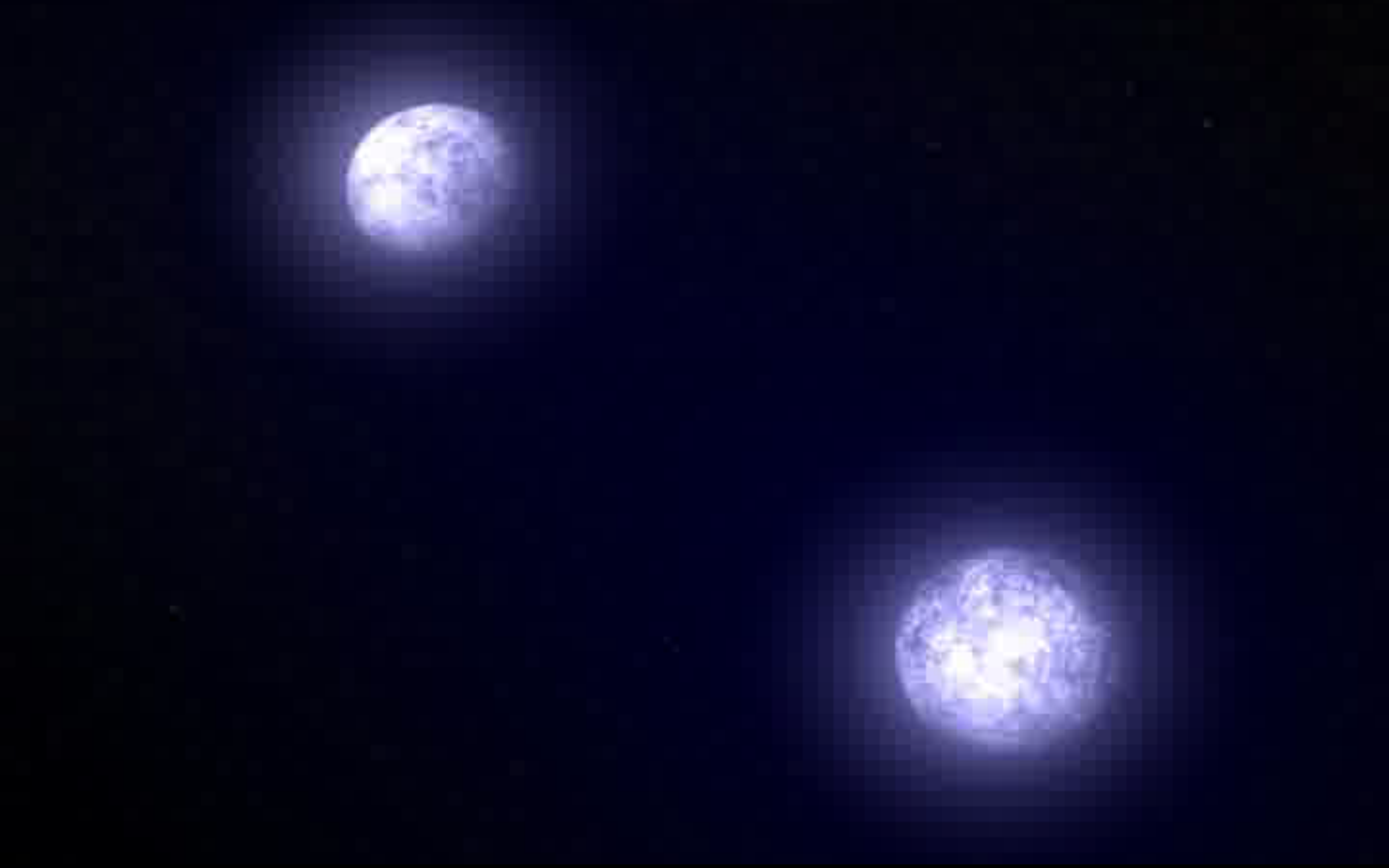
Announcements

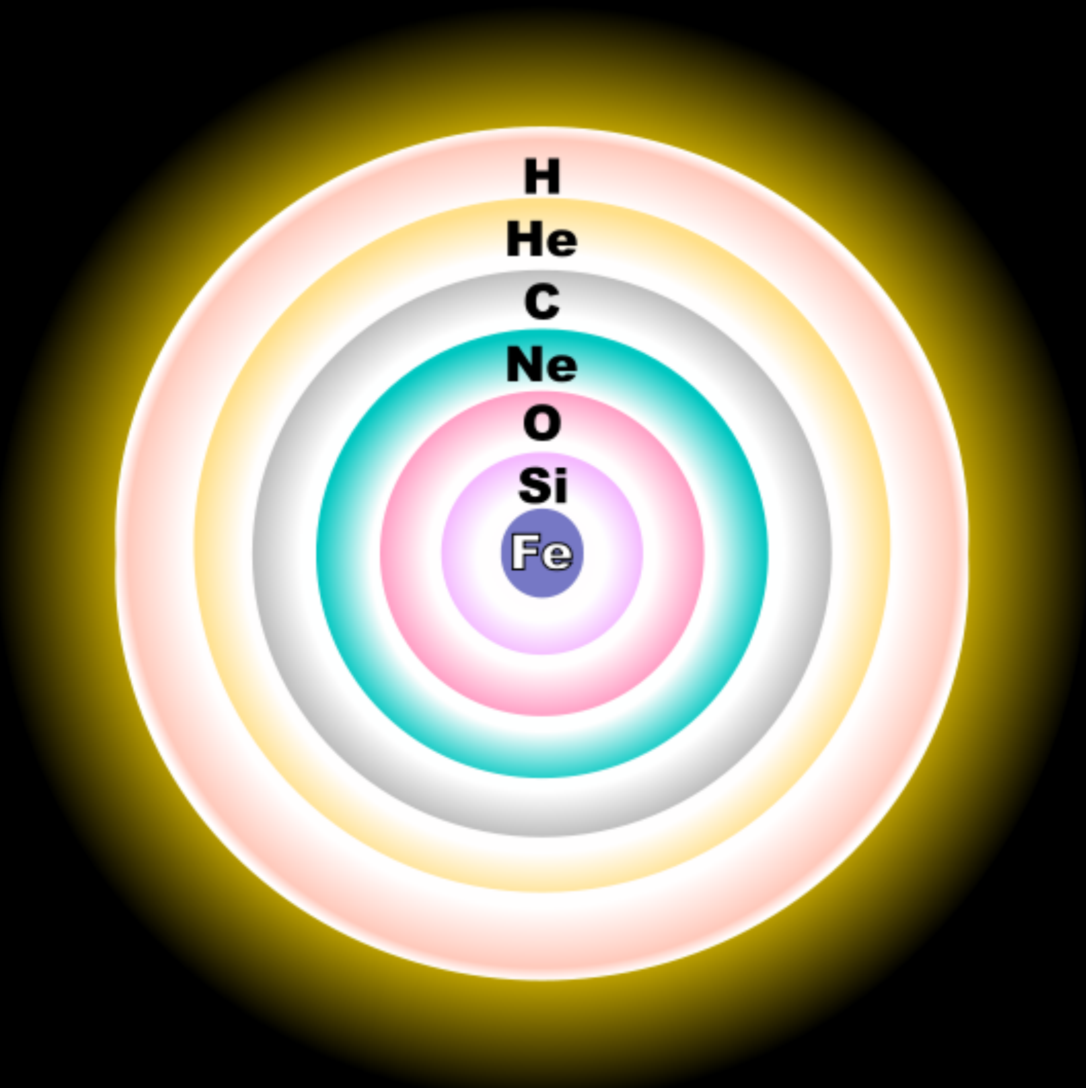
- **Quiz 7** due tonight, practice problems in **Problem Sets 7A, 7B**
- Approximate schedule for this week:
  - Today: Finish Chapter 12, Sections 13.1 – 13.3
  - Wednesday: 13.4 – 13.6
  - Friday: 13.7 – 13.8
- Next midterm: Wednesday after spring break, March 26
- Midterm will cover Chapter 3 and Chapters 9-12 (first part of today's lecture) – this is the material since last midterm
- Review in class Monday March 24

Announcements II

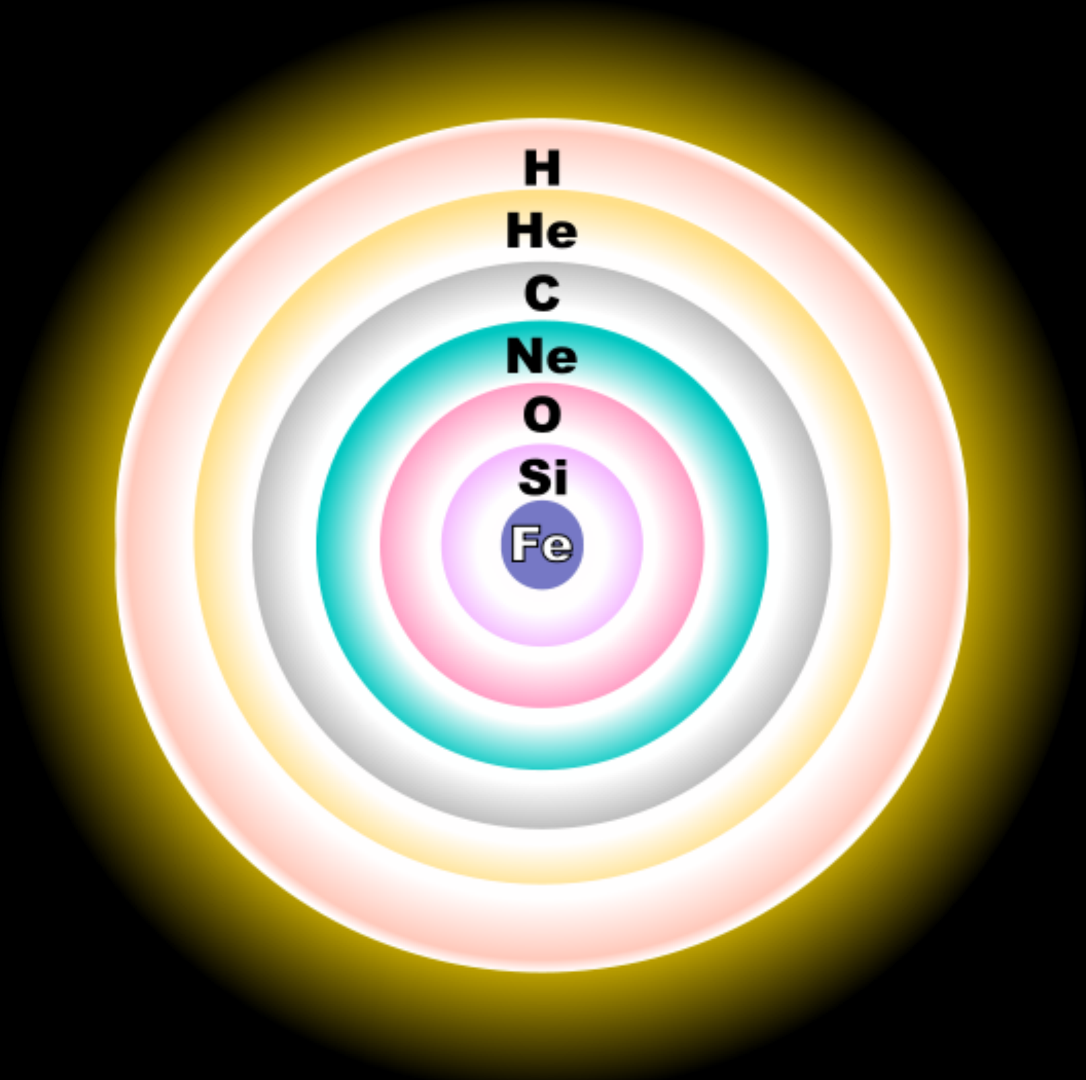
- Reminder: this is the last week to turn in astronomy news summary for **extra credit**
- Summary *in your own words* of an astronomy-related story in the news
  - Explain what, how and why it's important
  - At least three sources required, must be cited
- Turn in any time in class until Friday, or email electronic copy
- Info on D2L
- +1% on final grade

Type I supernova: collapse of a white dwarf star pushed over its upper mass limit

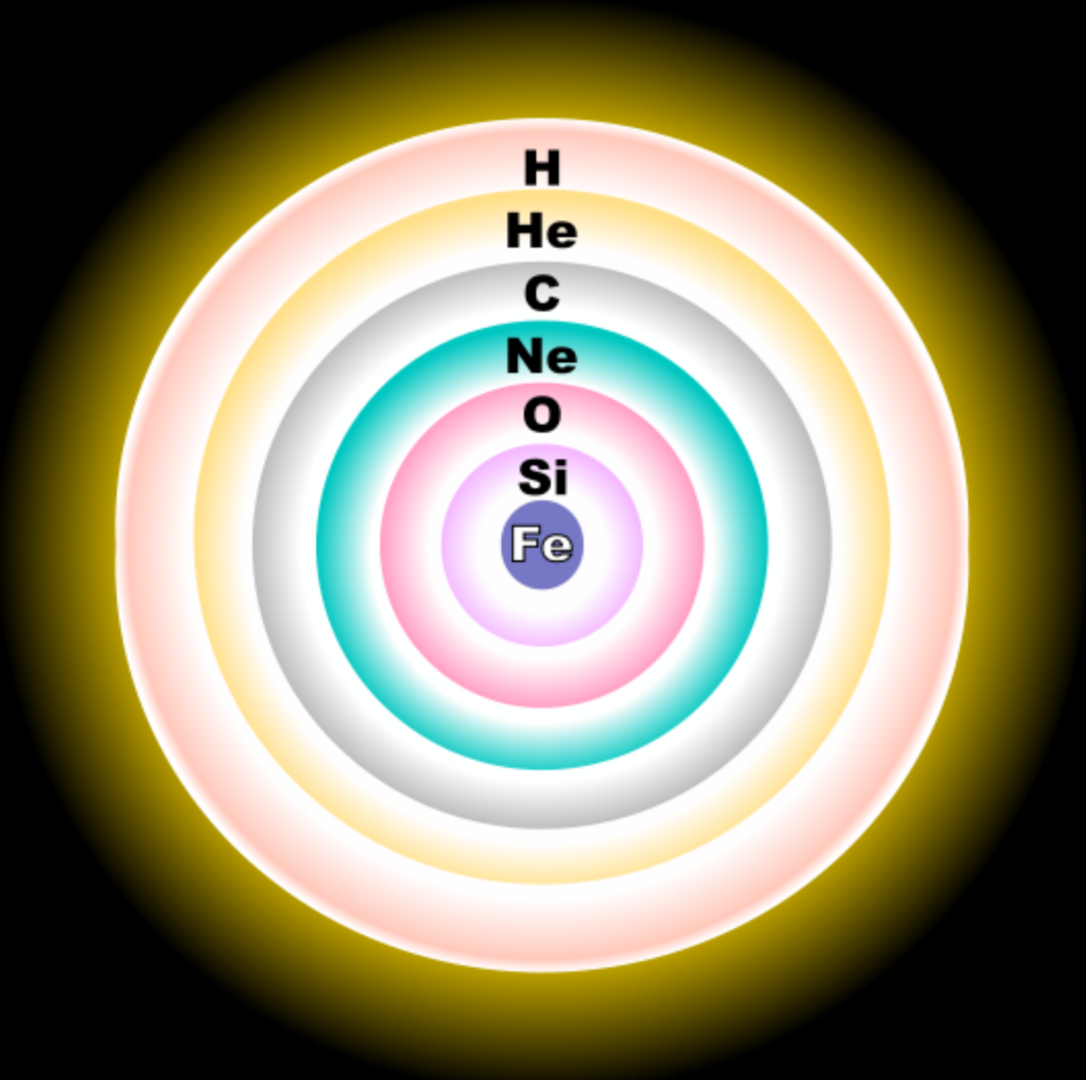




At the end of the life of a **massive star** (more than about 8 solar masses), its core is iron, and nuclear reactions around the core add more iron to it. But iron is the stablest element --- it will not fuse to make anything heavier.



