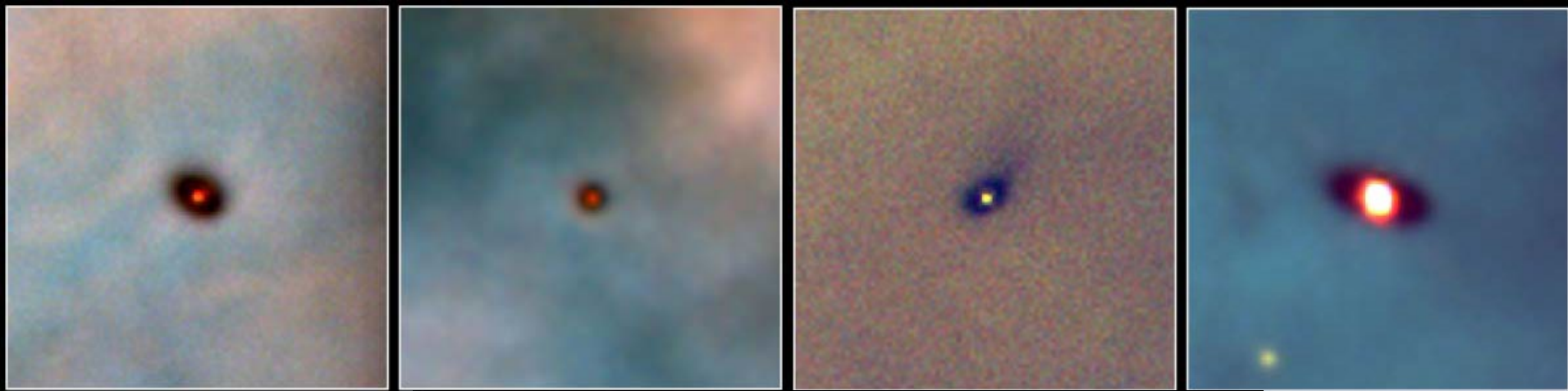
☆ Death Throes: Red Giant Stages

☆ Planetary Nebulae & White Dwarf Stars



Cloud Collapse to
solar system

Star Birth in Orion



**Protoplanetary Disks
Orion Nebula**

HST · WFPC2

PRC95-45b · ST ScI OPO · November 20, 1995

M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA



**Edge-On Protoplanetary Disk
Orion Nebula**

PRC95-45c · ST ScI OPO · November 20, 1995

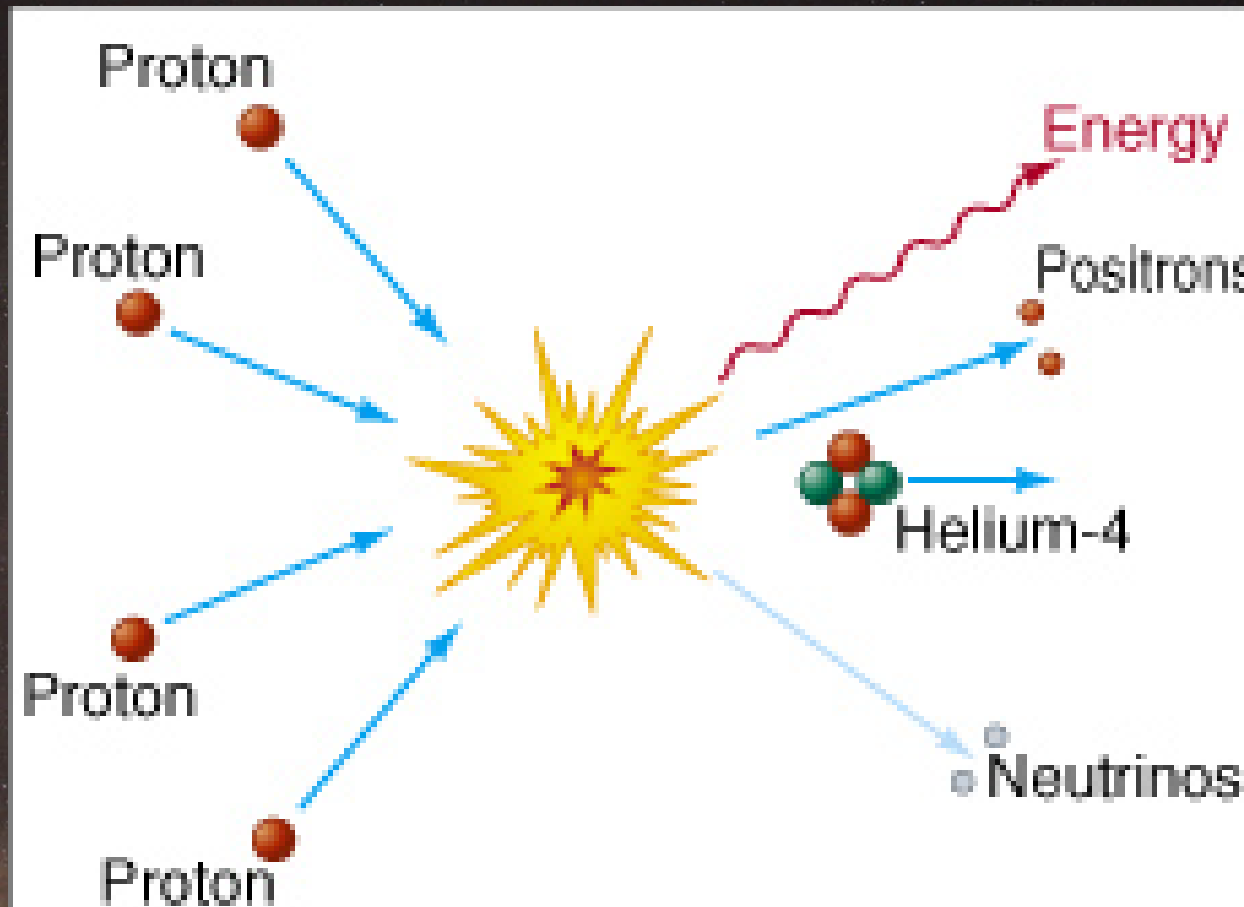
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

What Makes A Star?

☆ Nuclear Fusion

⊕ Light elements combine to make heavier elements.

Hydrogen
fuses to
Helium



Energy Of Fusion: Solar Power

Convert 1 kg of H to He:

1 kWh = 3.6 million Joules

= power to lift 1 liter of water 224 miles!!

0.7% (= 7 grams) becomes energy

by $E = mc^2$,

$(0.007 \text{ kg}) \times (3.0 \times 10^8 \text{ m/s})^2 = 630 \text{ trillion Joules}$

= 175 million kWh

Fusing 1 kg of Hydrogen to Helium
would yield

175 MILLION kWh

of energy,

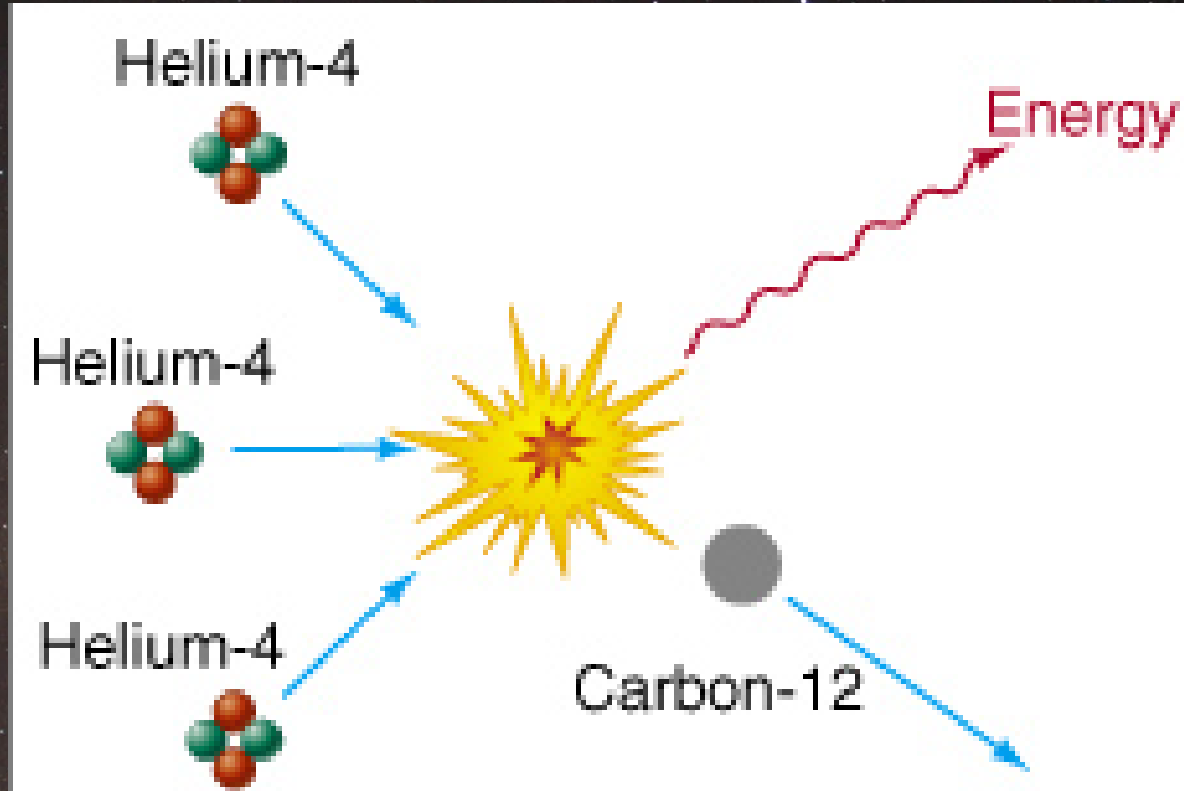
worth \$22.7 million at 13¢/kWh

What Makes A Star?

☆ Nuclear Fusion

🌍 Light elements combine to make heavier elements.

**Helium
fuses to
Carbon,
Oxygen,
Nitrogen ...**



What Makes A Star?

☆ Nuclear Fusion

- 🌍 Light elements combine to form heavier elements

EVERYTHING WE'RE
MADE OF EXCEPT
WATER

YOU ARE STAR-STUFF!!

EVERYTHING WE'RE
MADE OF
HYDROGEN
FROM THE STARS

Oxygen
Nitrogen



Carbon-12



Substance Of Life

☆ Life requires H, C, O, & N

🌍 All elements of life came from stars that lived AND DIED before the sun formed.

