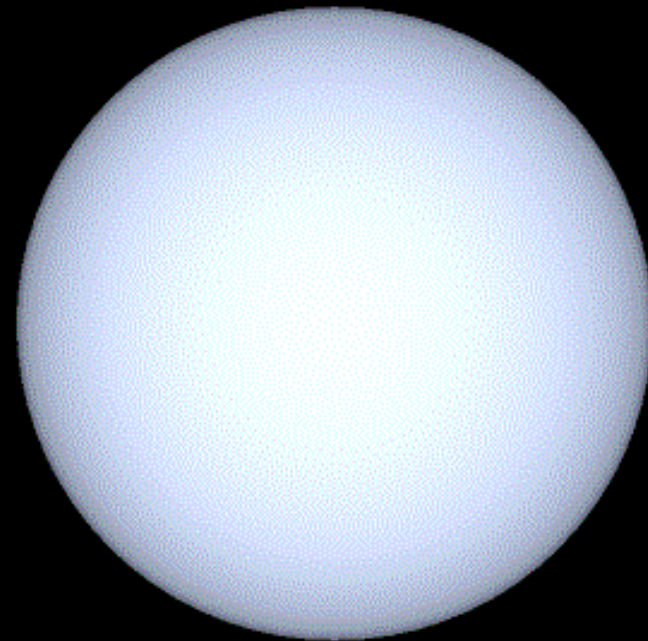


# White Dwarf Stars

- Low mass stars are unable to reach high enough temperatures to ignite elements heavier than carbon in their core become white dwarfs.
- Hot exposed core of an evolved low mass star.
- Supported by **electron degeneracy pressure**. This is the tendency of atoms to resist compression.
- The more massive a white dwarf, the **smaller** it is. A solar mass white dwarf is about the size of the Earth.
- As white dwarfs radiate energy, they become cooler and less luminous gradually fading into oblivion.