The iron core then acts like a white dwarf --- it contracts until it can't contract any more, held apart not by energy released in fusion, but by the **degeneracy pressure** of its electrons.



As more iron is added to the inert core, its mass approaches **1.4 solar masses**, and then the iron core **collapses**, blowing off the rest of the star.

This is a **Type II supernova,**
or **core collapse supernova**

The Deaths of Massive Stars

- No dead iron core of a star can have a mass greater than 1.4 solar masses
- A **Type II supernova** is the explosion caused by the violent gravitational collapse of the core of a massive star at the end of its evolution (when enough iron has been added to it to exceed the 1.4 solar mass limit)
- Most of the star is blown away, and the expanding cloud it becomes is called a supernova remnant
- The most massive main-sequence stars end their lives in supernovae

Elements that are formed in low mass stars stay inside the stars. Elements heavier than helium are distributed throughout the galaxy by the supernova explosions that blow apart the most massive stars.

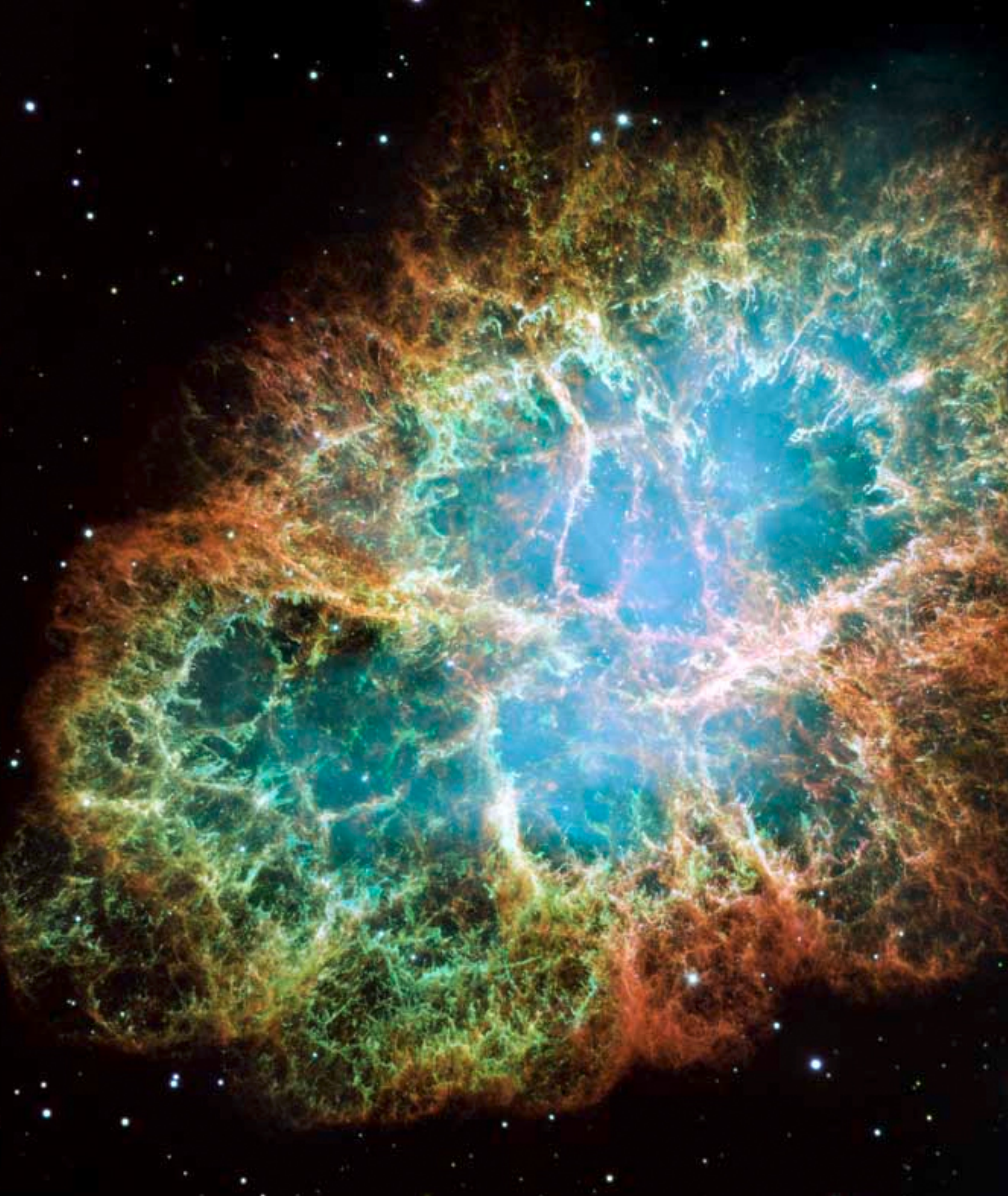
Nearly everything in you except hydrogen was once in a massive star that blew itself apart in a supernova.

Supernovae are the way elements heavier than helium get out of the stars where they form and are distributed through the universe.

Summary: Two types of supernovae

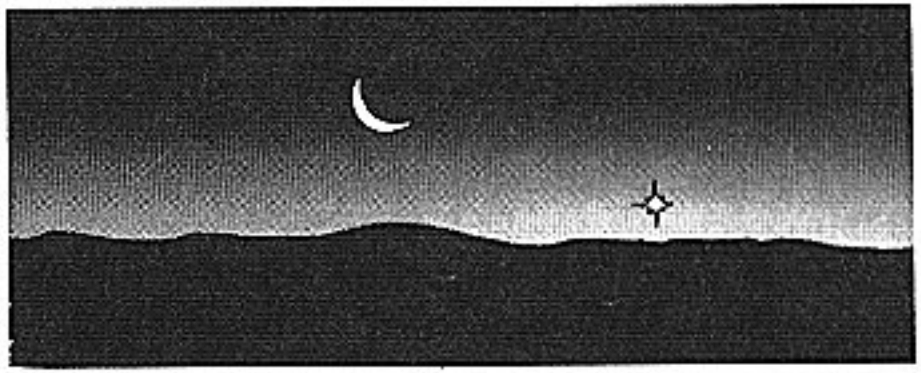
Type I: The collapse of an accreting white dwarf when its mass reaches 1.4 solar masses.

Type II: The collapse of the iron core of a massive star when its mass reaches 1.4 solar masses. The energy of matter falling during the gravitational collapse (and then rebounding) is the energy that explodes the rest of the star.

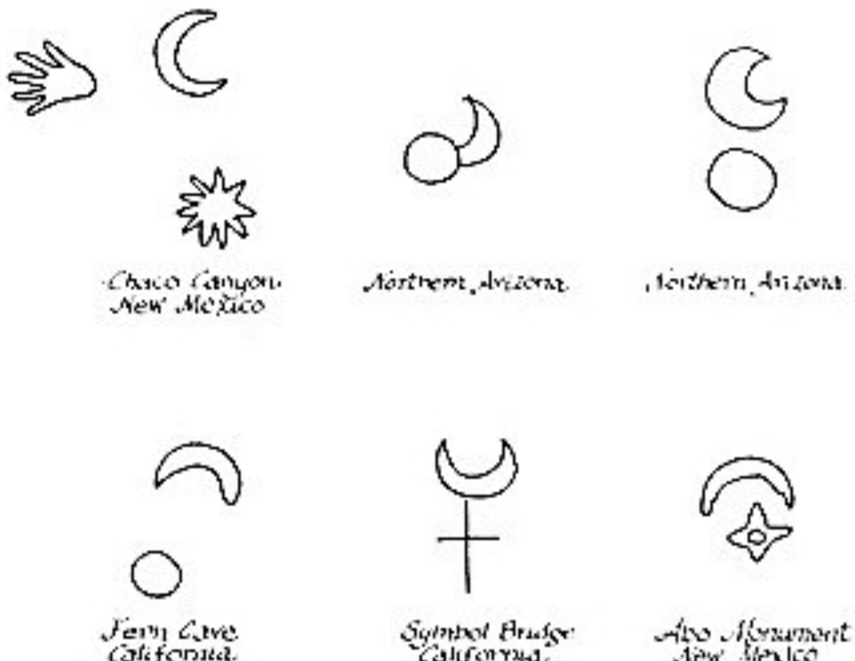


- One of the most famous supernova remnants is the Crab Nebula
- Supernova was in 1054: recorded by Chinese astronomers

- Crab Supernova was in 1054 -- probably also observed by the Anasazi in North America



The crescent moon was visible in western North America near the Crab supernova in the predawn eastern sky on July 5, A.D. 1054.



Several examples of crescents in rock art from the American Southwest are associated with what may be representations of the A.D. 1054 supernova.

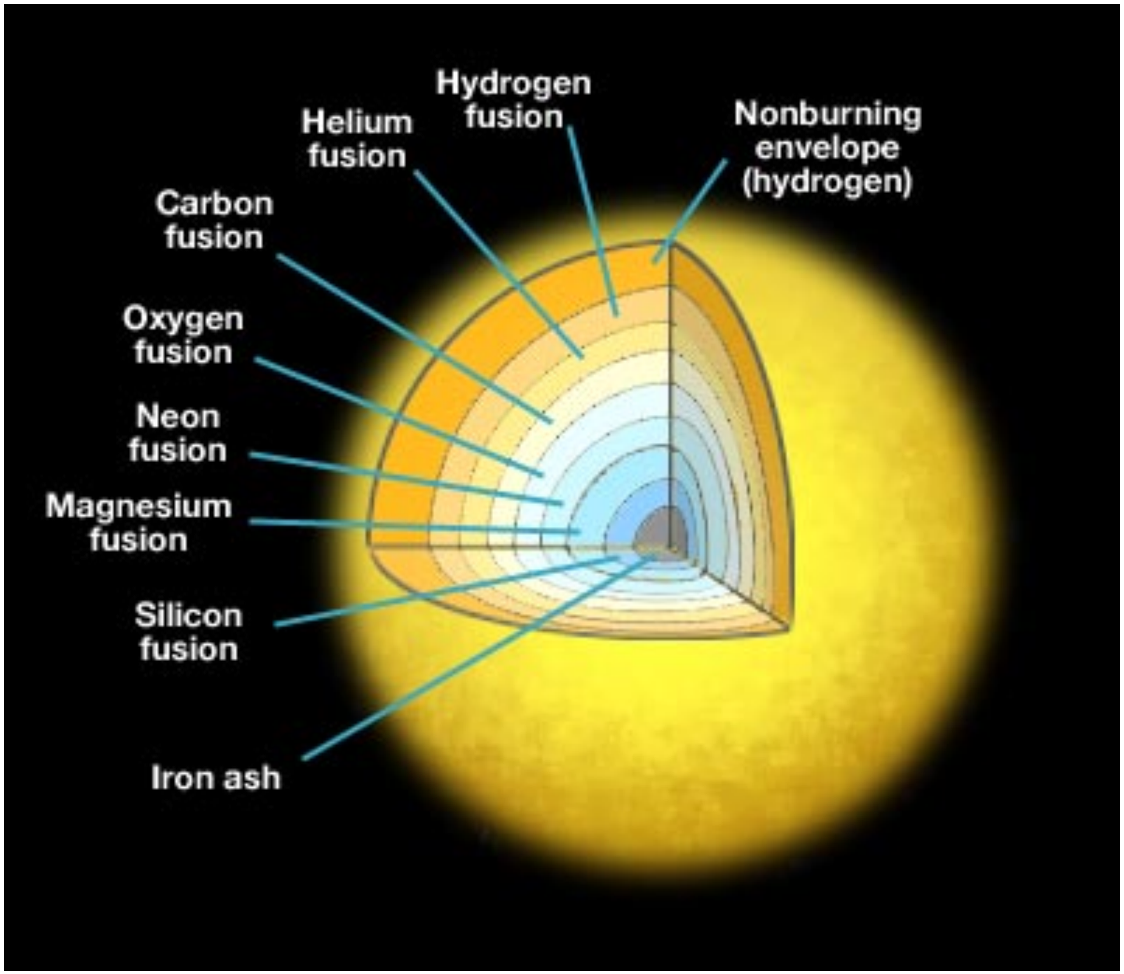
Evolution of Stars More Massive than the Sun

TABLE 12.3 End Points of Evolution for Stars of Different Masses

Initial Mass (Solar Masses)	Final State
Less than 0.08	(Hydrogen) brown dwarf
0.08–0.25	Helium white dwarf
0.25–8	Carbon–oxygen white dwarf
8–12 (approx.)*	Neon–oxygen white dwarf
Greater than 12*	Supernova

*Precise numbers depend on the (poorly known) amount of mass lost while the star is on, and after it leaves, the main sequence.

Which of these is the most likely mass of the star shown in this diagram?