🌍 Sun is a 2nd or 3rd generation star

› 1st stars were pure hydrogen and helium)

**"We are the matter of the cosmos
contemplating itself."**

- Carl Sagan

Outline

☆ Review Star Birth

☆ Star life on the Main Sequence

☉ Fusion & Thermodynamic Balance

☉ The Sun

› Sunspots, Solar Wind, Solar Storms, Aurorae

☆ Death Throes: Red Giant Stages

☆ Planetary Nebulae & White Dwarf Stars

Main Sequence Life

☆ Hydrostatic Equilibrium Fusing H to He

 Gravity pulling inward

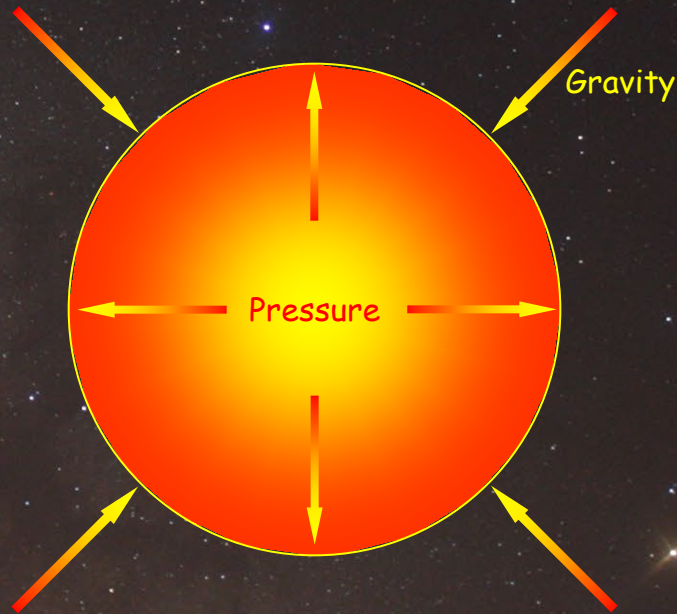
weight of upper layers tries to compress star

🌍 Pressure of heated gas pushing outward

» nuclear explosion tries to expand star

balance lost
when fuel runs out

Ultimately,
gravity will
win!



Sol

☆ Fusion core is ~ 25% of radius

🌍 99% of energy from inner 24% of Sun

$$R_{\text{Sol}} = 696,000 \text{ km}$$

$$R_{\text{Sol}} = 433,000 \text{ miles}$$

$$R_{\text{fusion}} = 108,000 \text{ km}$$

$$R_{\text{fusion}} = 67,000 \text{ miles}$$

$$R_{\text{Earth}} = 3,960 \text{ miles}$$

$$R_{\text{fusion}} \approx 17 R_{\text{Earth}}$$



So scale
it!

Sun fuses the mass of the Earth every 316,298 years

The Sun
A nuclear explosion
contained by gravity.



Sol turns 45 Aircraft Carrier masses of H
to pure energy each second ... every second!

The Sun

★ G2 V – normal dwarf, 5800K

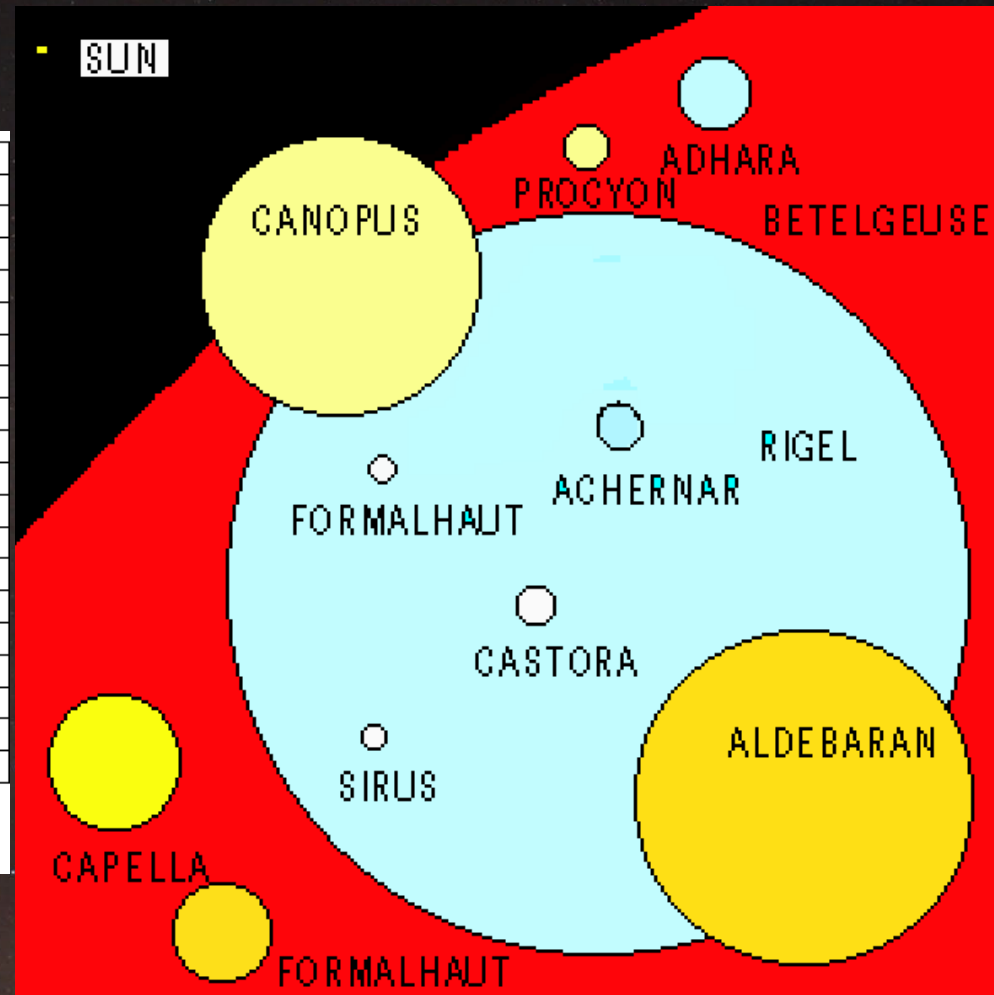
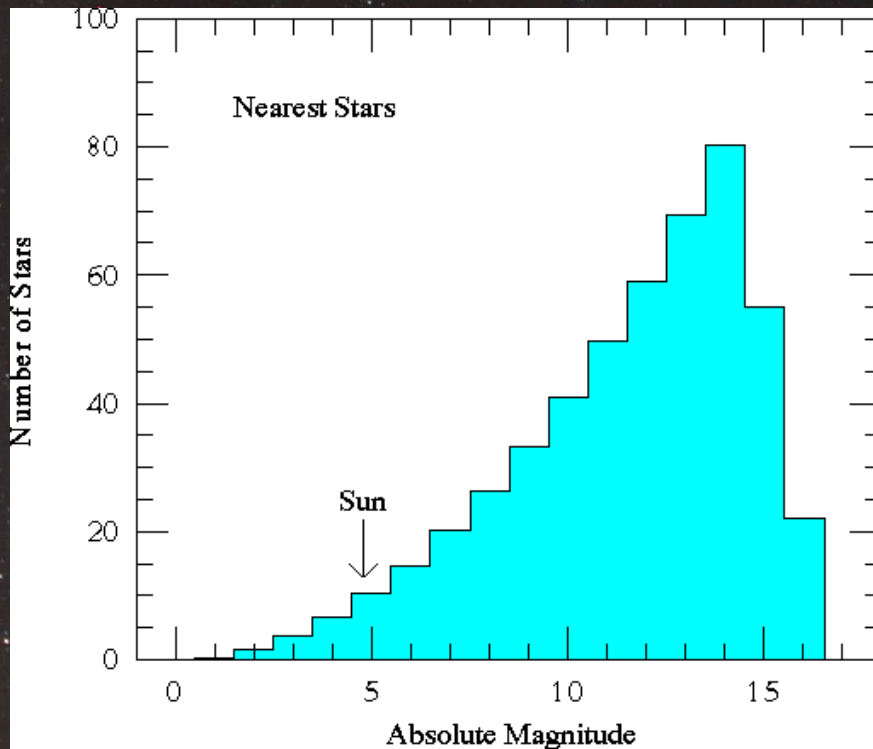
- 🌍 Small compared to giants
- 🌍 Big compared to most stars
- 🌍 Youngish – 5 by old $< \frac{1}{2}$ age of universe
- 🌍 Lots of metals in its spectrum (eg. Fe)

★ Data

- 🌍 $R_{\odot} = 6.96 \times 10^5 \text{ km} (\sim 700,000 \text{ km}) = 109R_{\oplus}$
- 🌍 $M_{\odot} = 1.99 \times 10^{30} \text{ kg} = 333,333M_{\oplus}$
- 🌍 $L_{\odot} = 3.90 \times 10^{26} \text{ W}$

The Sun

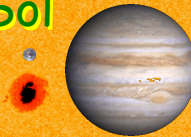
- ☆ Large compared to most stars
- ☆ Small compared to largest stars



The Sun Today

Current
Solar
Images
from NASA

Earth is 1/100
the diameter
of Sol



4378 Jupiter is 1/10 the diameter of Sol

4382

4384

4381

They're HUGE!

4380

Some
Sunspots!

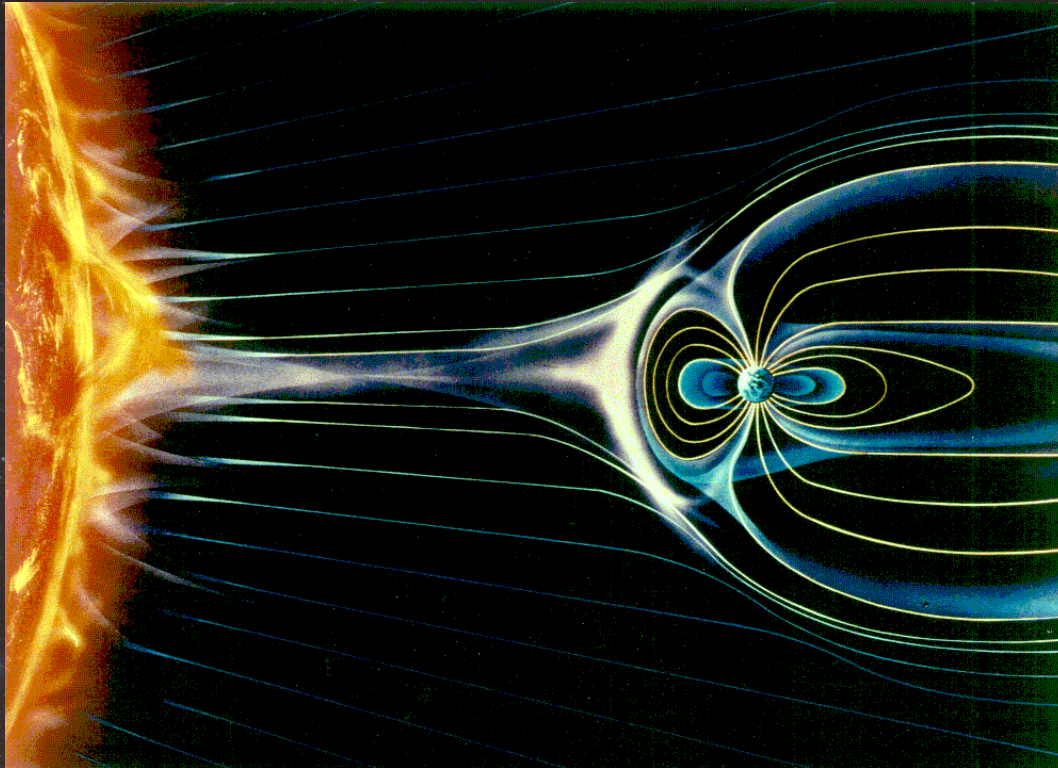


spaceweather.com

News and information about the Sun-Earth environment

Solar Wind

- ☆ Charged particles from Sun's surface
Stars = nuclear explosions contained by gravity!
- ☆ Steered to poles by Earth's mag. field
- 🌍 Can cause aurora by colliding with atmosphere