# White Dwarf

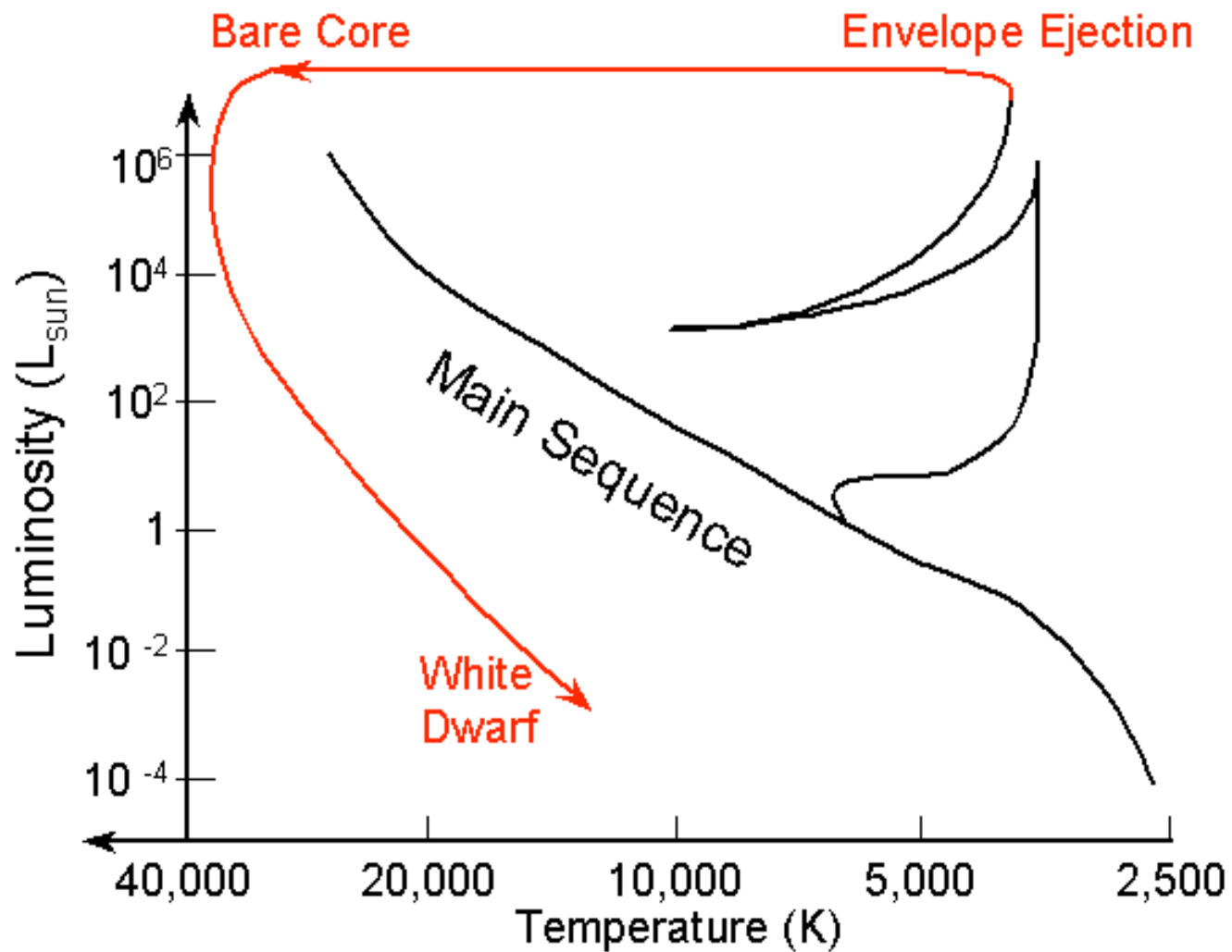


Sirius B

$M \approx 1.0 M_{\text{sun}}$

$R \approx 5800 \text{ km}$

# Planetary Nebula Phase



## clicker Quiz #25

The uniform expansion of the Universe can be characterized by which of the following?

- A. Absolutely everything in the Universe is expanding
- B. The Universe expanded faster than the speed of light in its very early phases
- C. The expansion is now slowing down because of the mutual gravitational attraction of galaxies in the Universe
- D. The effects of dark matter are dominant over the effects of dark energy today
- E. There is more anti-matter than matter in the Universe and this is known as baryon asymmetry

# Neutron Stars

- Neutron stars are stellar cores that are more massive than the **Chandrasekhar limit** ( $1.44 M_{\odot}$ ).
- They are held up against their own intense gravity by the tendency for neutrons to be incompressible (**neutron degeneracy pressure**).
- Their gravity is too strong to be supported by electron degeneracy pressure.
- The more massive a neutron star, the **smaller** it is.  
A  $1.44 M_{\odot}$  neutron star is only about 10 km in radius.

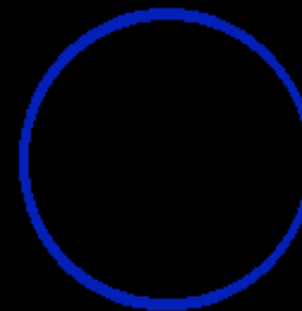
# Neutron Star vs. Black Hole



Manhattan  
(spaceimaging.com)