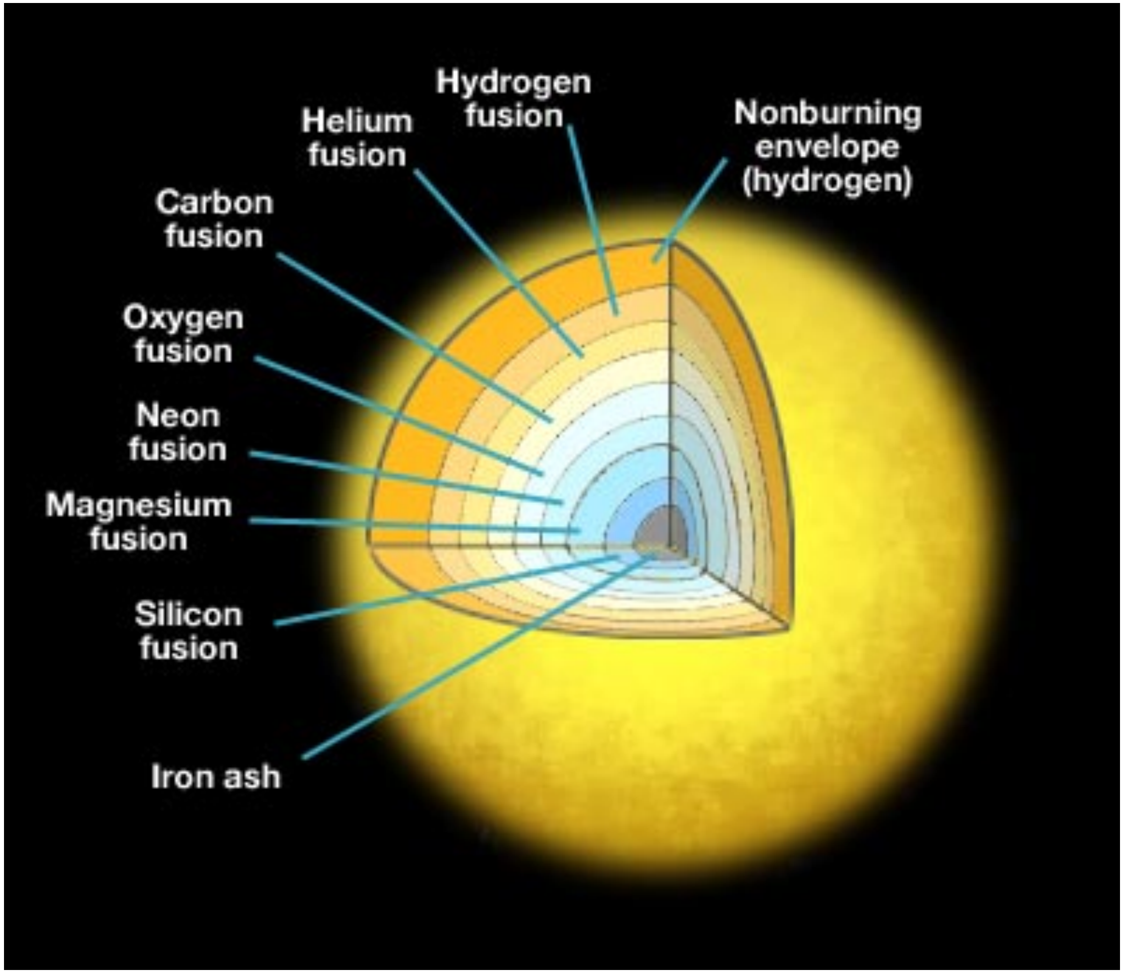
A — $0.4\ M_{sun}$

B — $1\ M_{sun}$

C — $4\ M_{sun}$

D — $10\ M_{sun}$

Which of these is the most likely mass of the star shown in this diagram?



- **A** — 0.4 M_{sun}
- **B** — 1 M_{sun}
- **C** — 4 M_{sun}
- **D** — 10 M_{sun}

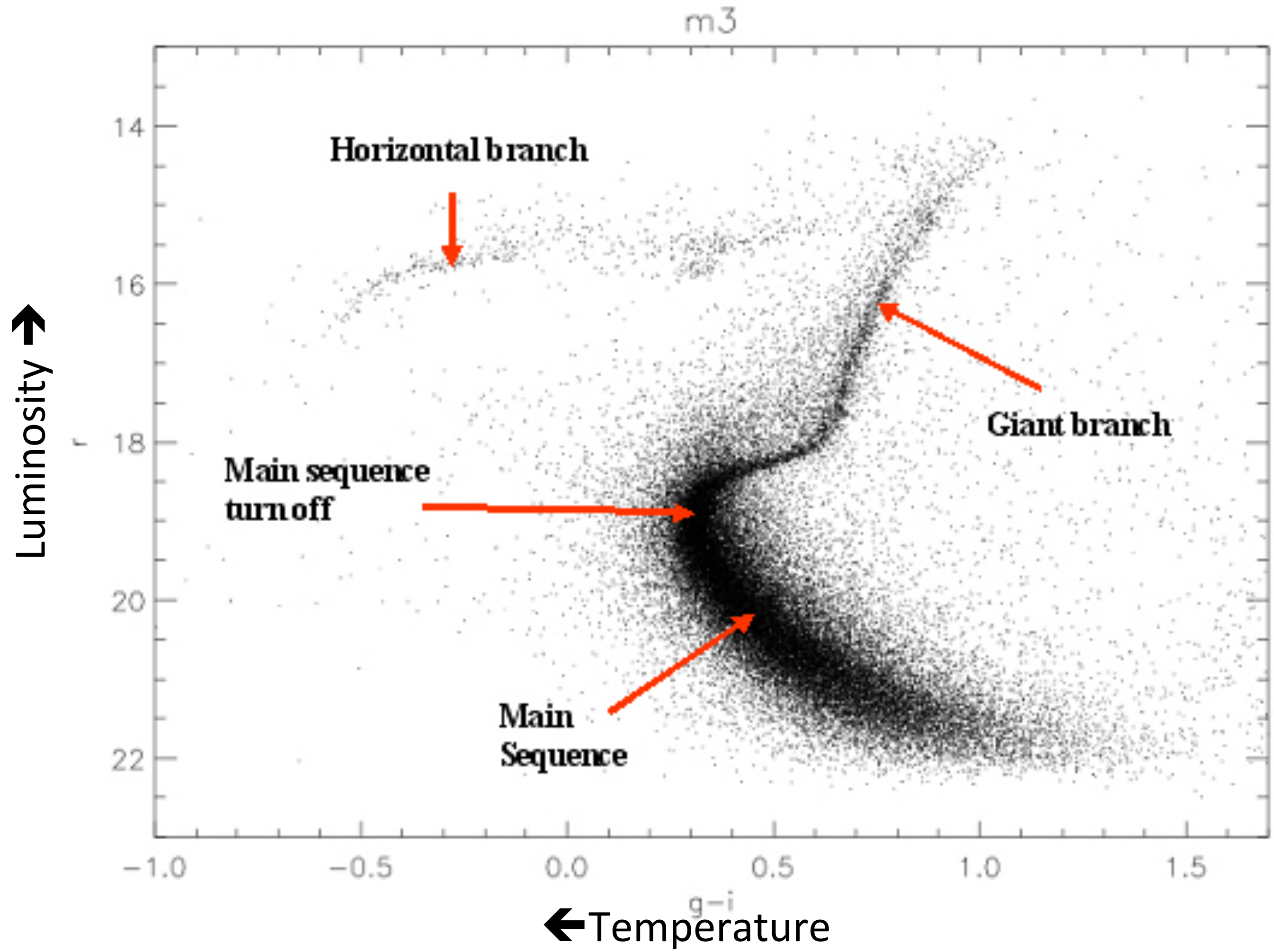
The Ages of Star Clusters

The more massive a star is, the more quickly it evolves.

One can find the age of a cluster of stars by observing which stars have left the main sequence

In the youngest clusters even the most massive stars (O and B) are still on the main sequence

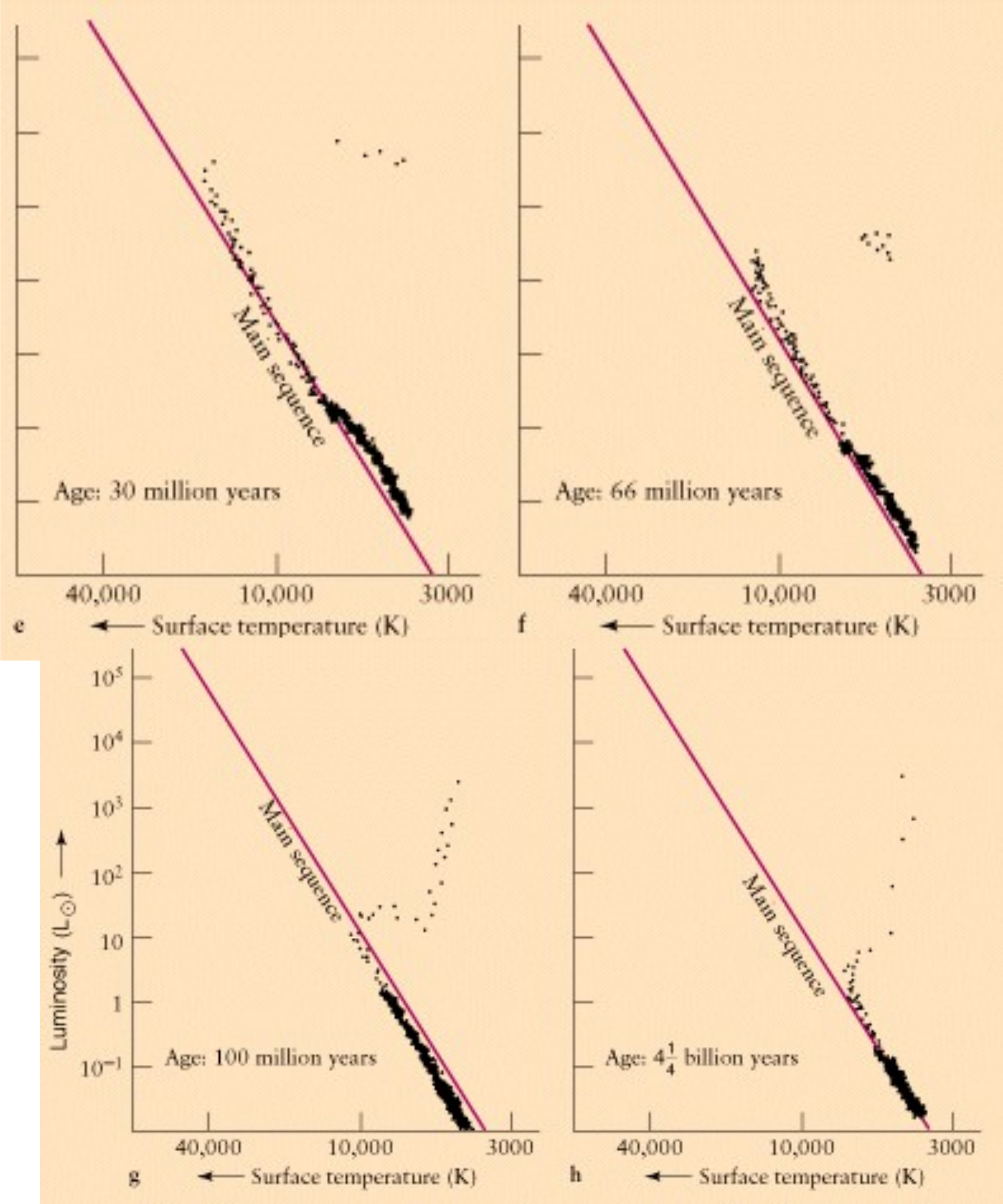
In the oldest clusters, stars with mass as small as the Sun’s (spectral types O, B, A, F, G) have evolved to red giants

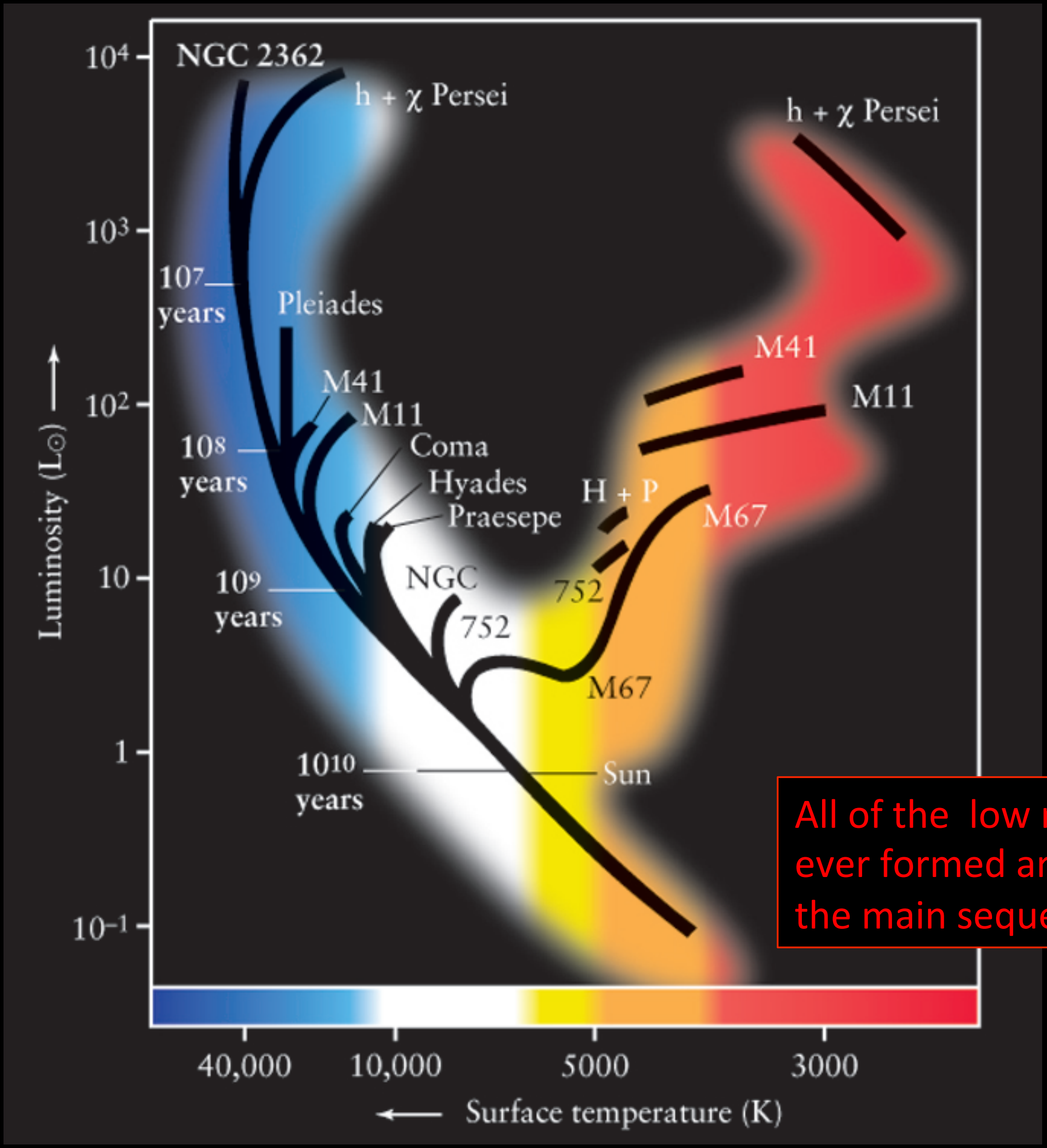


- Find a star cluster, plot all the stars on an H-R diagram
- Find the point where stars leave the main sequence: **main sequence turnoff**
- The age of the cluster is the main sequence lifetime of a star with the mass of the stars that have just left main sequence

Younger clusters

Older clusters





All of the low mass stars ever formed are still on the main sequence!