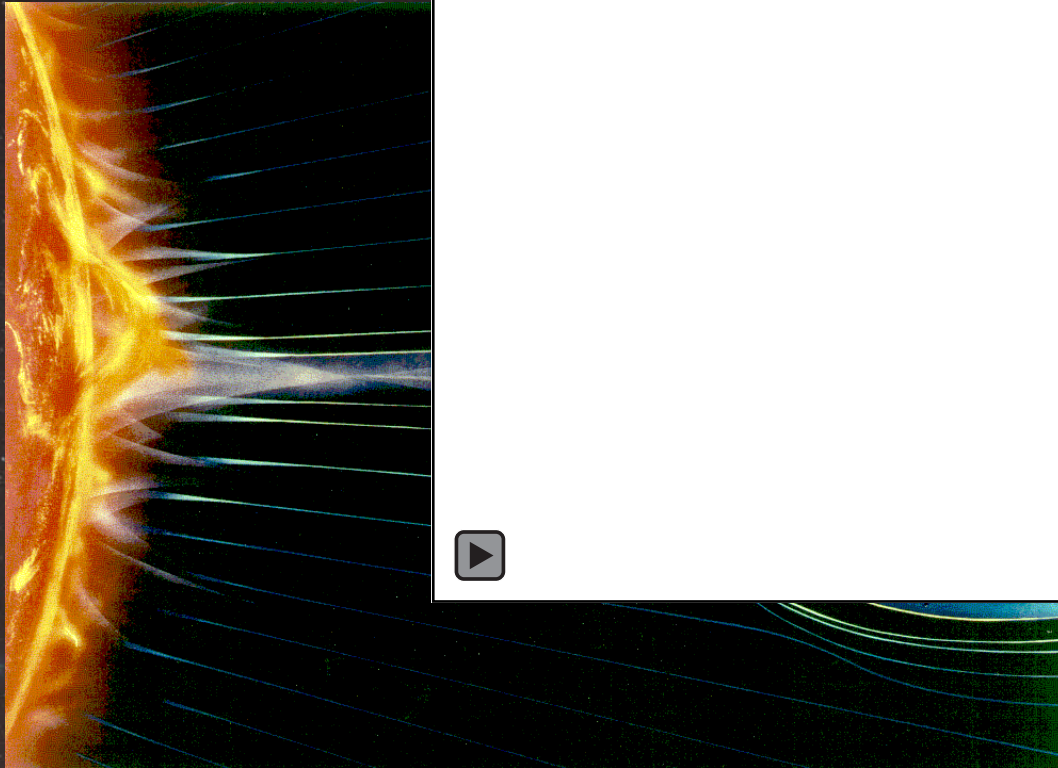
Aurora on
11/20/03,
Zagreb,
Croatia.
Photo by
Hrvoje
Horvat



www.spaceweather.com

Solar Wind

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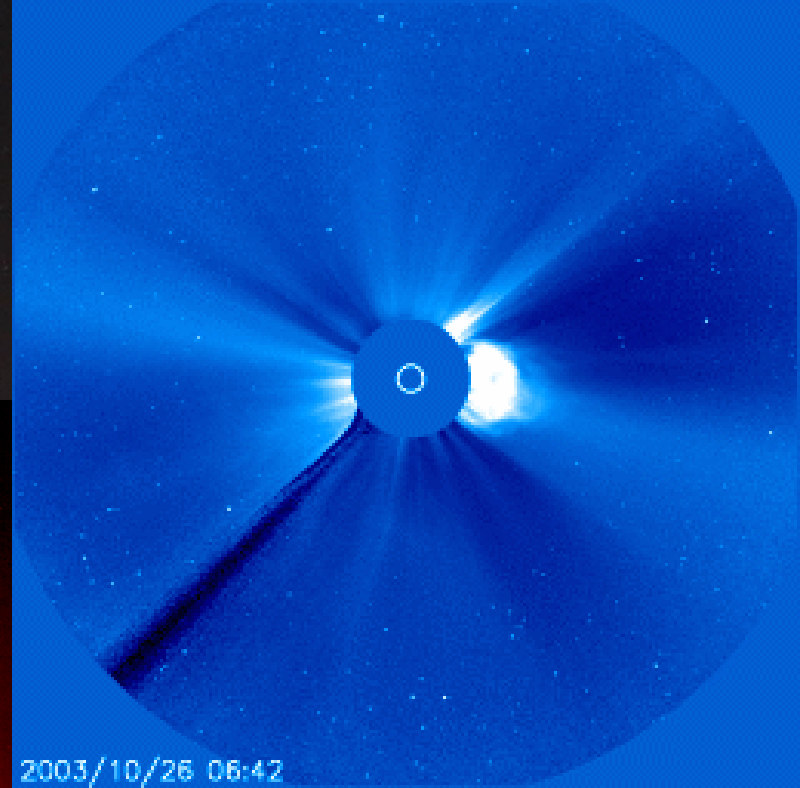


Coronal Mass Ejections: Solar Storms

Extreme UV Image

Size of Earth $\approx$ •
1/100 Size of Sol

CME and Comet October 9, 2024, 10:06 pm EDT

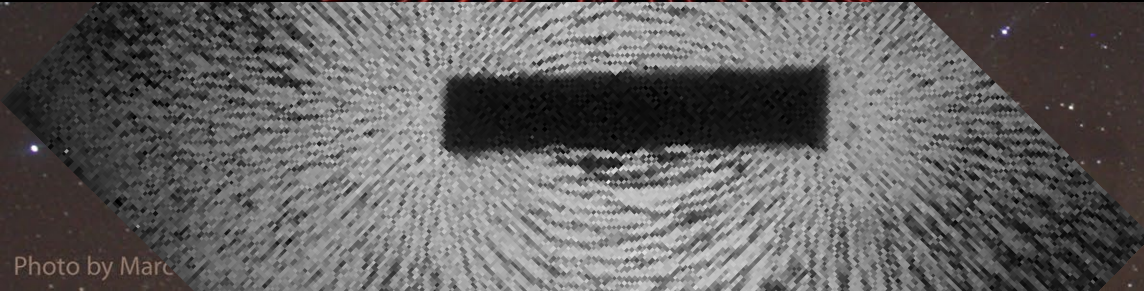
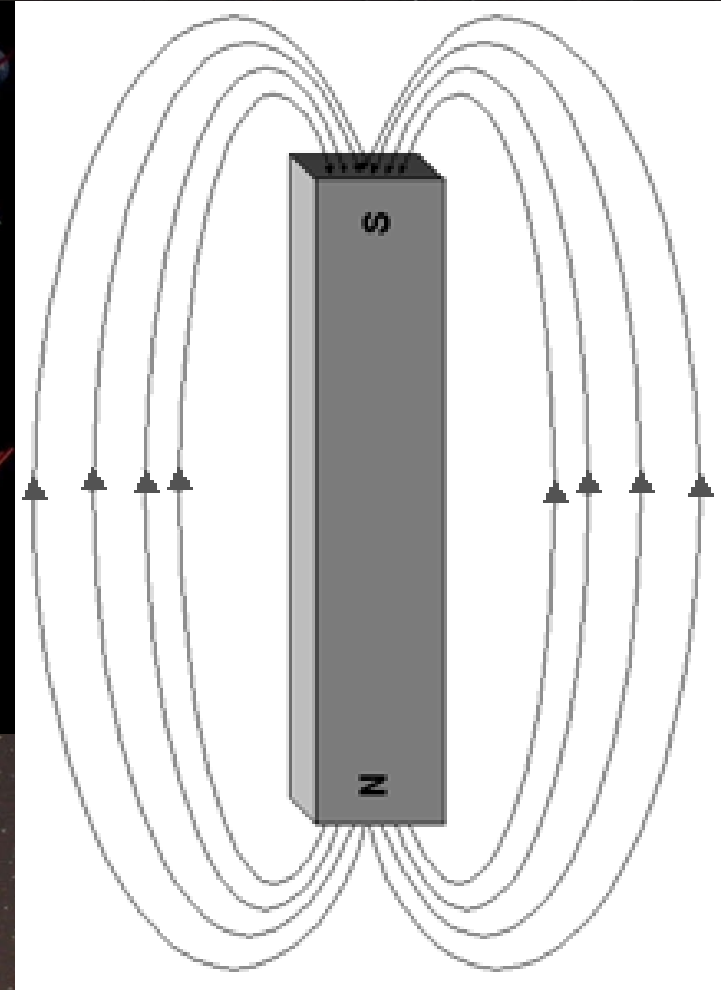
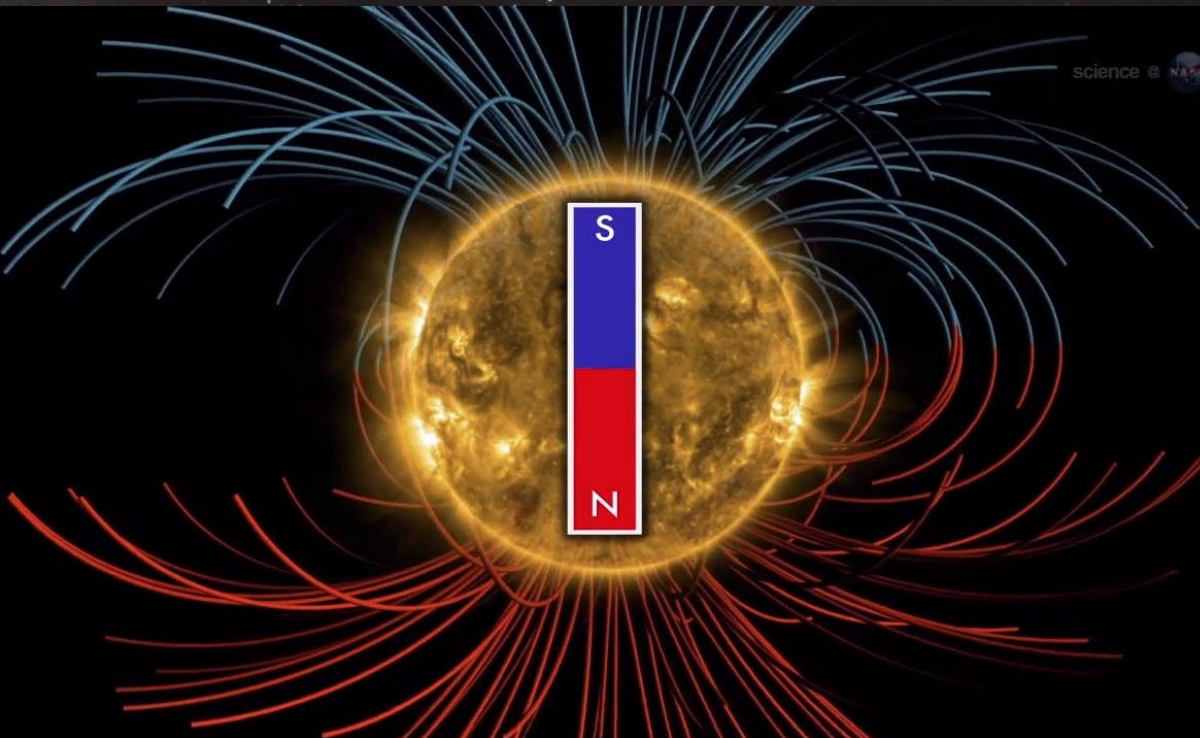