Neutron Star  
 $M=1.5 M_{\text{sun}}$   
 $R=10 \text{ km}$

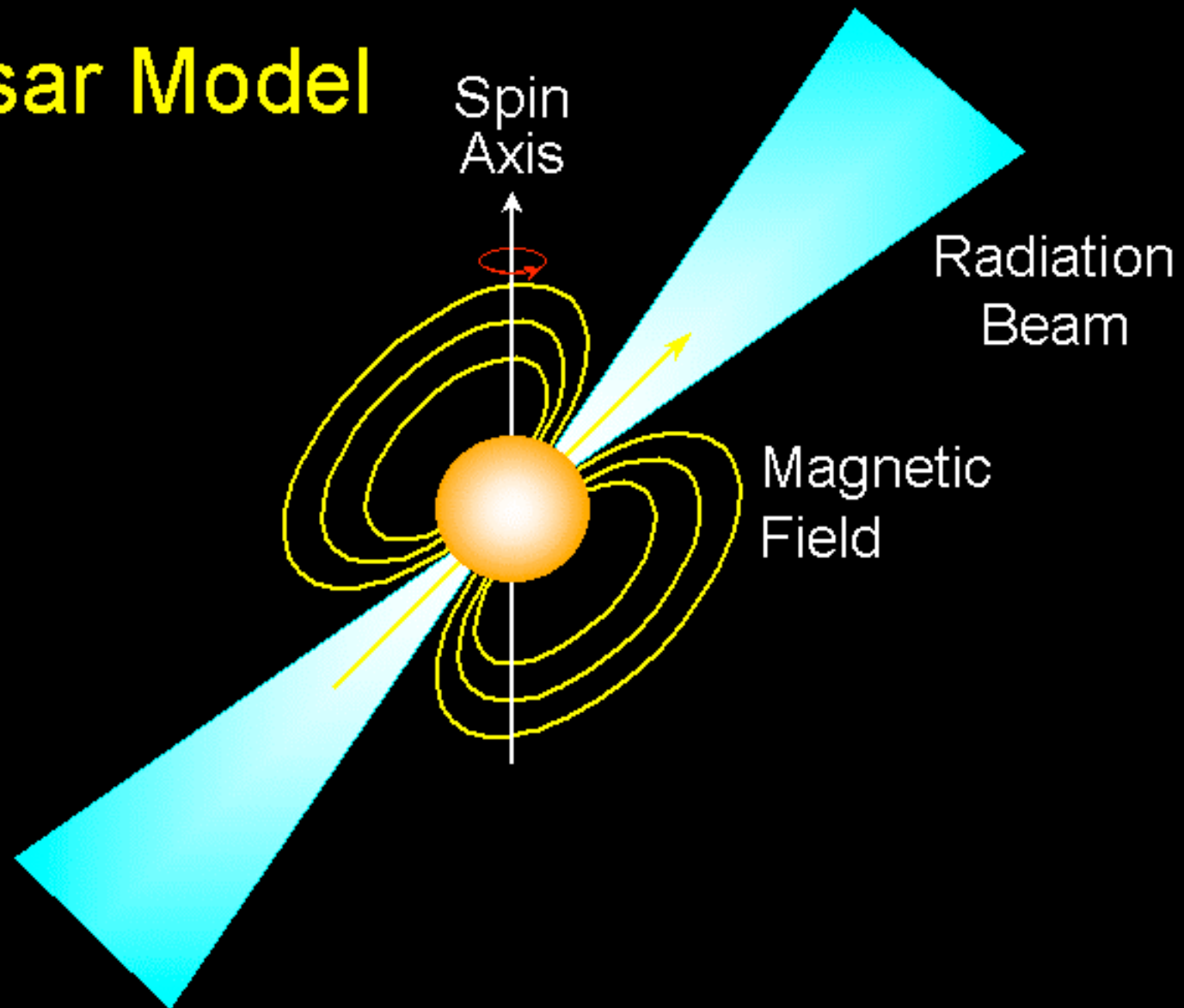


Black Hole  
 $M=1.5 M_{\text{sun}}$   
 $R_S=4.5 \text{ km}$

# Pulsars

- Neutron stars contain strong magnetic fields.
- Charged particles moving in the neutron stars magnetic field emit synchrotron radiation at radio wavelengths.
- Most neutron stars spin rapidly, slowing down with age. As the radio emission is beamed towards us periodically, we see pulses of radiation. Such objects are called **pulsars**. Not all neutron stars are observable as pulsars.
- Pulsars were discovered by Anthony Hewish and Jocelyn Bell.
- Recently, Joe Taylor and Russell Hulse won a Nobel Prize for their study of pulsars.
- These objects act as cosmic clocks and are useful for probing the dynamics of stars.

# Pulsar Model



# Black Holes

- Stellar cores that are more massive than about  $3 M_{\odot}$  have too strong a gravitational field to be supported by even neutron degeneracy pressure → **black holes**.
- The more massive a black hole, the larger its event horizon.
- Stellar mass black holes are detected via their X-ray radiation.
- A black hole accelerates its surrounding material (often gas from a binary companion) to very high speeds in an accretion disk.
- The heat generated by viscosity (friction) in this high speed gas produces X-rays. Some of the gas is ultimately swallowed by the black hole.

# Supernovae

- In the process of the core of a massive star collapsing under its own gravity to become a neutron star (or black hole), the material in the outer envelope may be ejected in a spectacular explosion known as a **supernova**.
- Stars that are more massive than about  $5 M_{\odot}$  explode as supernovae.
- The explosion is associated with the production of neutrinos and with lots of radiation at all wavelengths. A typical supernova is comparable in brightness to an entire galaxy!
- The supernova blast wave results in a tangle of interstellar gas and dust that is called a supernova remnant.

# Crab Nebula

Remnant of Supernova in 1054 AD



凡十一日没三年三月乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃速行經軒轅太星入太微垣掩右執法犯次將歷屏星西北凡七十五日入濁没明道元年六月乙巳出東北方近濁有芒彗至丁巳凡十三日没至和元年五月己丑出天關東南可數寸歲餘稍没熙寧二年六月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天因元祐六年十一月辛亥出參度中犯掩側星壬子犯九游星十二月癸酉入奎至七年三月辛亥乃散紹興八年五月守婁

東史志卷九

## clicker Quiz #26

In a Hubble tuning fork diagram that describes galaxy morphology, which of the following is **TRUE**?

- A. An SBc galaxy has more tightly wound spiral arms than an Sbc galaxy
- B. An Sbc galaxy has a “bar” shaped (i.e., linear) configuration of stars near its center
- C. An SBc galaxy has a smaller bulge-to-disk ratio than an Sbc galaxy
- D. An E7 galaxy is an elliptical galaxy with a perfectly circular shape
- E. An Sa galaxy has younger stars on average than an Sd galaxy

## clicker Quiz #27

Which of the following statements about our observable Universe is FALSE?

- A. It is shaped like a sphere
- B. We are at its center
- C. It has a radius of 14 billion light years
- D. It is infinite in size
- E. It is uniform on large scales