Jewel Box: a young open cluster

Young open cluster, about 500 million years old

M11

An even younger open cluster

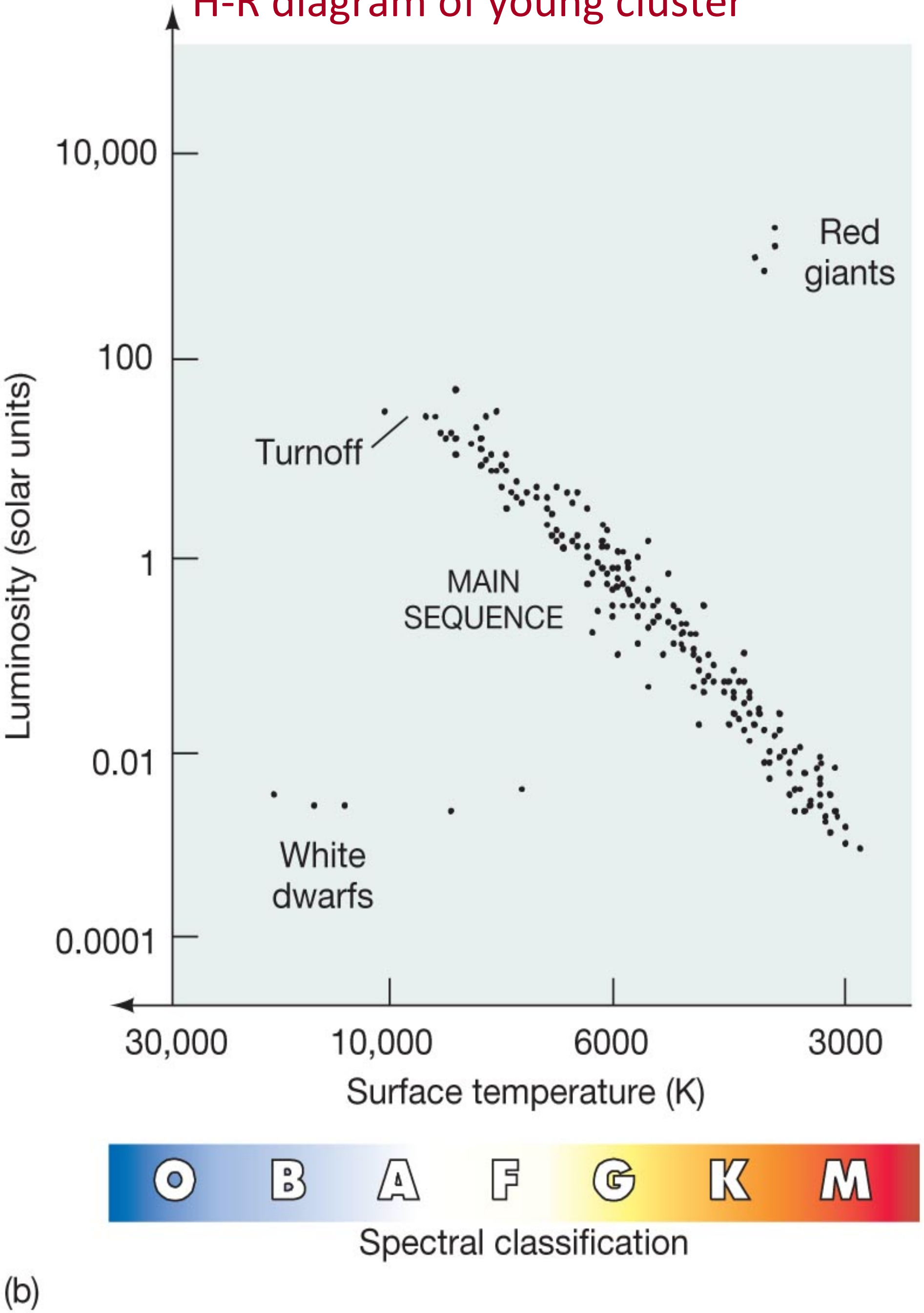
NGC 3293

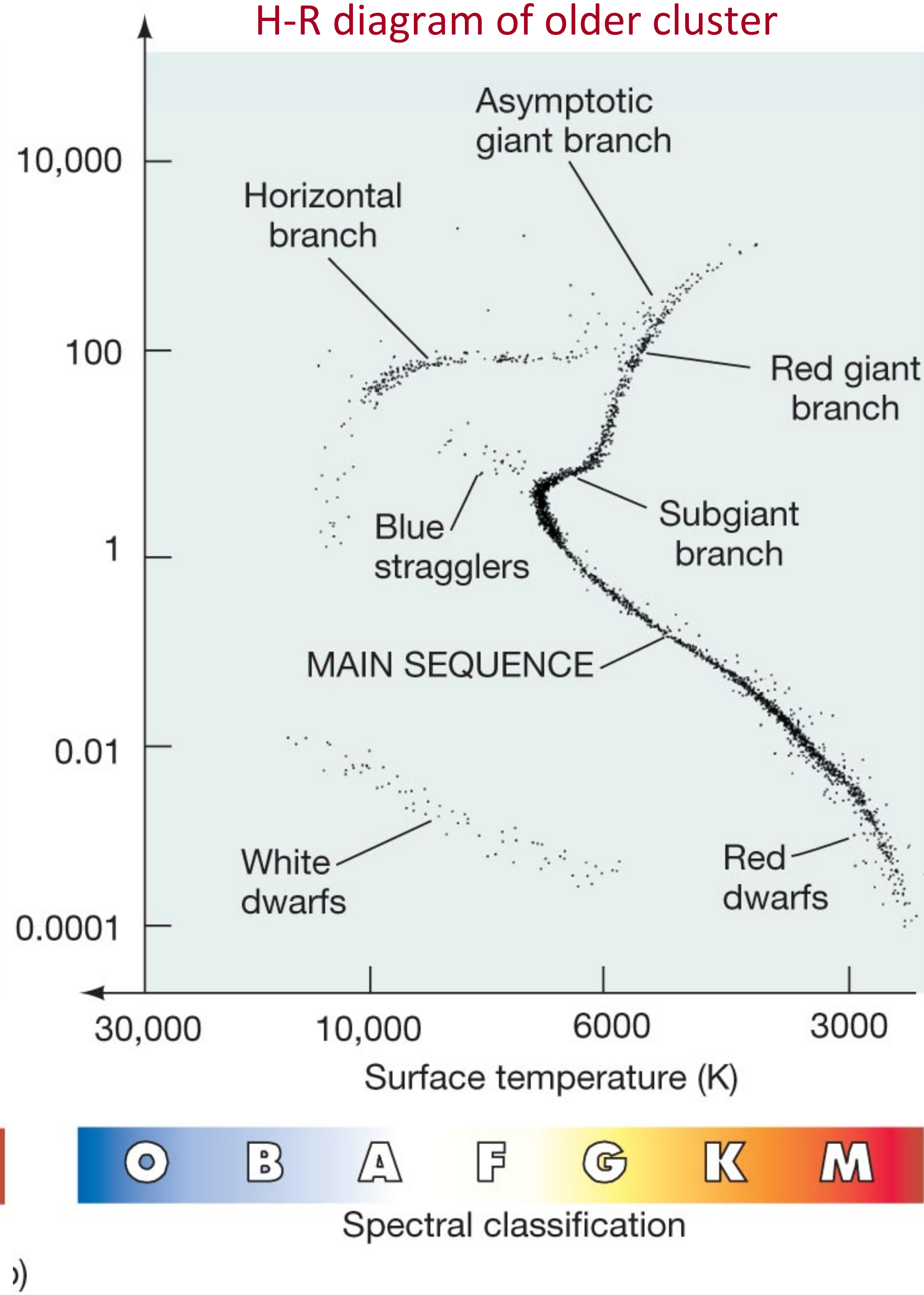
Old globular clusters

M10

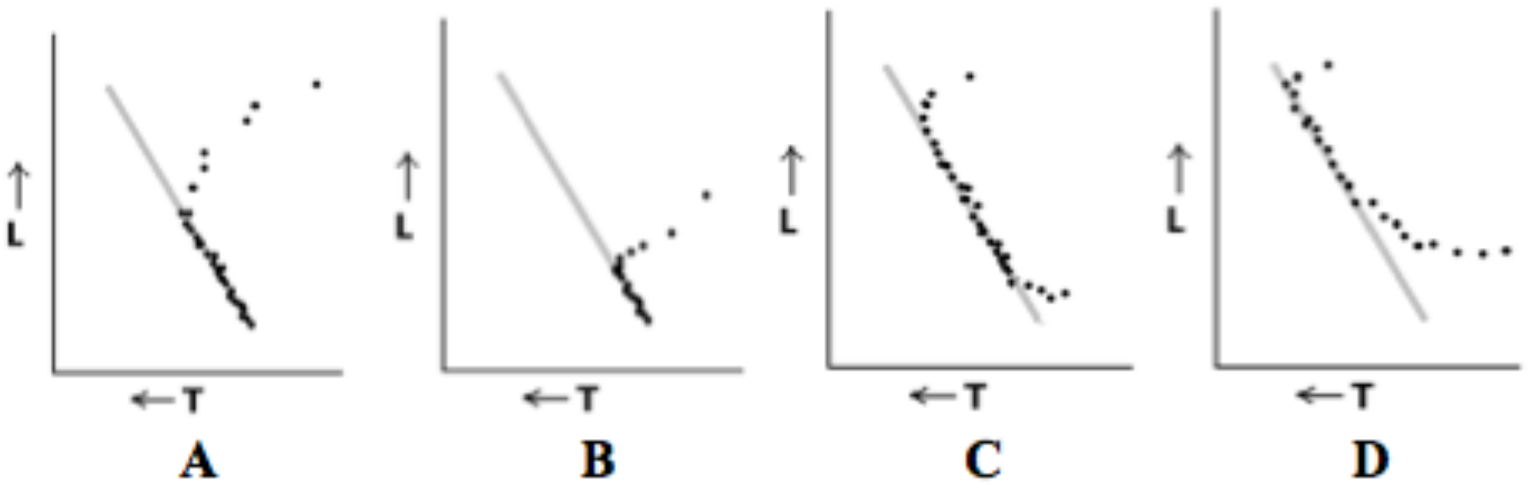
Old globular clusters

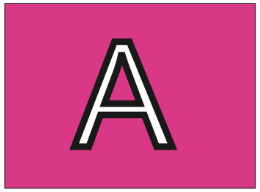
M13 in Hercules


H-R diagram of young cluster
Luminosity (solar units)
10,000
100
1
0.01
0.0001
Red
giants
Turnoff
MAIN
SEQUENCE
White
dwarfs
30,000
10,000
6000
3000
Surface temperature (K)
O
B
A
F
G
K
M
Spectral classification
(b)

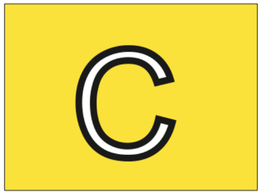

H-R diagram of older cluster
10,000
100
1
0.01
0.0001
Asymptotic
giant branch
Horizontal
branch
Red giant
branch
Blue
stragglers
Subgiant
branch
MAIN SEQUENCE
White
dwarfs
Red
dwarfs
30,000
10,000
6000
3000
Surface temperature (K)
O
B
A
F
G
K
M
Spectral classification

This figure shows H-R diagrams for four star clusters. Which one is the oldest?



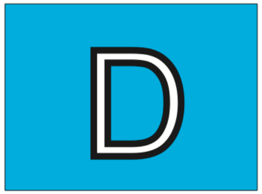


A



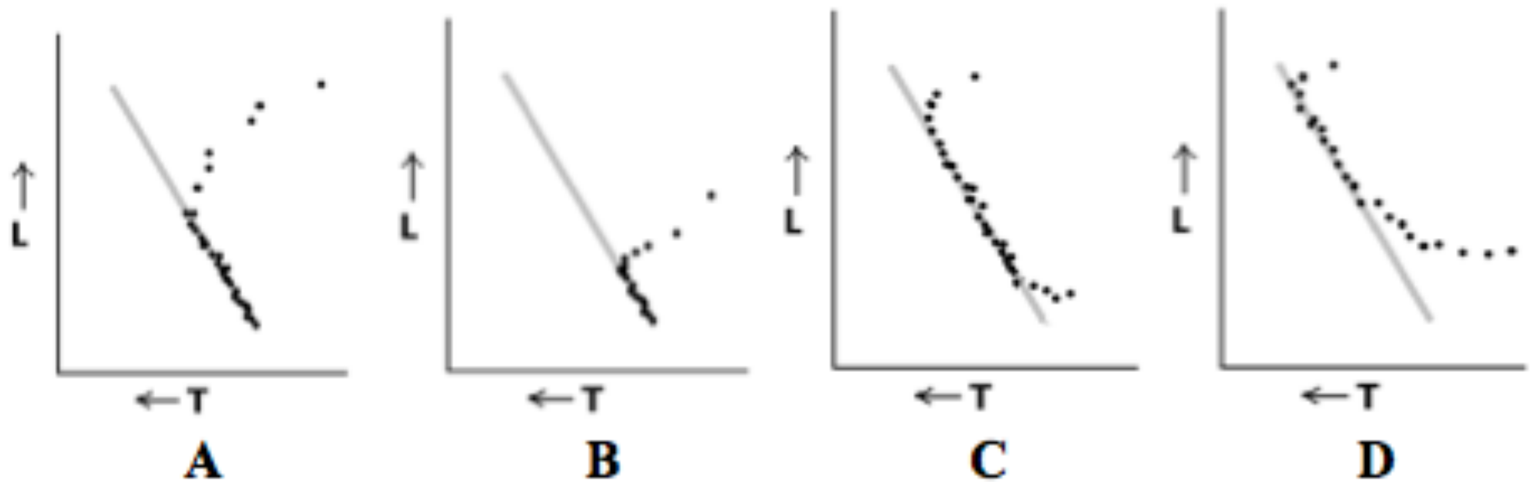
C

B



D

This figure shows H-R diagrams for four star clusters. Which one is the oldest?