Associated with
giant spots and
auroral displays

Sol's Magnetic Field

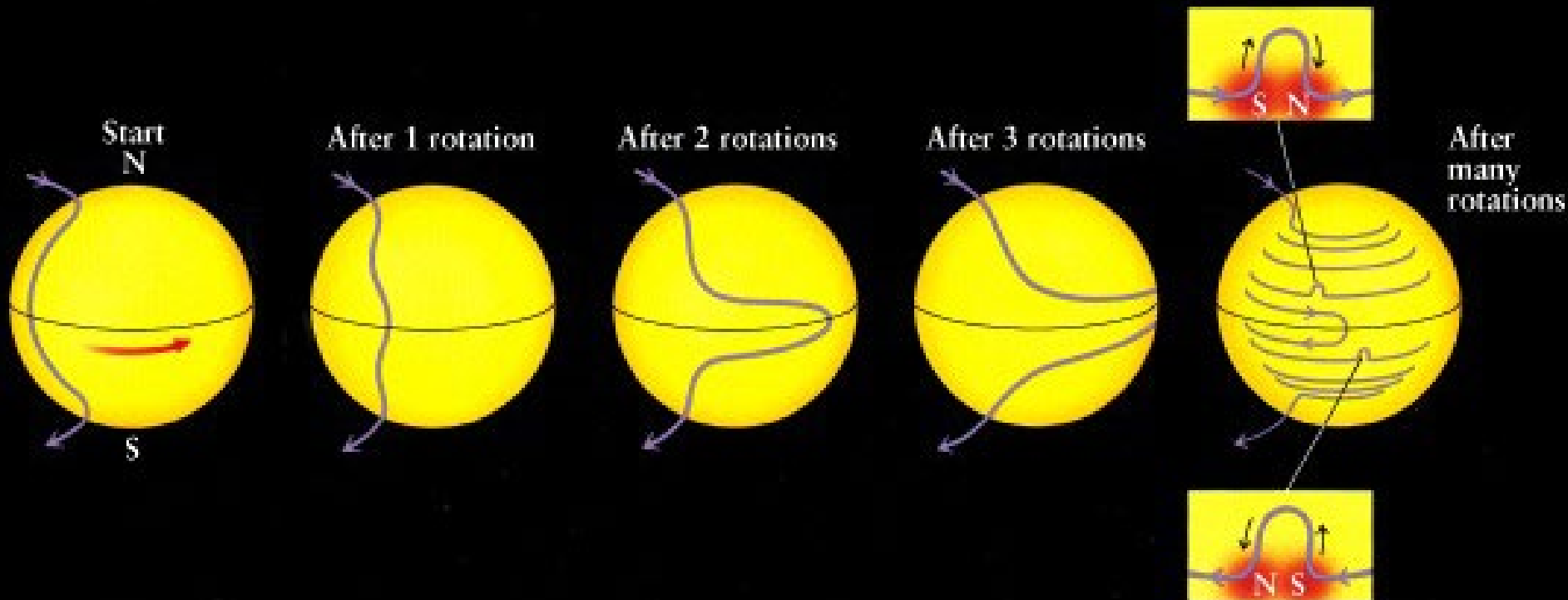
☆ Field of a bar magnet

🌐 Lines go from north to south (by definition)



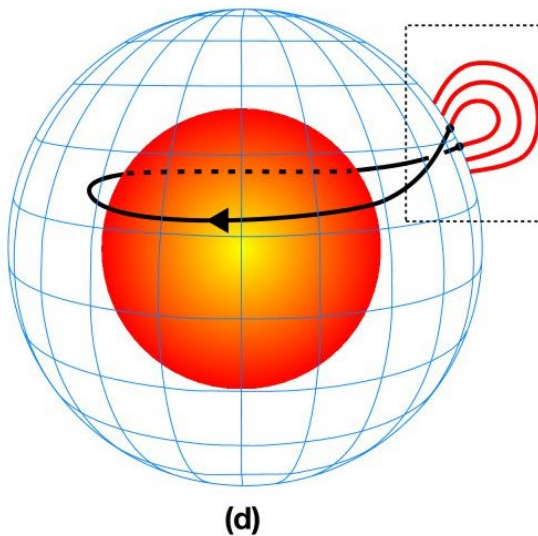
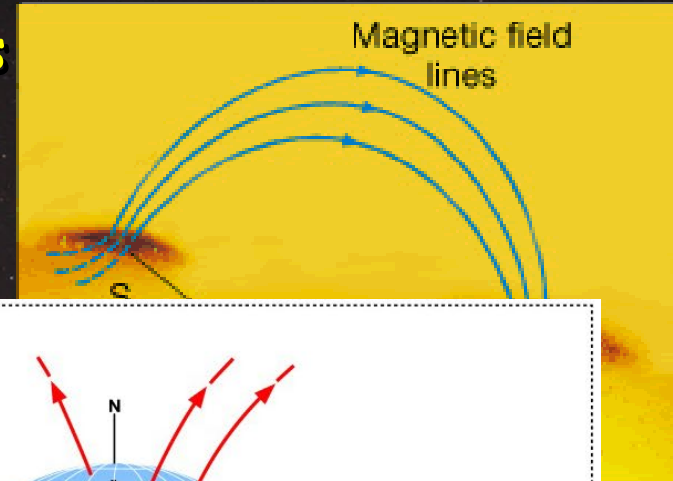
Sunspots from Magnetic Field

- ☆ Sun has differential rotation
 - 🌐 Equator rotates in about 24 days
 - 🌐 Poles rotate in about 30 days
- ☆ Magnetic field lines wrap up

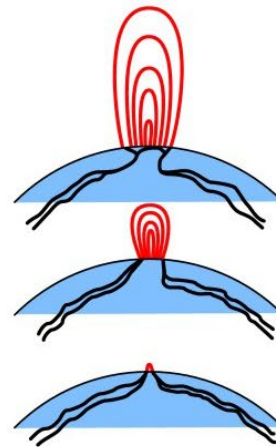


Sunspots: Magnetic Hernias

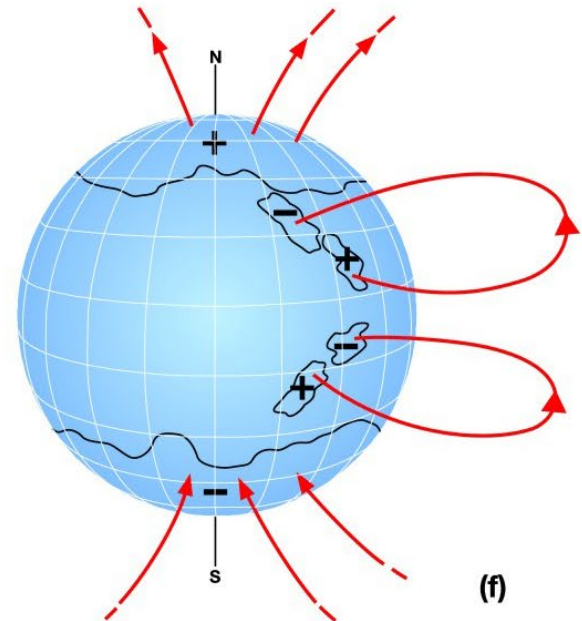
- ☆ Wrapped magnetic field bulges out from surface
- 🌐 charged particles travel up along field lines
 - › removes energy from surface, cooling it
 - › Sunspots are darker than surroundings



(d)



(e)



(f)

Sunspot Cycle

☆ Sunspot number varies over 11-yr cycle

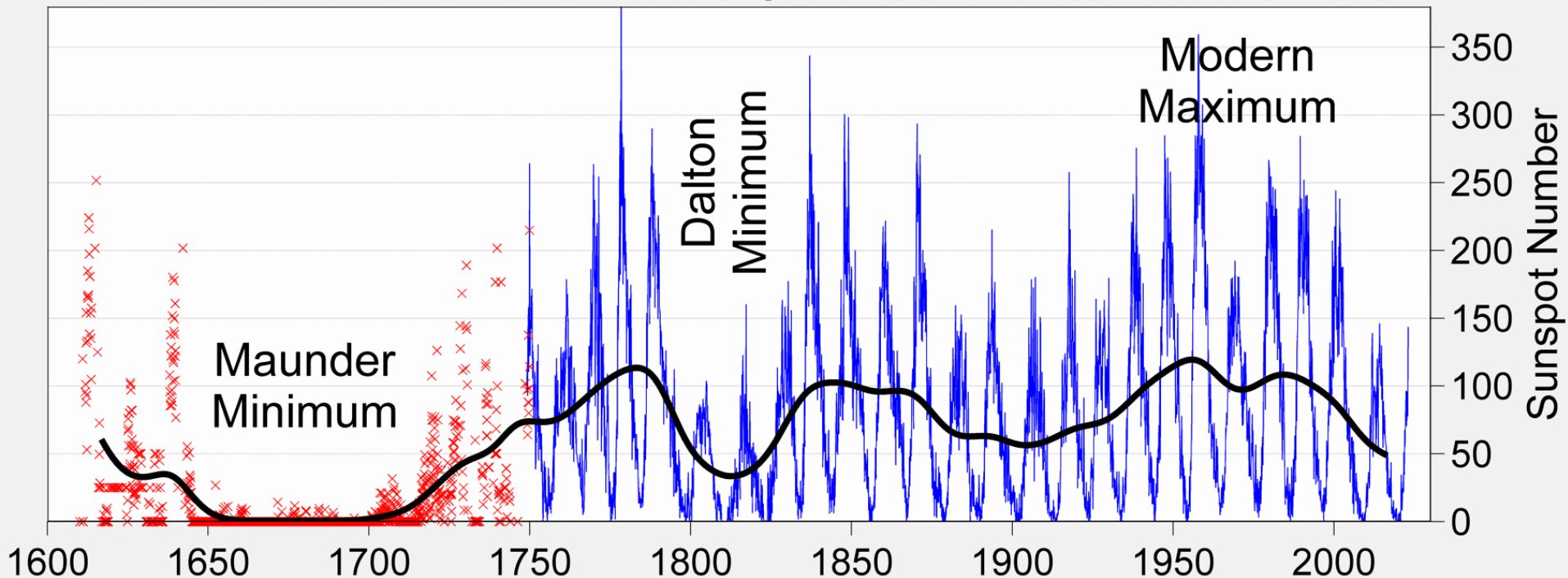
🌐 Fairly Constant except for Maunder Minimum