A — A

B — B

C — C

D — D

Astronomy 103

Neutron stars, black holes, and spacetime

Please read Chapter 13

At the end of the life of a massive star, we have seen that its iron core collapses. When the core collapses, the electrons are pushed down onto the nuclei – the core collapses from the size of the Earth to the size of a city, about 20 km (13 mi) in diameter. 100 times more energy is released in these few seconds by the collapse than the star released during its entire lifetime.

This creates a **neutron star**: a star that is composed of neutrons – a star that is almost a giant atomic nucleus.

Neutron stars

Immediately after the neutron was discovered in 1930, physicist Lev Landau suggested the possibility that the pressure in the cores of stars might push the electrons onto their protons to make a core entirely of neutrons. He wasn't quite right: The pressure is high enough only when the star collapses in a supernova.

Neutron stars

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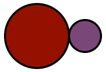
proton  electron

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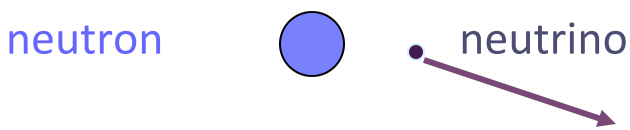
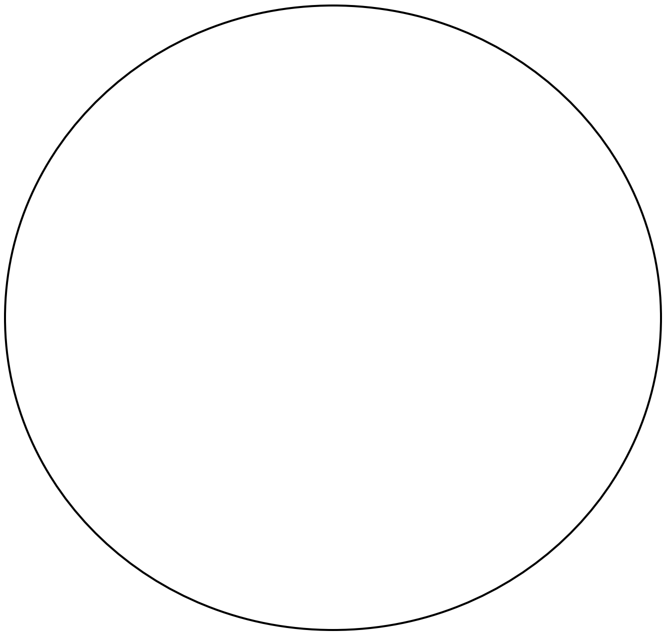
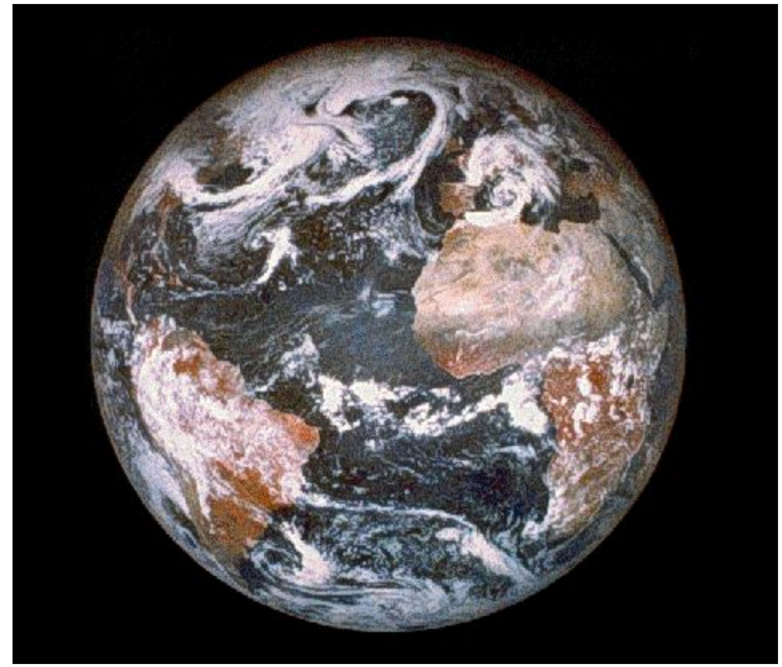


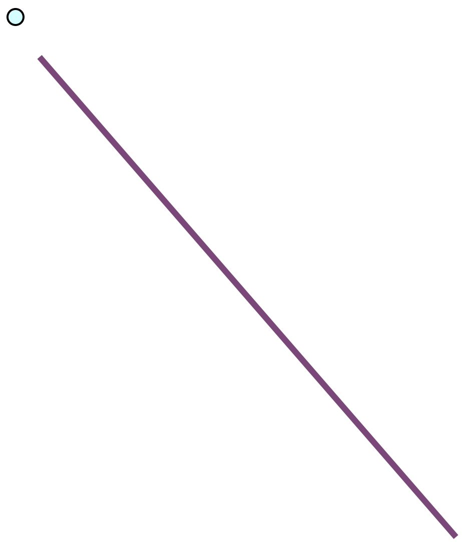
How does this work?

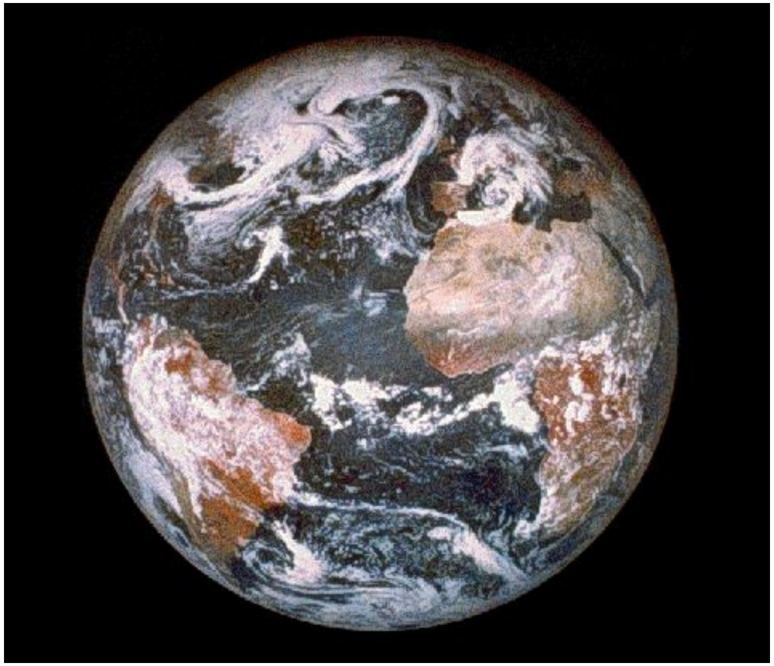




a white dwarf is roughly the size of the Earth

How does this work?





A neutron star has a radius of about 10 km, roughly 1/1000 that of the Earth

Remember that atoms are mostly empty space

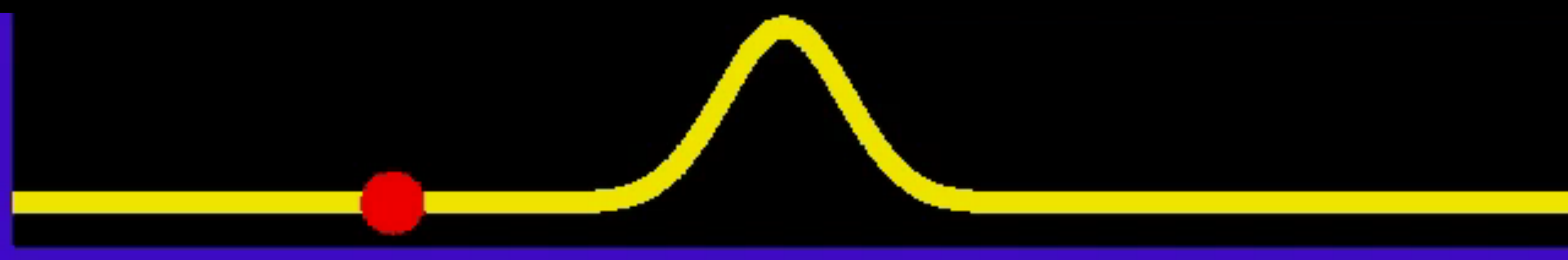
If you compressed all of Mt. Everest, pushing its electrons onto their nuclei, you would get a single teaspoonful of neutron-star matter.

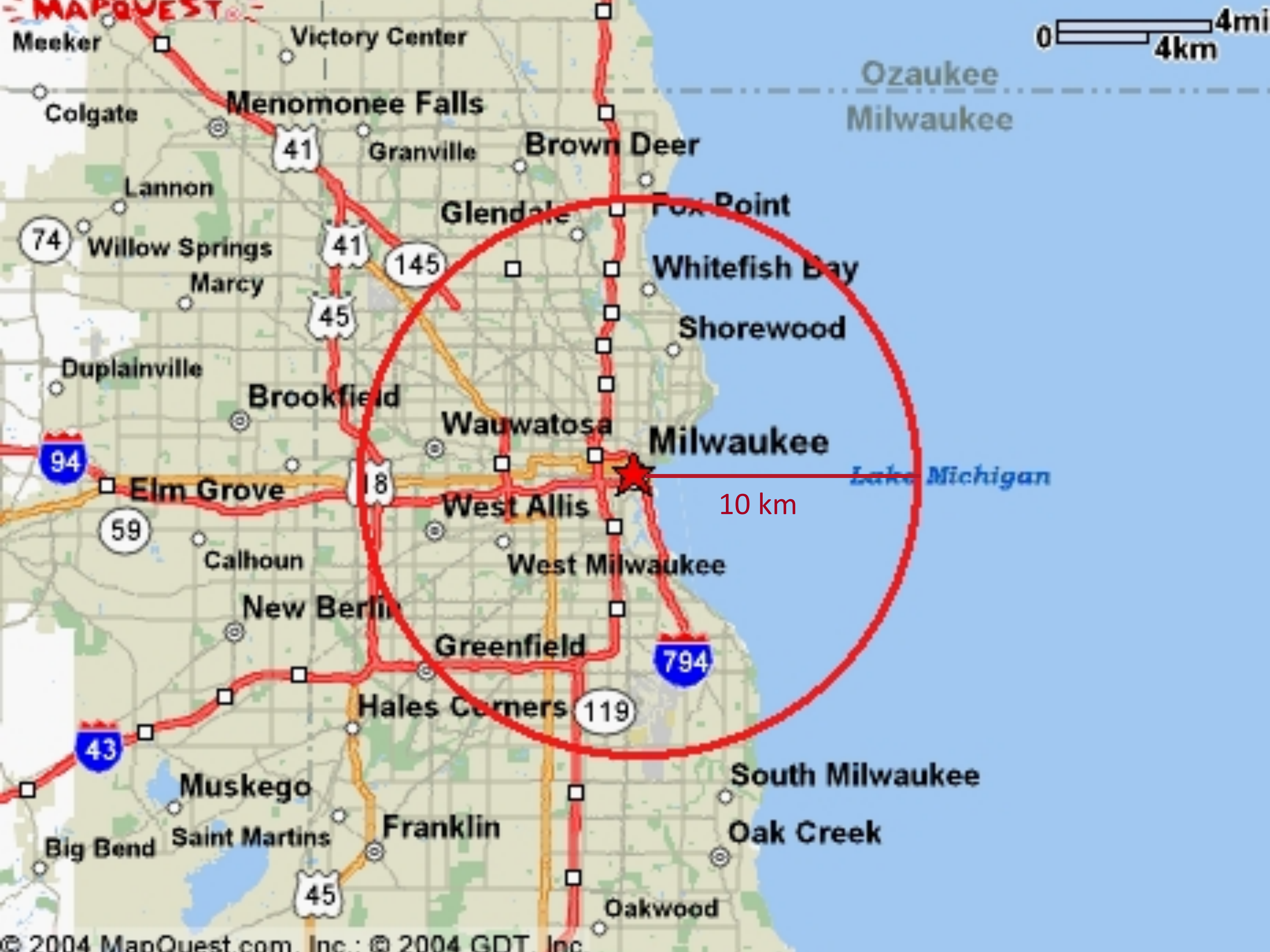
!

Neutron Star Fun Facts

- R≈15 km and M≈1.5 M_{Sun}
- Central density 2-10 times that of atomic nucleus
    - 1 teaspoon is about 10^{12} kg
    - a cube 300 meters on a side has the same mass as the Earth

- Magnetic field >10^{12} times that on Earth
    - erase credit cards from 30,000 km & kill from 200 km
- Spin frequencies from 0.1 Hz to 716 Hz → **pulsars**
    - faster than a kitchen blender!





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Fox Point
Willow Springs
Marcy
Whitefish Bay
Shorewood
Duplainville
Brookfield
Wauwatosa
Milwaukee
Lake Michigan
Elm Grove
West Allis
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Calhoun
West Milwaukee
New Berlin
Greenfield
Hales Corners
South Milwaukee
Muskego
Franklin
Oak Creek
Big Bend
Saint Martins
Oakwood
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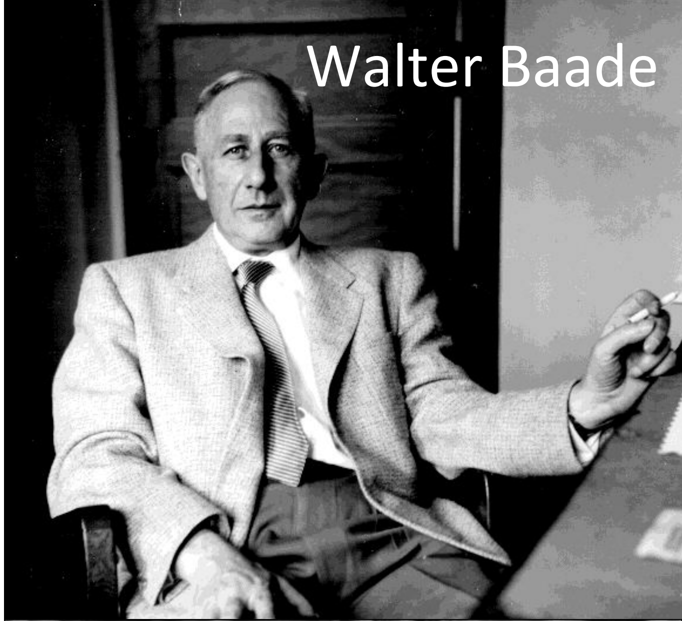
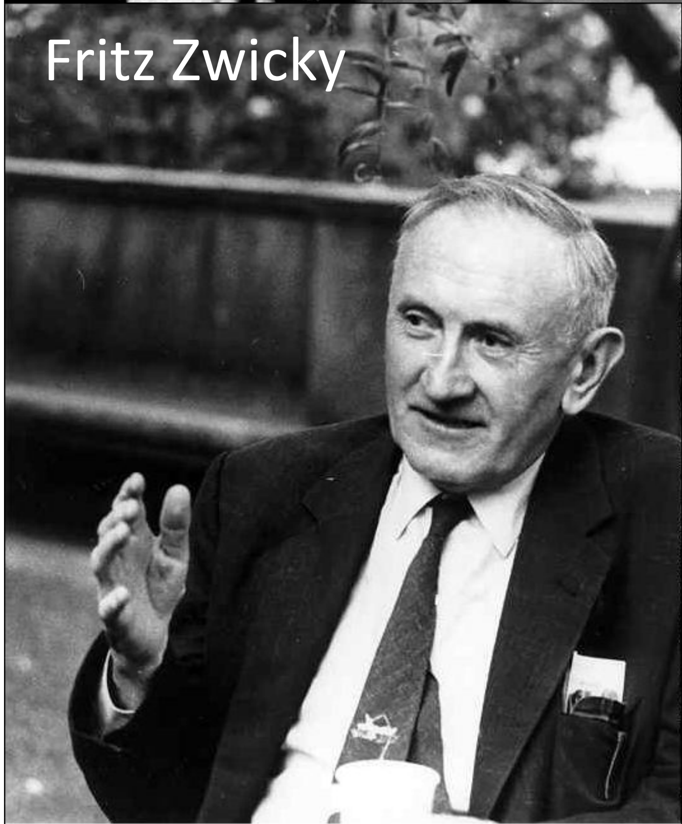
Energy of a supernova

Baade and Zwicky pointed out that the gravitational energy released by a star falling inward to become a neutron star would be about 1 billion times as large as the energy emitted by the Sun over its entire lifetime — the observed energy of a supernova. Based on this observation, they suggested that "...supernovae represent the transitions from ordinary stars into neutron stars." This was two years after the discovery of neutrons and 33 years before discovery of neutron stars.



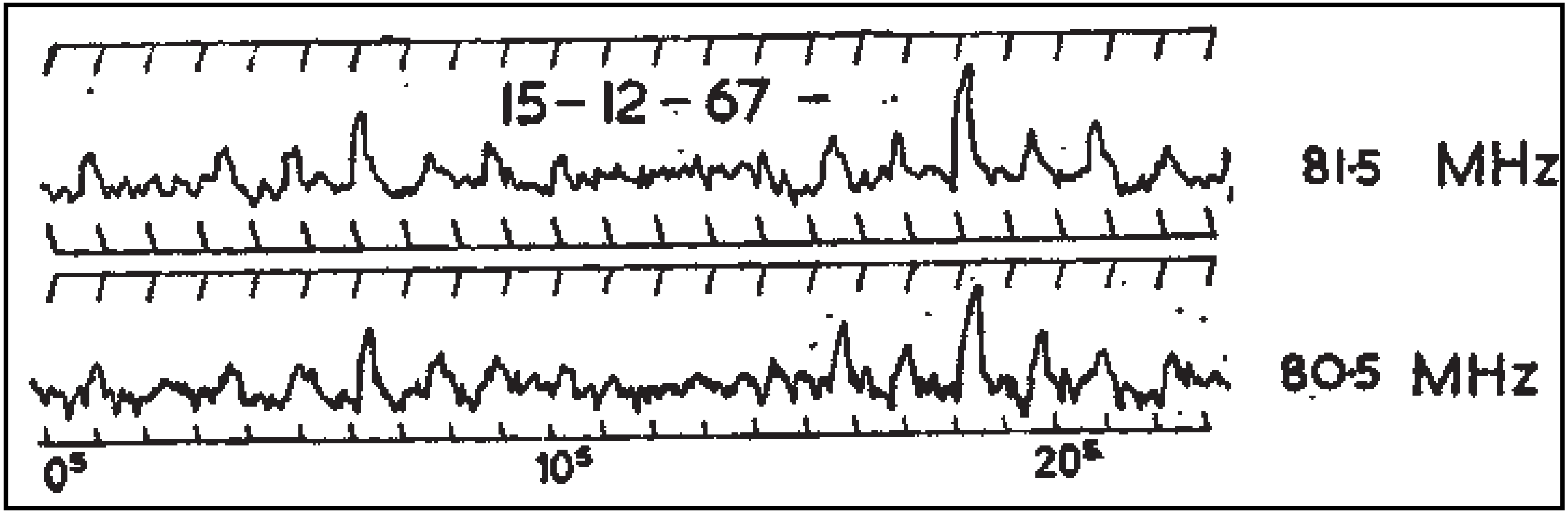


Baade and Zwicky realized that the energy released by a star collapsing to a neutron star would be about the same as the observed energy of a supernova

Although Baade and Zwicky suggested in 1934 that neutron stars might exist and might be the outcome of a supernova, no neutron stars were seen for the next 33 years.

In 1967 Jocelyn Bell, a graduate student at the University of Cambridge, saw a set of mysterious radio sources that they called pulsars, because they saw from each object a pulse of radio waves once every second or so, with extremely regular periods. What was Bell looking at?

Jocelyn Bell and her radio telescope



Jocelyn Bell, at about the time she discovered the first neutron stars.

Her discovery won the Nobel prize, but for her advisors and not for her – one of the great mistakes in Nobel Prize history.

This is what she saw, converted to an audio signal

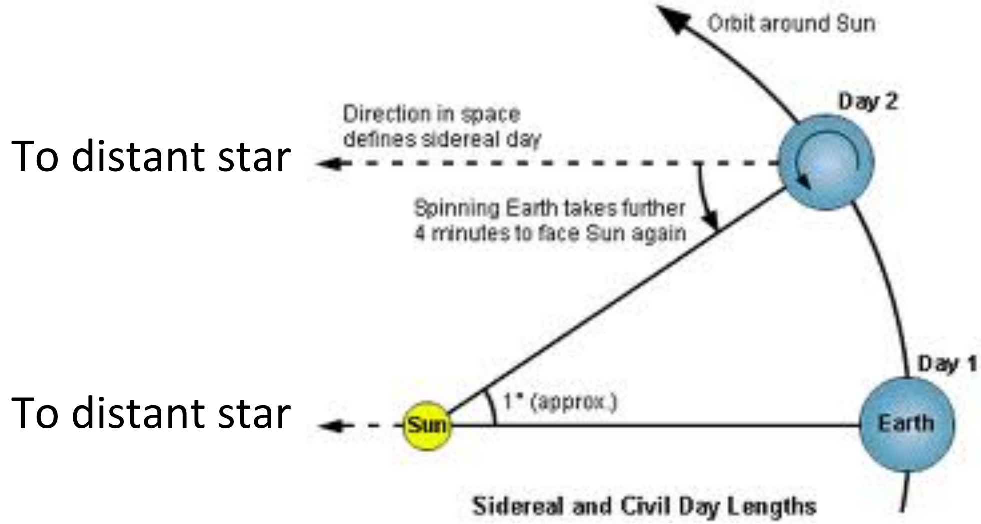
PSR B0329+54
0.7 s period

Pulses happen with great regularity. Here in this case it is once every 0.7 seconds.

Because they didn't know what these objects were at first, this was dubbed LGM-1 or Little Green Men-1.

Not the cause of the pulses!

Remember this?



- Solar day: Sun returns to same position
- Sidereal day: Stars return to same position
- Because of Earth's rotation around Sun, it takes 4 minutes longer for Sun to return to same position
- Sidereal day is 4 minutes shorter, and **stars rise 4 minutes earlier each day**
- **Mysterious pulsing radio source rose 4 minutes earlier each day, and was therefore not coming from the Earth!**

It was soon realized that these pulsating stars had to be neutron stars because anything larger that rotated with a period of 1.3 seconds would fly apart.

The radio waves are thought to be generated by the intense, rotating magnetic field of neutron stars – a electric generator in space. For these pulsing stars or **pulsars**, the magnetic field is 10^{12} or one trillion times stronger than the earth's magnetic field.

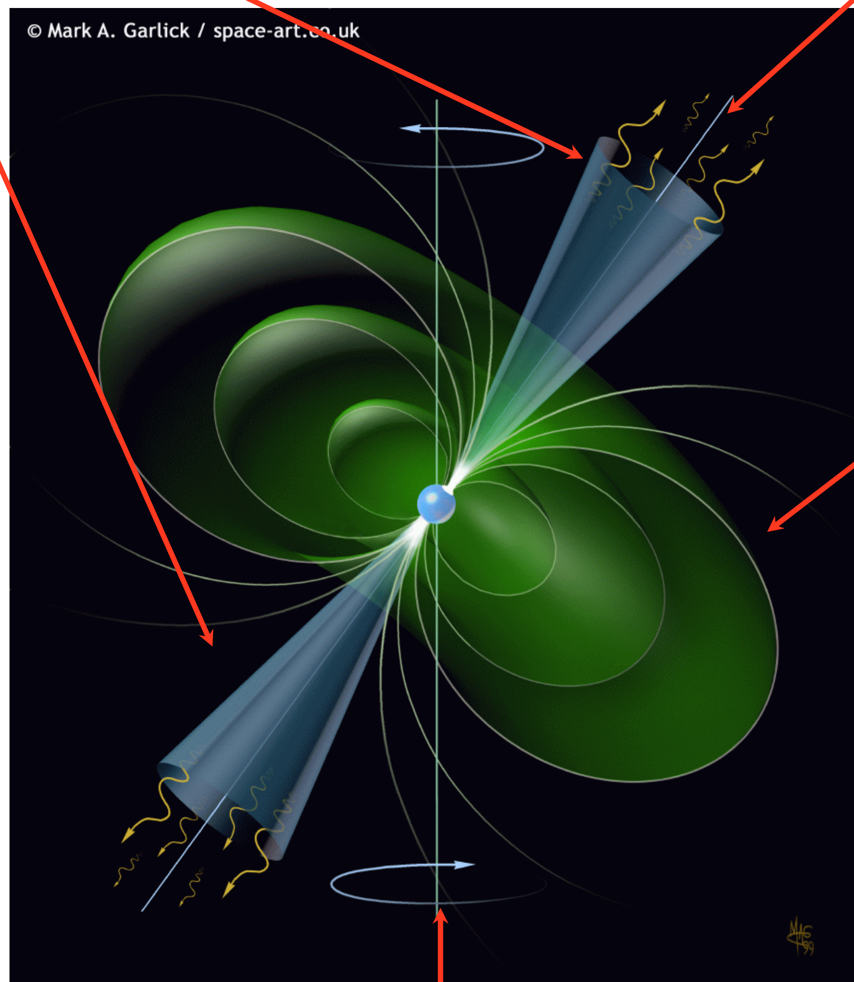
As the N or S pole of the pulsar points toward us, we see a flash of radio emission.