› Cold in Europe

› Canals in Holland froze regularly

} Link with Sunspots
in debate

400 Years of Sunspot Observations

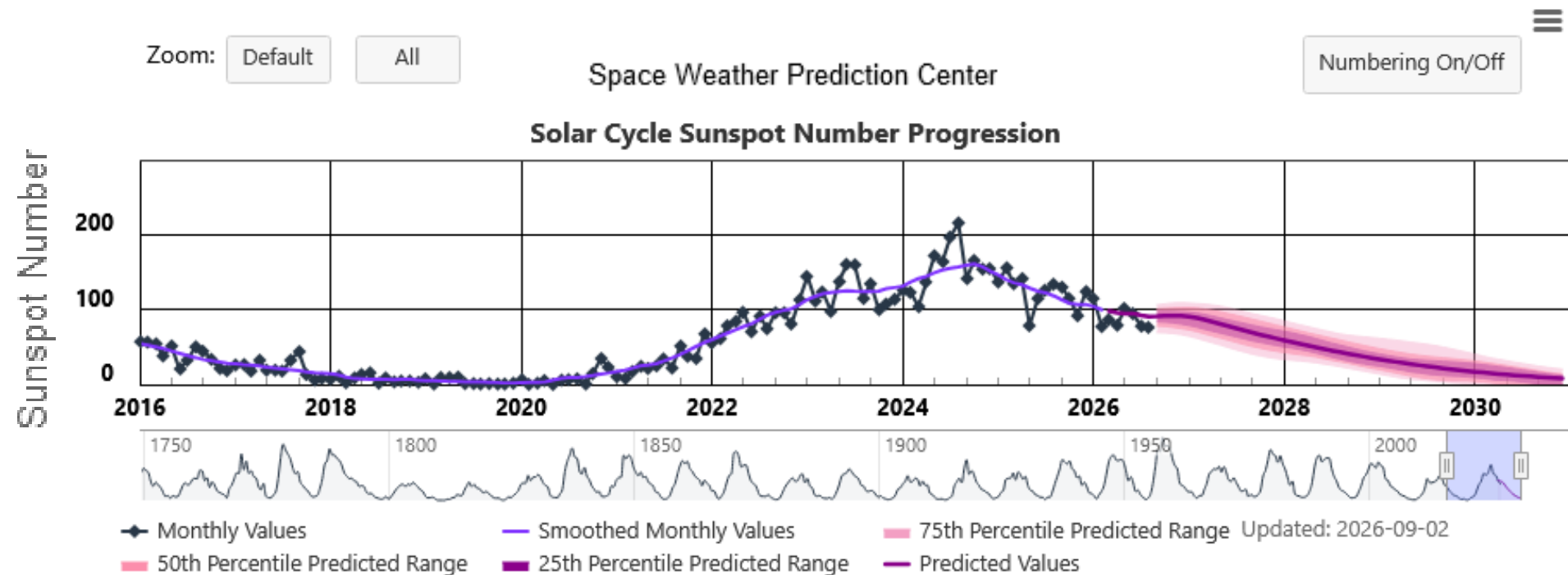


Sunspot Cycle # 25

☆ We're past Solar Max 2024-2026

🌍 Another dud of a Solar Max

SOLAR CYCLE PROGRESSION



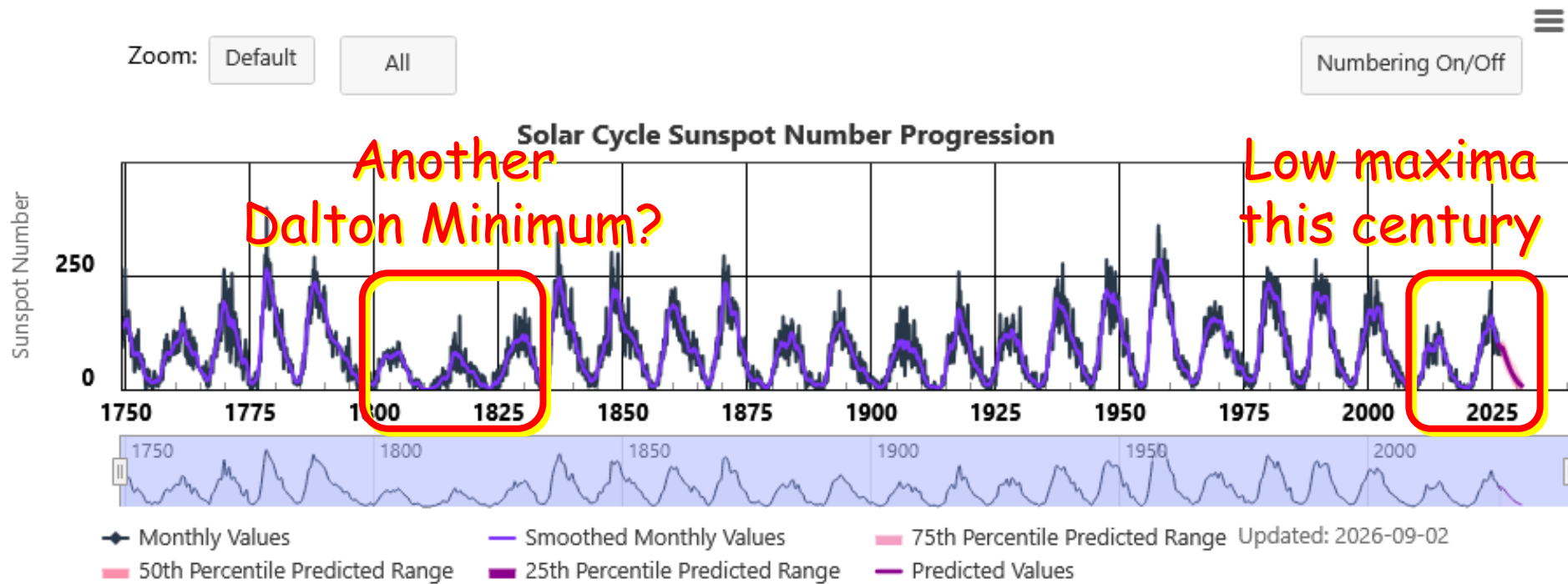
<https://www.swpc.noaa.gov/products/solar-cycle-progression>

Sunspot Cycle # 25

☆ We're past Solar Max 2024-2026

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SOLAR CYCLE PROGRESSION



<https://www.swpc.noaa.gov/products/solar-cycle-progression>

Solar Storm History

☆ September 1859

🌐 Telegraph wires shorted out in US & Europe

➤ Caused fires

🌐 Auroral displays in N & S

🌐 What would happen today?

Science@NASA:

www.science.nasa.gov



Solar Superstorm



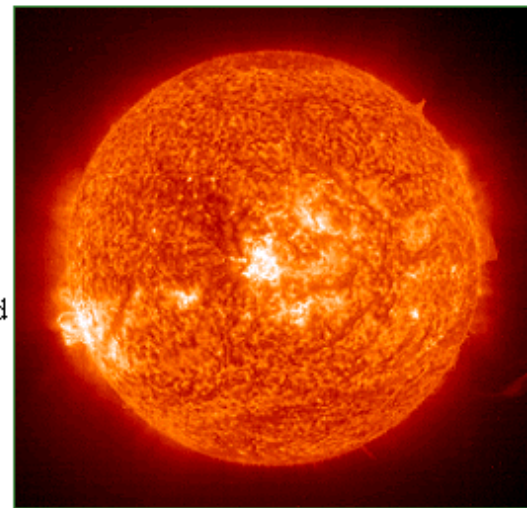
Scientists are beginning to understand a historic solar storm in 1859. One day, they say, it could happen again.

🔊 Listen to this story via [streaming audio](#), a [downloadable file](#), or [get help](#).

October 23, 2003: Newly uncovered scientific data of recorded history's most massive space storm is helping a NASA scientist investigate its intensity and the probability that what occurred on Earth and in the heavens almost a century-and-a-half ago could happen again.

Right: An ultraviolet-wavelength picture of the sun taken by the ESA/NASA Solar and Heliospheric Observatory ([SOHO](#)) on Oct. 23, 2003.

In scientific circles where solar flares, magnetic storms and other unique solar events are discussed, the occurrences of September 1-2, 1859, are the star stuff of legend. Even 144 years ago, many of Earth's inhabitants realized something momentous had just occurred. Within hours, telegraph wires in both the United States and Europe spontaneously shorted out, causing numerous fires, while the Northern Lights, solar-induced phenomena more closely associated with regions near Earth's North Pole, were documented as far south as Rome, Havana and Hawaii, with similar effects at the South Pole.



What happened in 1859 was a combination of several events that occurred on the Sun at the same time. If they took place separately they would be somewhat notable events. But together they caused the most potent disruption of Earth's ionosphere in recorded history. "What they generated was the perfect space storm," says Bruce Tsurutani, a plasma physicist at NASA's Jet

☆ Sep



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www.science.com

March 13, 1989

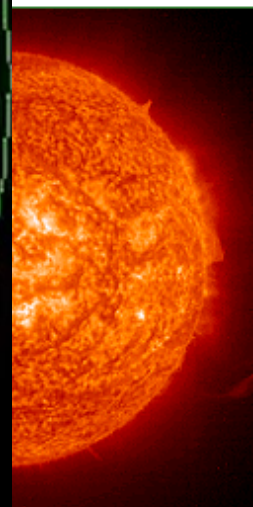
Aurora causes
Quebec blackout!

<https://www.astronomy.com/science/the-aurora/html>



storm

most massive space
that what occurred
again.



ects at the South

on the Sun at the
ents. But together
ory. "What they
scient at NASA's Jet

Outline

- ☆ Review Star Birth

- ☆ Star life on the Main Sequence

 - 🌍 Fusion & Thermodynamic Balance

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 - › Sunspots, Solar Wind, Solar Storms, Aurorae

- ☆ **Death Throes: Red Giant Stages**

- ☆ Planetary Nebulae & White Dwarf Stars

First Red Giant Stage

☆ Core fusion stops

⇒ He Core contracts under gravity

⇒ Shell of H around core keeps fusing

 › adds He to core, increasing mass & gravity

 › further heats H shell, increasing fusion & heat

⇒ Fusing shell heats envelope

⇒ Envelope expands

⇒ Outer surface cools

⇒ Outer surface turns red

A Red Giant Is Born!

Sol as a Red Giant

☆ Sol as red giant will engulf ☿ and ♀

The Sun as a main-sequence star
(diameter = 1.4×10^6 km $\approx \frac{1}{100}$ AU)