Pulsar

Beams of radio waves

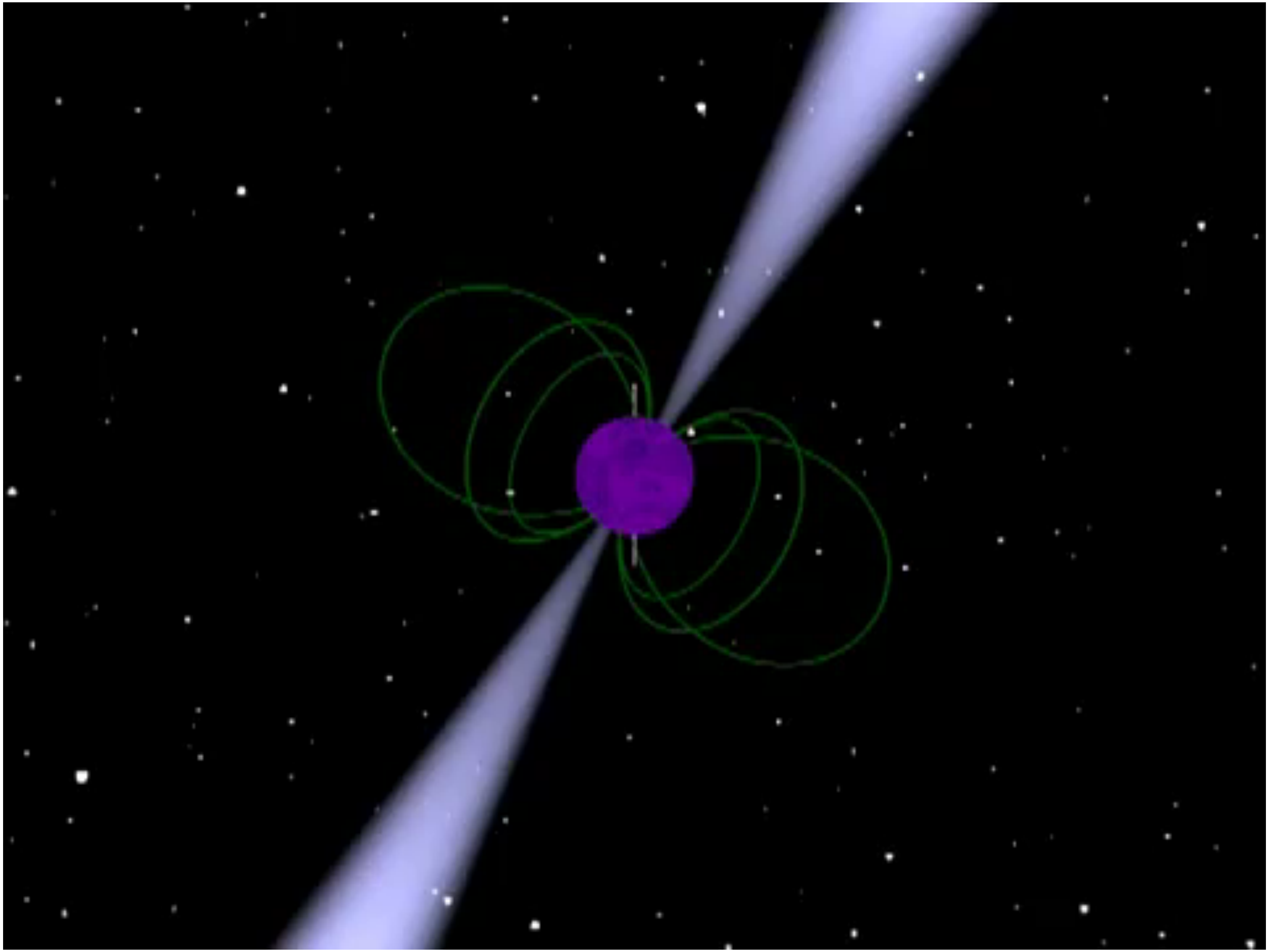
Magnetic axis

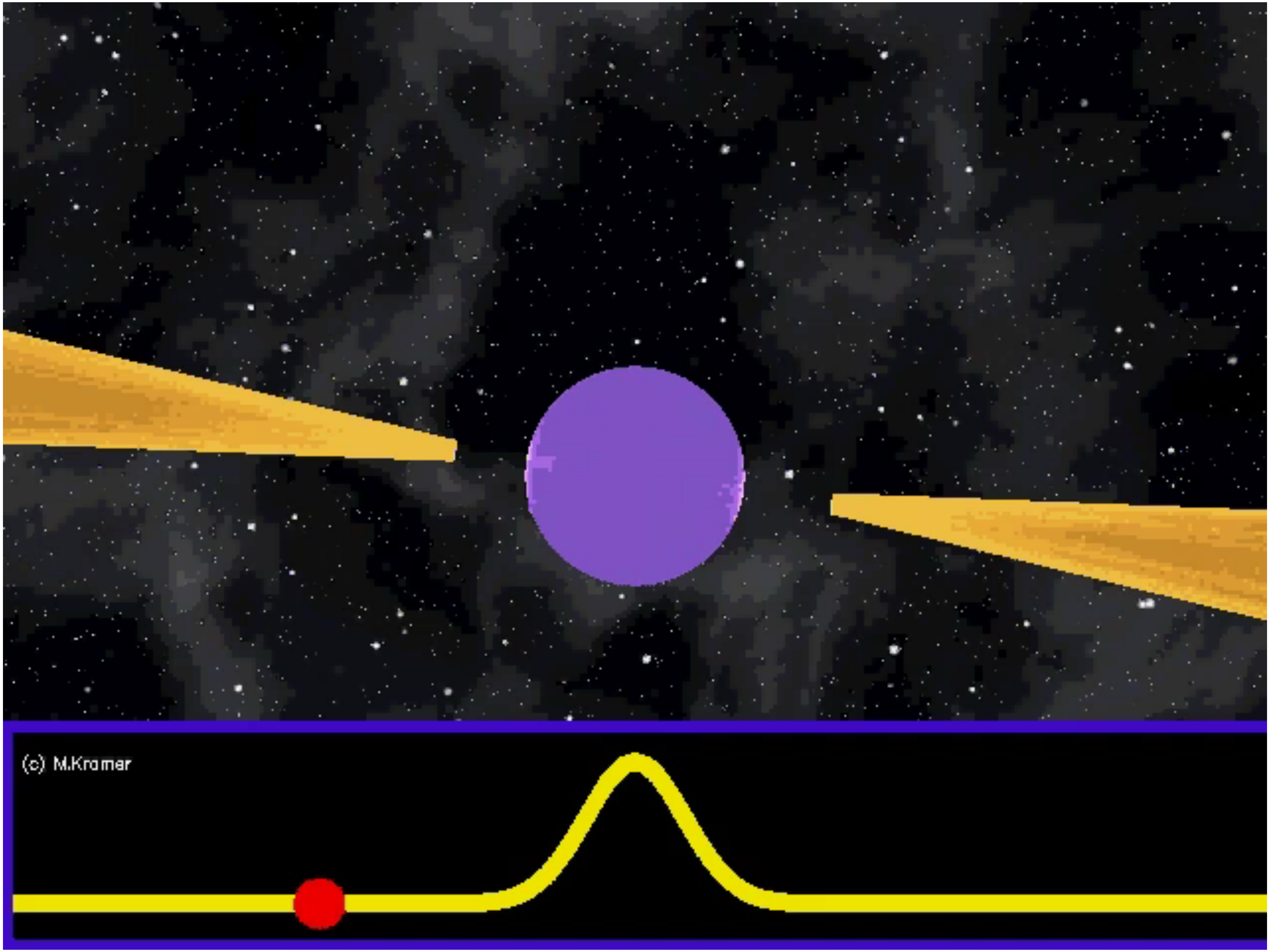
Magnetic field



Rotational axis

Pulsar

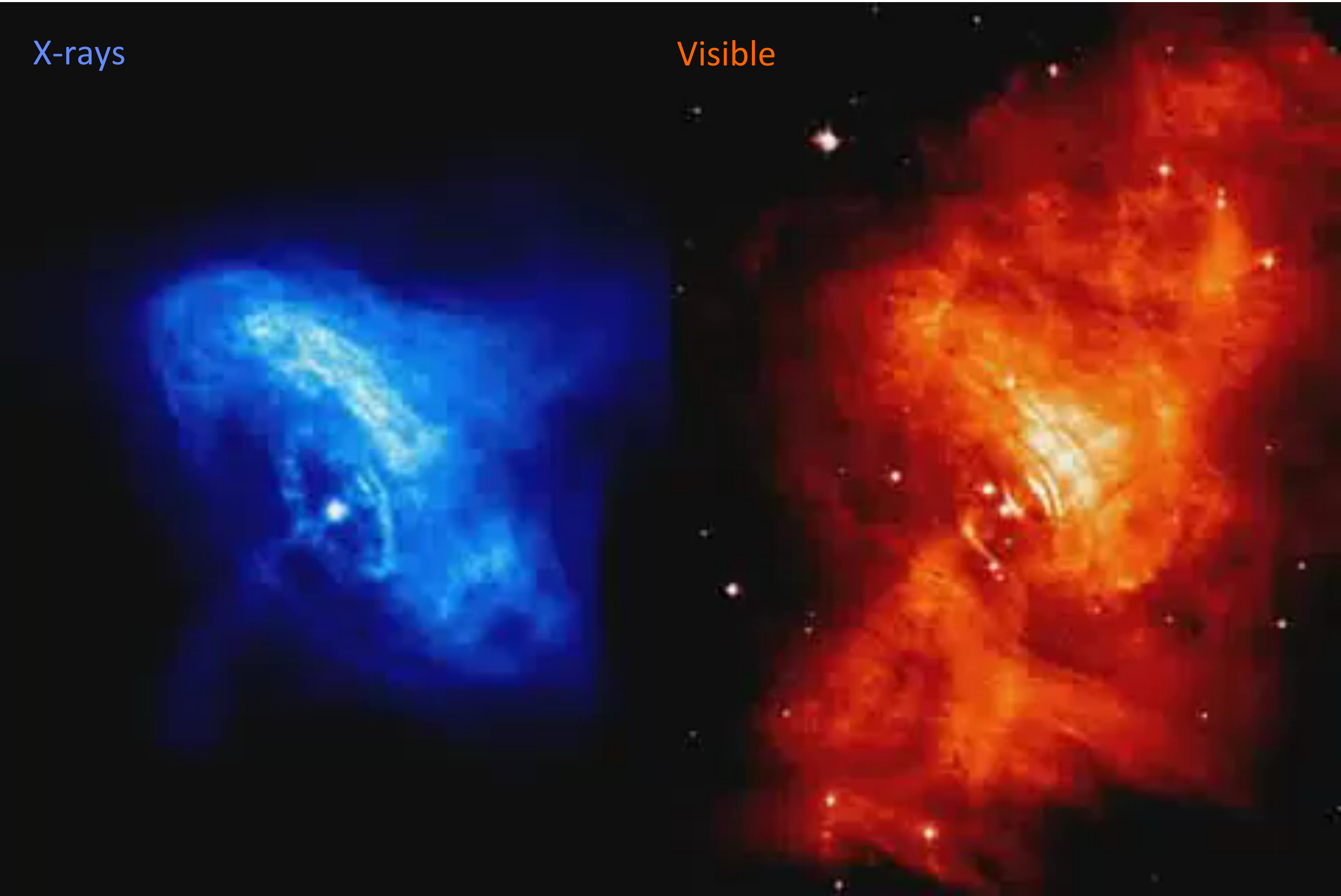



(c) M.Kramer

At the center of the Crab supernova remnant, just where you would expect one to be, a pulsar was discovered – so **neutron stars are associated with supernovae.**

After a year of watching it, the Crab pulsar was found to be less regular than a perfect clock – it was slowing down. And the energy lost by the spinning neutron star is equal to the energy emitted by the Crab nebula: energy from the pulsar is deposited in the surrounding gas, heating it.

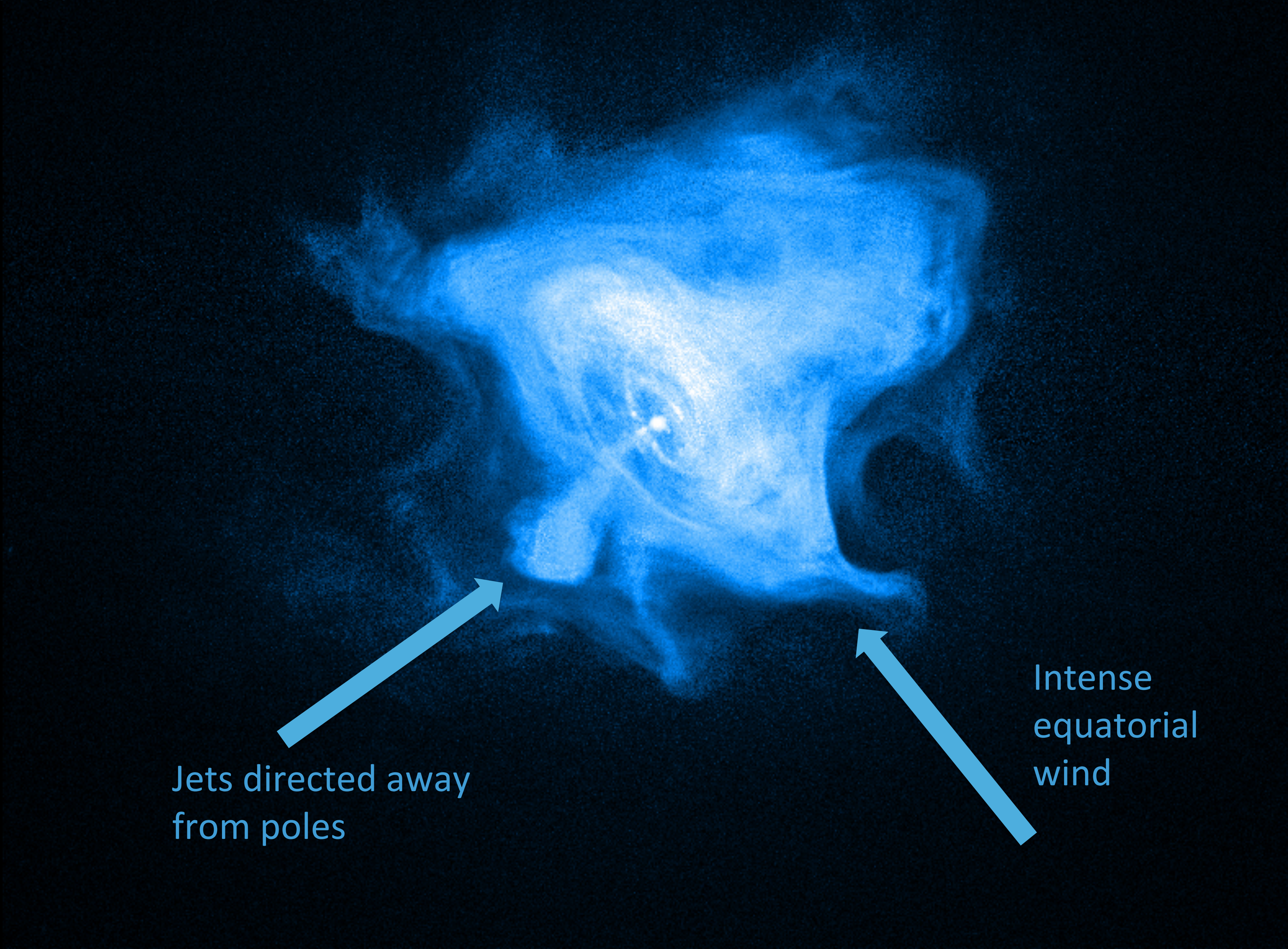
Crab Pulsar Wind Nebula



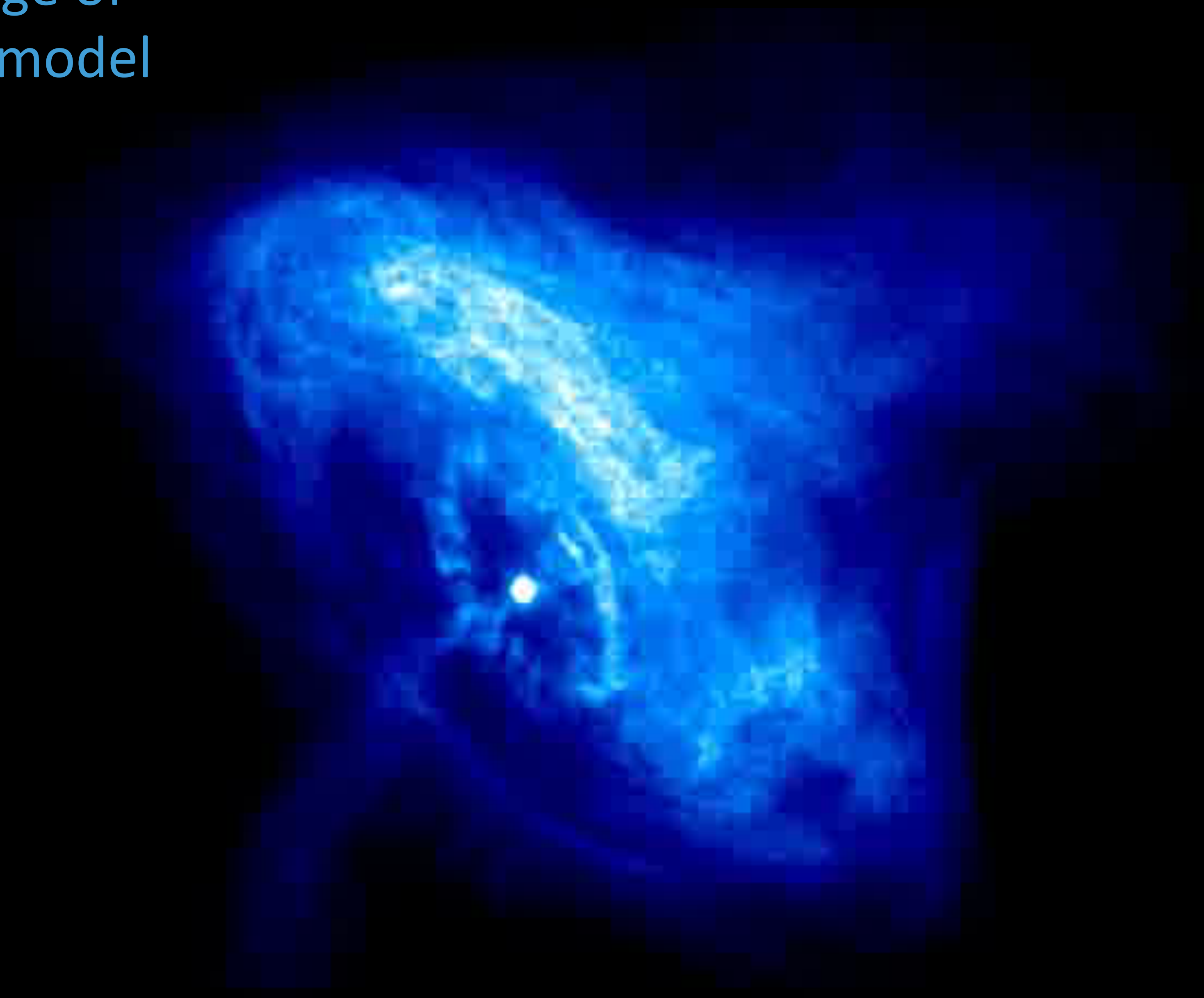
Crab Pulsar Wind Nebula

- The Crab pulsar also powers much of the emission from the Crab nebula
- This is most evident in the center of the nebula, where we see the pulsar wind nebula
- Wind of charged particles is accelerated by the rapidly rotating, superstrong magnetic field of the spinning pulsar
- Pulsar wind streams into the interstellar medium, creating a shock wave

X-ray image of Crab Pulsar Wind Nebula



X-ray image of nebula + model



Pulsars come in a great variety:

Vela Pulsar
89 ms period

Crab Pulsar
67 ms period

PSR B1937+21
1.5 ms period

PSR B1937+21 is the second known fastest pulsar and is known as a millisecond pulsar because its period is < 10 ms.

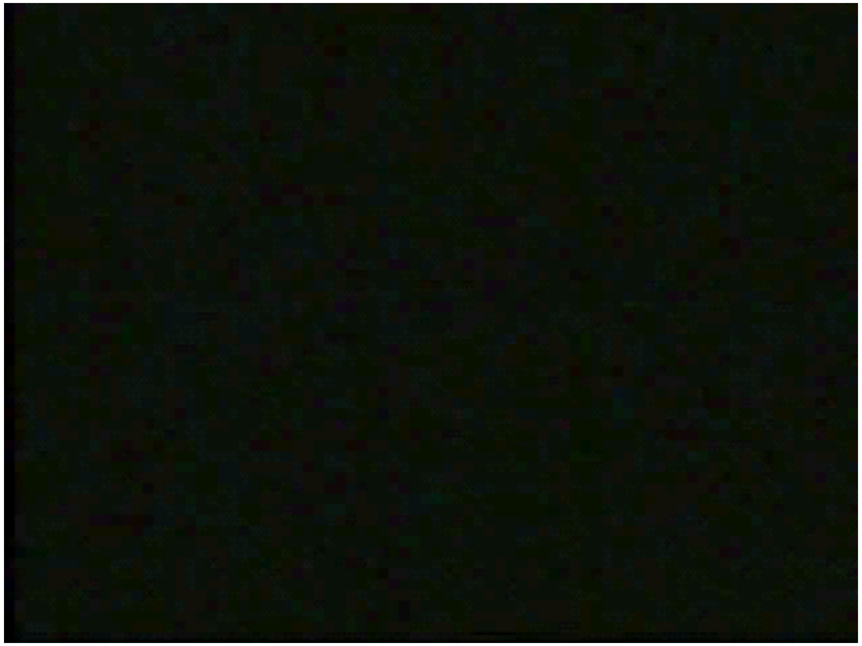
Millisecond pulsars

- Some pulsars spin nearly 1000 times a second
  - More massive than the Sun, only around 20 km across!
  - Equator of star moving at around 20% of the speed of light!
- As we saw with the Crab pulsar, pulsars lose energy over time and slow down
- So how do some of them end up spinning so fast?

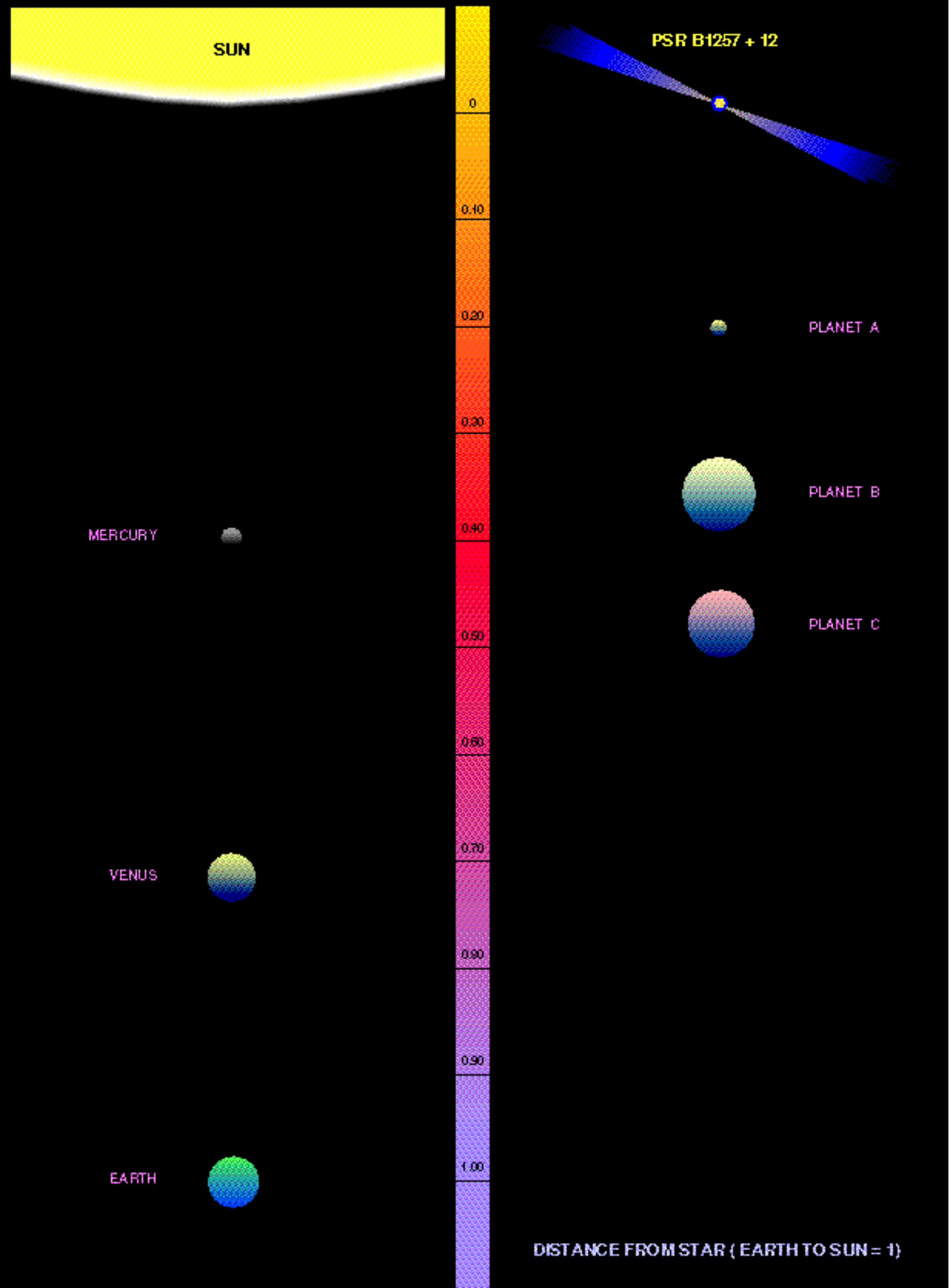
Millisecond pulsars

A neutron star accretes matter from a close binary companion, and the infalling matter makes the star spin faster

Millisecond Pulsars



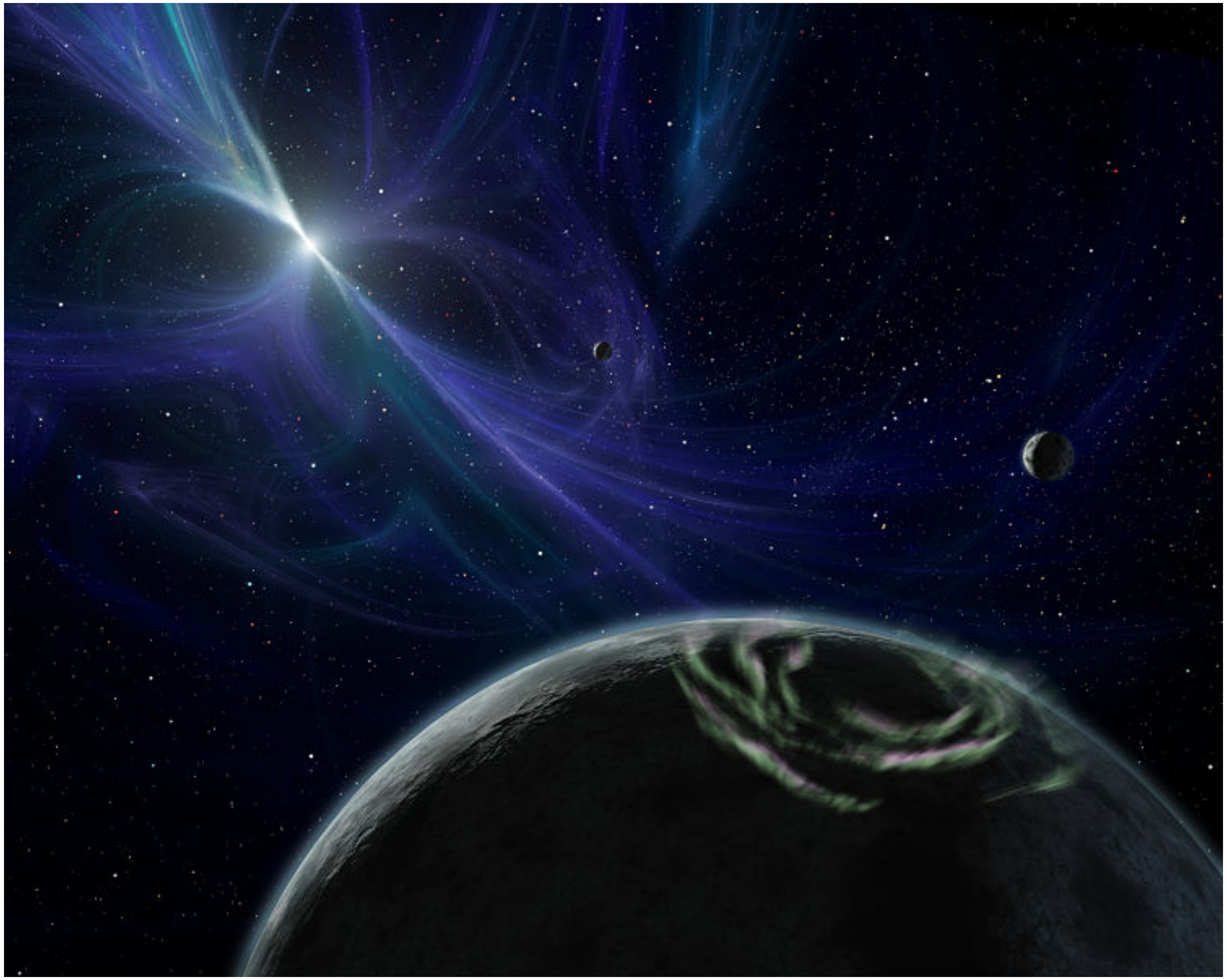
- Binary star system: one star becomes red giant, supernova, neutron star
- Neutron star then accretes matter from companion, spins faster, becomes millisecond pulsar



Pulsar Planets

- First planets discovered outside our solar system orbit a pulsar!
- Discovered by very precise timing of pulses with radio telescopes – orbit of planets causes changes in pulsations

Pulsar Planets



Artist's conception of planets around a pulsar

How do planets form around a pulsar? Do they survive supernova explosion, or form later?