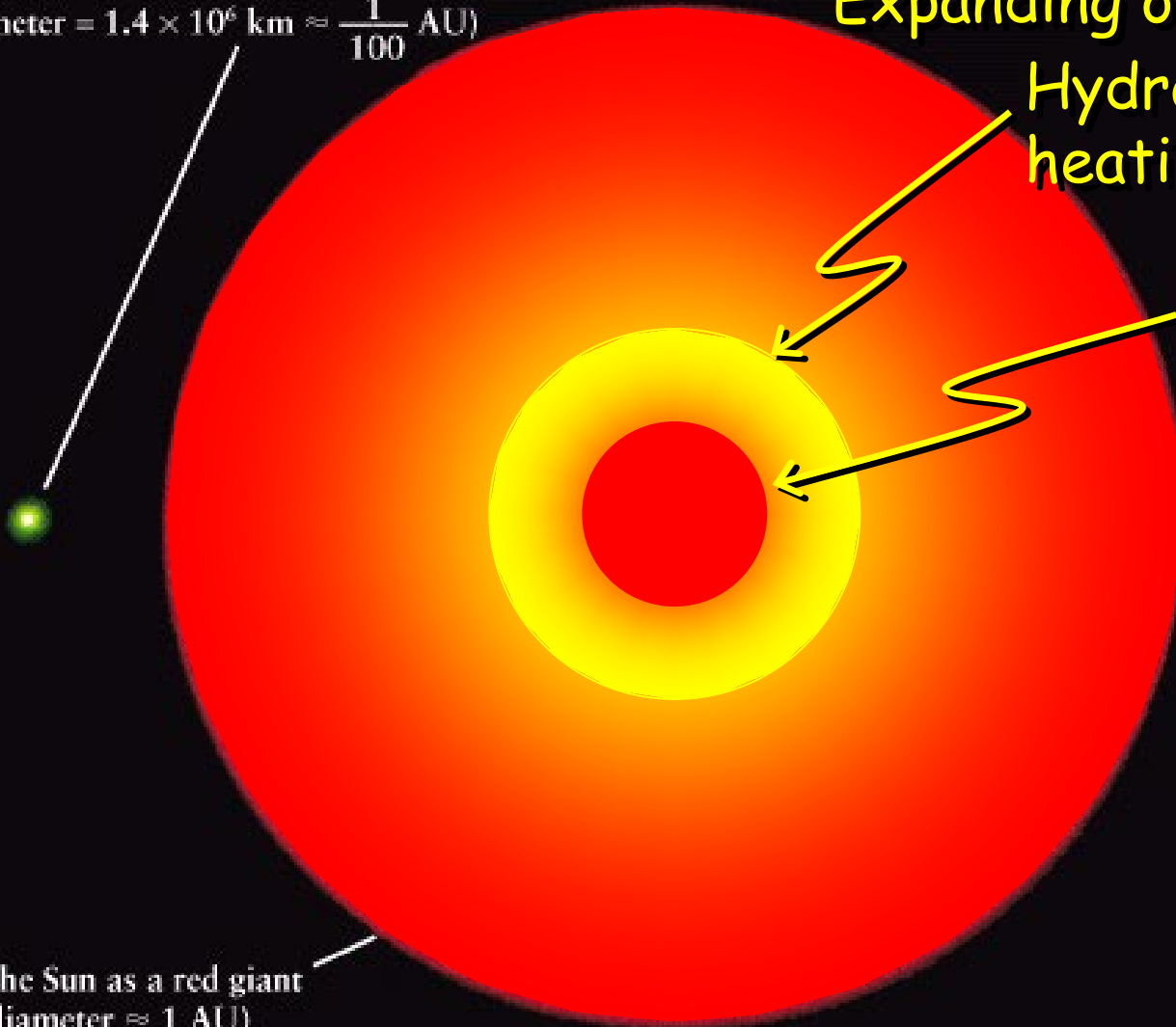
Expanding outer layers

Hydrogen fusing shell
heating outer layers

Shrinking He core
becoming
degenerate
electron gas

Sol may
engulf
Earth

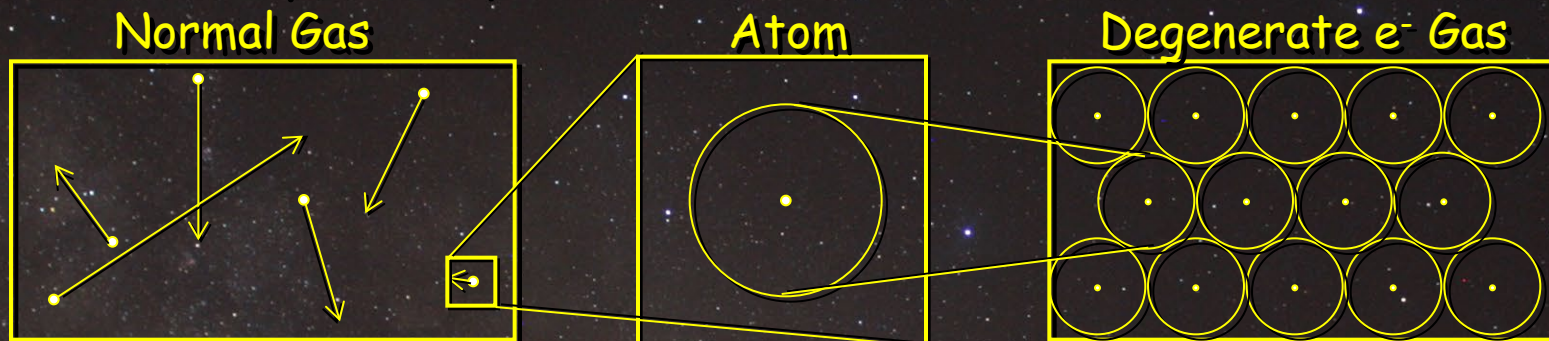
The Sun as a red giant
(diameter ≈ 1 AU)



Core of a Red Giant

★ Degenerate e^- gas

- ① atoms packed as close as possible
 - › electron clouds packed together
 - › all **space squeezed out from between atoms**



- ① does not expand on heating
 - ① keeps absorbing heat from fusing H shell
 - ① at 100 Million K, He fusion begins
 - › entire core begins fusion at same time
- ⇒ Core explodes! **Helium Flash**

Helium "Flash"

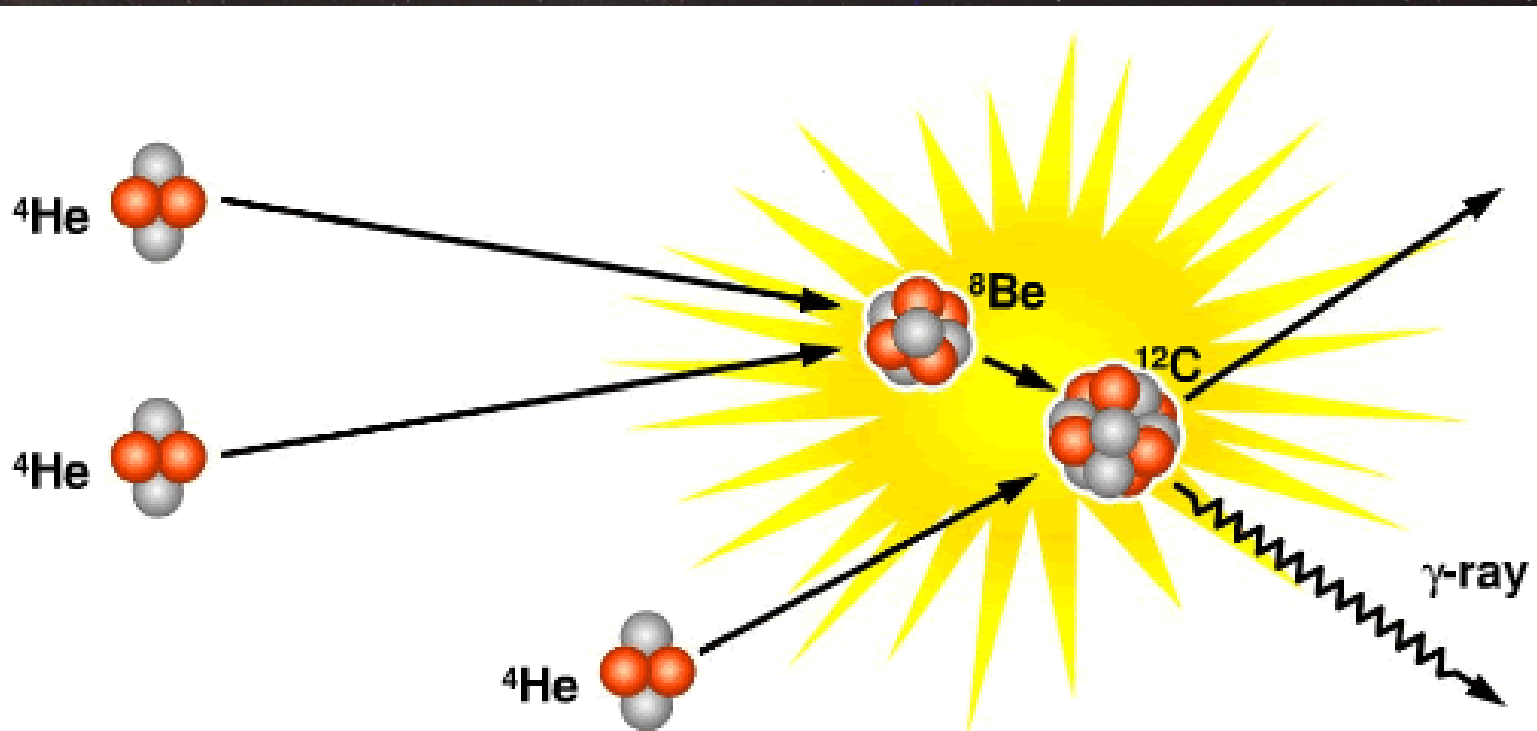
☆ Core heats to ~100 million K

🌍 Helium fusion begins in entire core at once

⇒ Core explodes within star

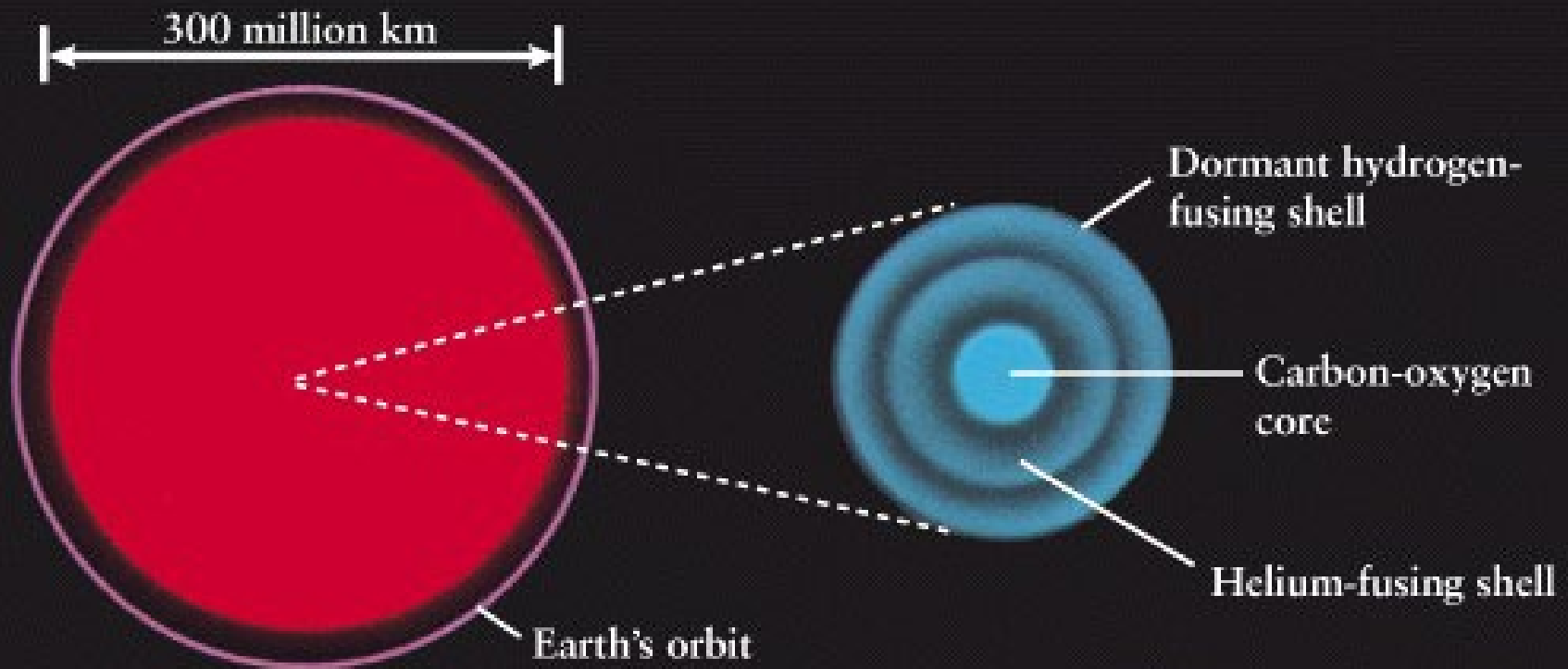
⇒ Not seen from outside star ←

⇒ Core becomes normal gas fusing He to C, O, N

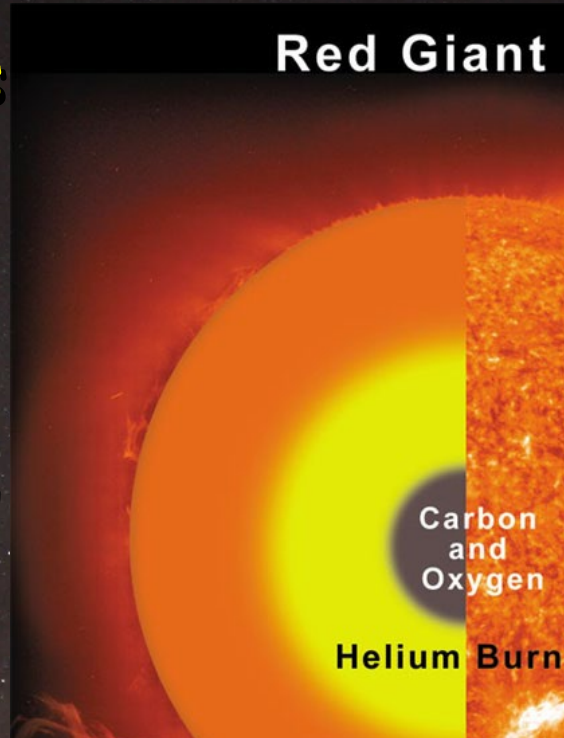


Post He-Flash Stars

- ☆ Helium fuses to C and O (and some N)
 - 🌍 the carbon in your tongue came from one of these that died before the sun formed!
- ☆ Star shrinks slightly, lasts ~100 million yr.



2nd Red Giant Stage

- ☆ Helium fusion has built C & O core
 - 🌍 C & O core is a degenerate e^- gas
 - › Can't fuse
 - › He-fusing shell forms
 - › Outer layers swell
 - › 2nd Red Giant Stage
 - γ Lasts ~ a few million more years
 - 🌍 Outer layers heated
 - › Swell away from core
 - › No Carbon flash!
- 
- A diagram of a Red Giant star. The star is shown in cross-section, revealing its internal structure. At the center is a dark grey core labeled 'Carbon and Oxygen'. Surrounding this core is a bright yellow-orange shell labeled 'Helium Burn'. The outermost layer is a thick, reddish-orange envelope. The title 'Red Giant' is at the top right.



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Planetary Nebula

☆ Outer star layers continue expanding

🌍 He fusing shell runs out of fuel

› sputters, pushing thermal waves through star

🌍 C-O core exposed as outer layers expand

› stellar winds from core sculpt outer layers

› UV from core ionizes & illuminates layers

☆ Outer layers become Planetary Nebula

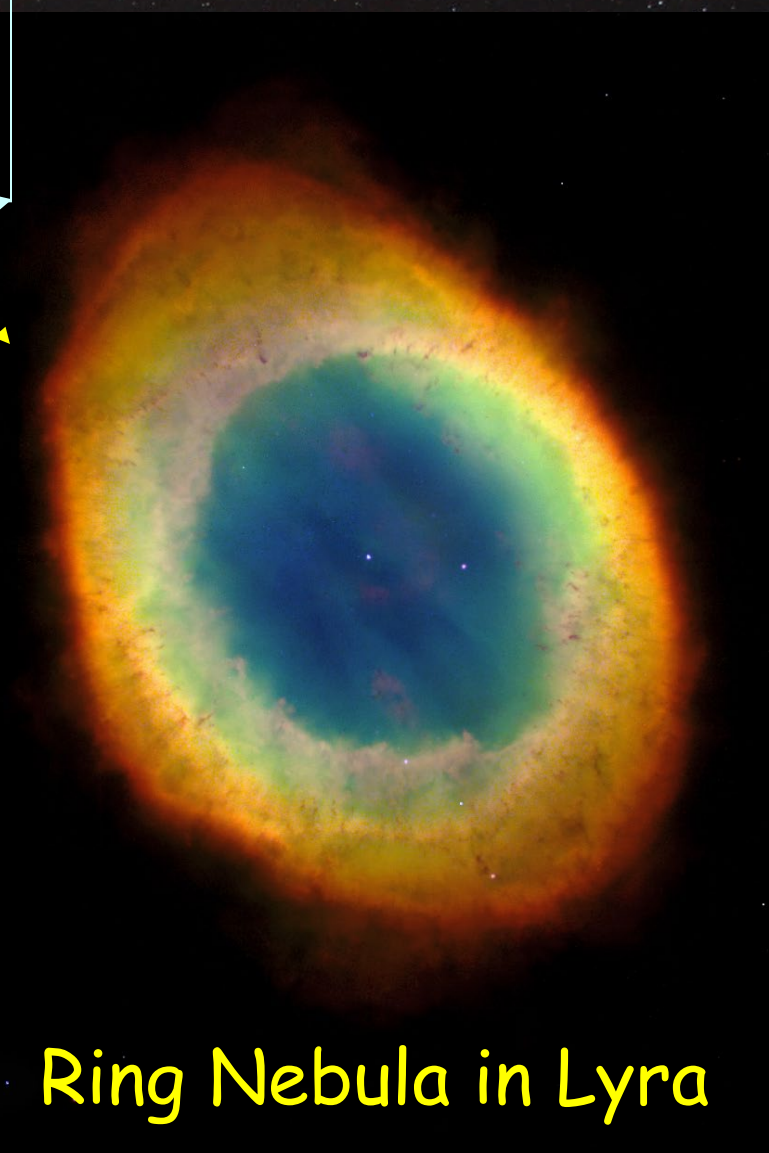
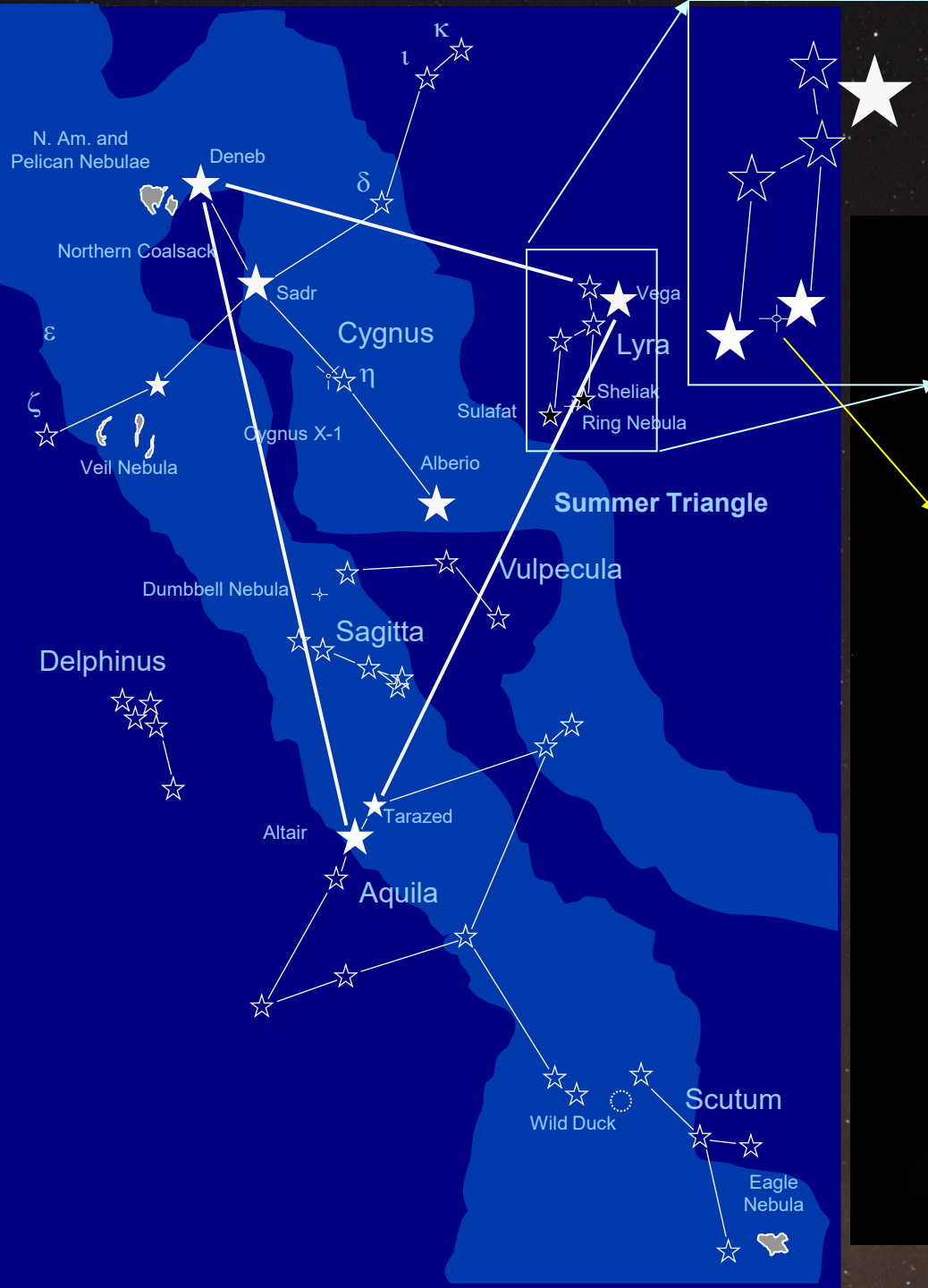
🌍 He, C, O, N blown into ISM (InterStellar Medium)

☆ Core left as White Dwarf Star

🌍 Carbon - Oxygen degenerate e^- gas

🌍 1 cm^3 would weigh a ton on Earth

Planetary Nebulae



Ring Nebula in Lyra

Astronomy Picture of the Day

Discover the cosmos! Each day a different image or photograph of our fascinating universe is featured, along with a brief explanation written by a professional astronomer.

2026 March 4

3/4/26 Astronomy Picture of the Day

<https://apod.nasa.gov/apod/>

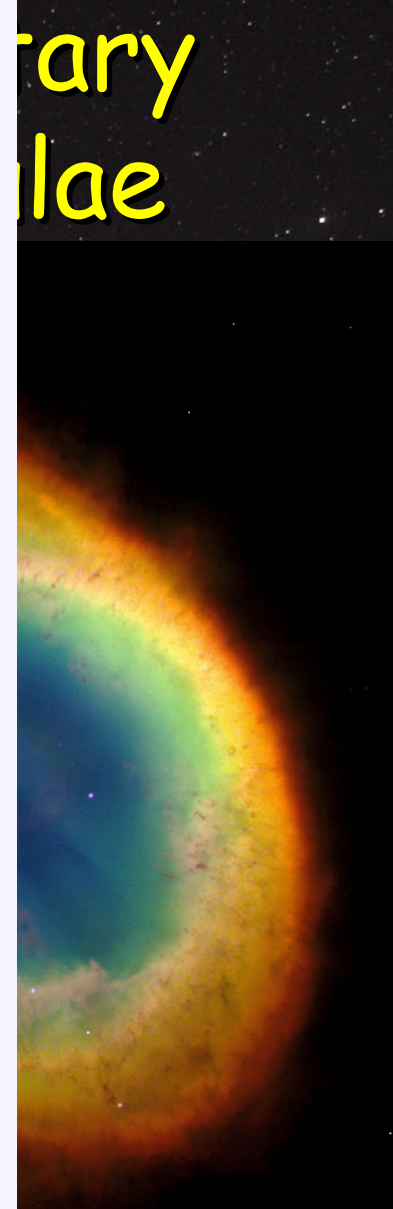


White Dwarf & Companion Star
orbit each other every 2.9 days
within planetary nebula!

Shapley 1: An Annular Planetary Nebula

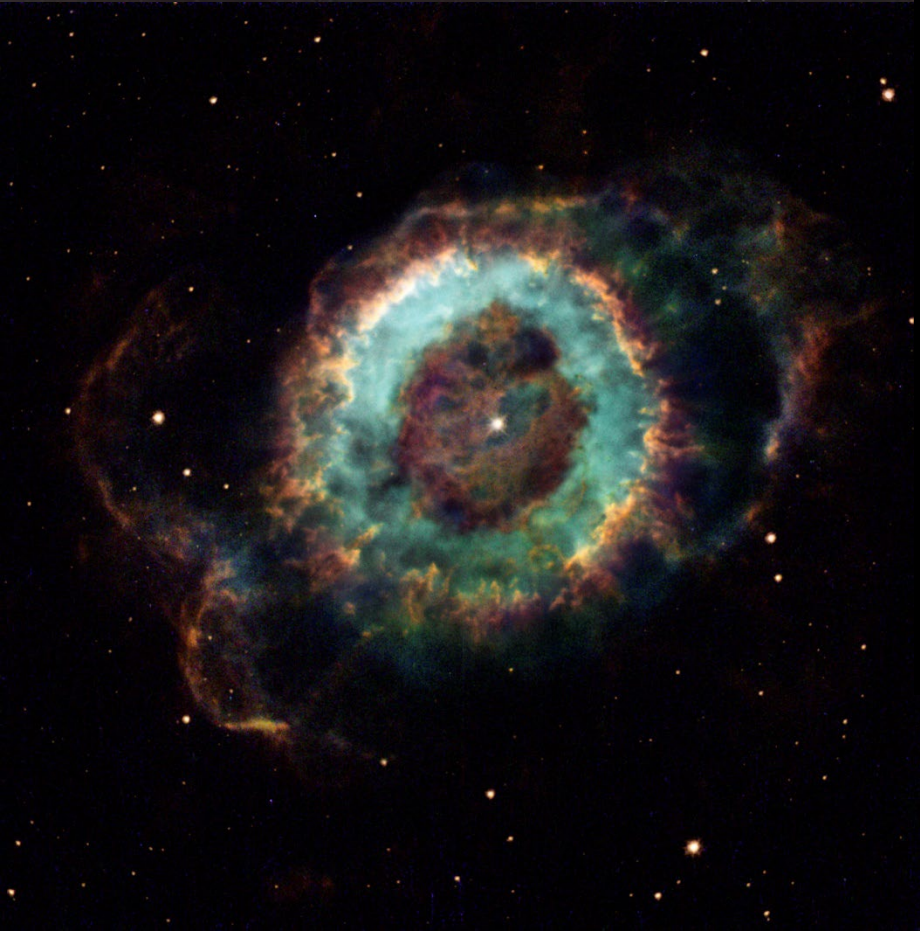
Image Credit & Copyright: [Peter Bresseler](#); Text: [Keighley Rockcliffe](#) ([NASA GSFC](#), [UMBC CSST](#), [CRESST II](#))

Explanation: What's looking back at you isn't a cosmic eye, but [Shapley 1](#), a beautifully symmetric [planetary nebula](#). Shapley 1, also known as the [Fine Ring Nebula](#) or [PLN 329+2.1](#), bejewels the southern sky constellation of the [Carpenter's Square](#) ([Norma](#)). The nebula is the result of a star near the mass of our Sun [running out of fuel and shedding its outer layers](#). Glowing oxygen from those expelled layers makes up the circular halo. The bright central point is actually a binary: a [white dwarf](#), the remaining stellar core after the outer layers are expelled into space, and another star, orbiting each other every 2.9 days. Shapley 1's [annular shape](#) is due to our [top-down view](#) of the system and provides insight into the [influence of central stars on planetary nebula structures](#).



Planetary Nebulae

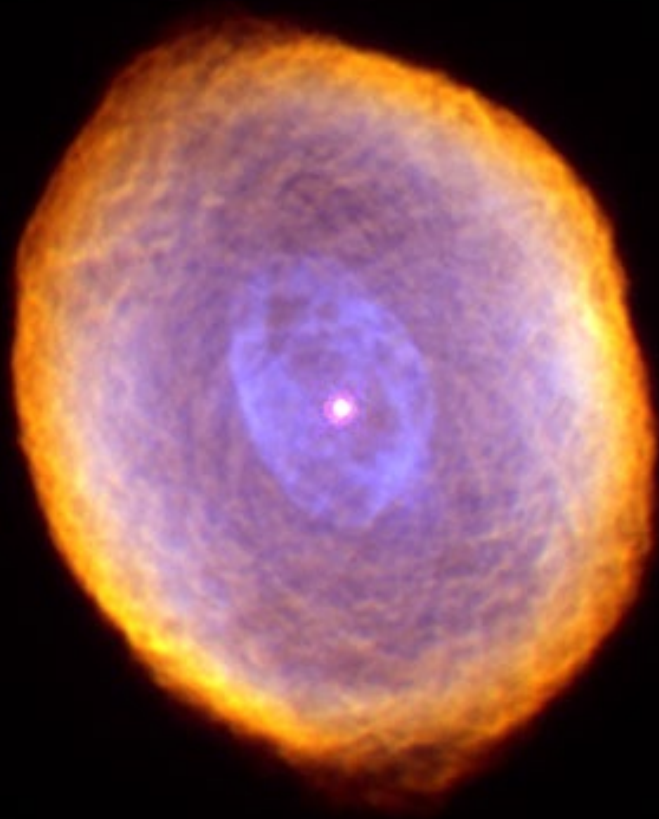
NGC 6369



NGC 6751

Planetary Nebulae

Spirograph Nebula



The Southern Ring Nebula — NGC 3132  HUBBLESITE.org

The Southern Ring Nebula



Planetary Nebula

Bright star orbits
white dwarf,
"stirs" nebula

White dwarfs can
have normal stars
as companions!

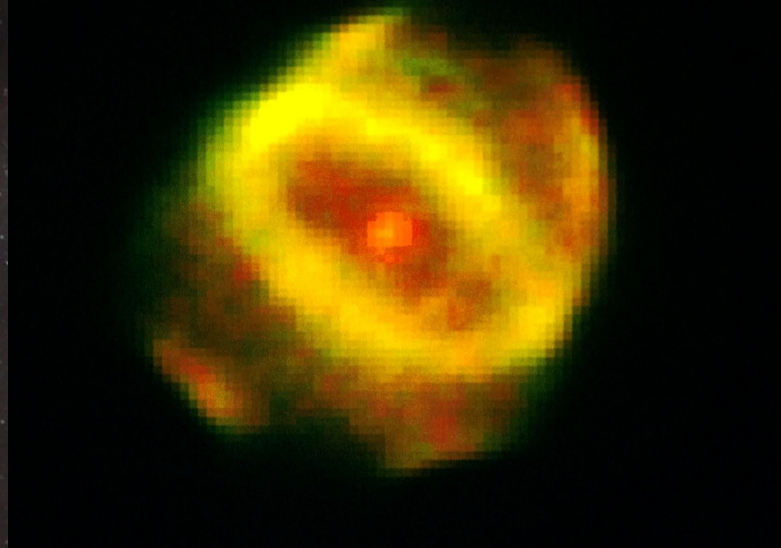
White Dwarf =
abandoned core

Ring Nebula

JWST NIRCam (Near IR Camera) Image

g Nebula — NGC 3132  HUBBLESITE.org

Hen 1357



Planetary Nebulae

Hourglass Nebula



Stingray Nebula





Helix Detail



Planetary Nebulae

Photo by Marc Staves 2011



Helix Nebula

Planetary Nebulae

Helix Nebula in Aquarius



IR (Spitzer) image

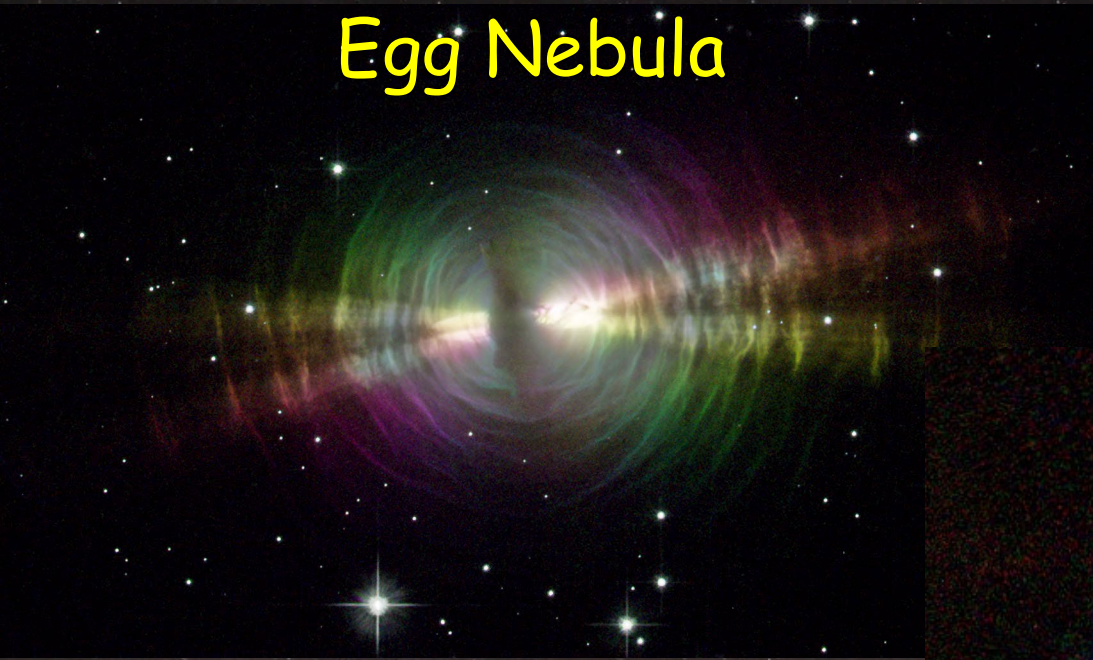
Planetary Nebulae



Ant Nebula

Planetary Nebulae

Egg Nebula



Butterfly Nebula



Rotten Egg Nebula



The carbon & nitrogen
atoms you're made of
were once in one of
these!!!

Planetary Nebulae

NGC 6826

We are all
made of
star stuff!



Our ancient ancestors ...

Exploring the STARS!

THE ADVENTURE CONTINUES!