Announcements

- Exam #2: November 08
  - Covers Chaps: 5, S4, 14, 15, (16), 17, 18
Exam #2: November 08

- Covers Chaps: 5, S4, 14, 15, (16), 17, 18

Today:

- Review: the end state of a star
  - White dwarfs
  - Neutron stars
    - Origin
    - Features
  - Pulsars

Read: S3, Chap 18
Announcements

Exam #2: November 08

- Covers Chaps: 5, S4, 14, 15, (16), 17, 18

Today:

- Review: the end state of a star
  - White dwarfs
  - Neutron stars
    - Origin
    - Features
  - Pulsars

Questions?

Read: S3, Chap 18
**Stellar death: massive stars**

- Iron builds up in core until degeneracy pressure can no longer resist gravity
- Core degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos
- Neutrons collapse to the center
  - Forms a **neutron star**
  - Creates **supernova explosion**
- Energy and neutrons released in supernova explosion enable elements heavier than iron to form, including Au and U
Supernova remnant

- Energy released by collapse of core drives outer layers into space
- The Crab Nebula is the remnant of the supernova seen in A.D. 1054

Energy released by collapse of core drives outer layers into space

The Crab Nebula is the remnant of the supernova seen in A.D. 1054

Read: S3, Chap 18
A star’s mass determines its entire life story because mass determines its core temperature

High-mass stars with $> 8M_{\text{Sun}}$ have short lives, eventually becoming hot enough to make iron, and end in supernova explosions

Low-mass stars with $< 2M_{\text{Sun}}$ have long lives, never become hot enough to fuse carbon nuclei, and end as carbon white dwarfs

Very low-mass stars with $< 0.5M_{\text{Sun}}$ never become hot enough to fuse helium nuclei, and end as helium white dwarfs

Intermediate mass stars can make elements heavier than carbon but end as white dwarfs
1. Main Sequence: H fuses to He in core

2. Red Giant: H fuses to He in shell around He core

3. Helium Core Burning: He fuses to C in core, H fuses to He in shell

4. Double Shell Burning:

5. H and He both fuse in shells

6. *Planetary Nebula* leaves white dwarf behind
1. Main Sequence: H fuses to He in core

2. Red Supergiant: H fuses to He in shell around He core

3. Helium Core Burning:  
   He fuses to C in core while H fuses to He in shell

4. Multiple Shell Burning: Many elements fuse in shells

5. Supernova leaves neutron star behind
Reasons for life stages

- Core shrinks and heats until it’s hot enough for fusion
- Nuclei with larger charge require higher temperature for fusion
- Core thermostat is broken while core is not hot enough for fusion (shell burning)
- Core fusion can’t happen if degeneracy pressure keeps core from shrinking

Read: S3, Chap 18
White dwarfs are the remaining cores of dead stars

Electron degeneracy pressure supports them against gravity
White dwarfs cool off and grow dimmer with time

- White dwarf cooling
- White dwarfs
- White dwarf limit
- White dwarf binary
- Accretion disks
- Thought question
- Nova
- Thought question
- 2 types of SN
- Nova or supernova?
- Standard candles
- Neutron stars
- Discovery
- Crab pulsar
- Pulsars
- Pulsars are NS!
- Magnetic fields
- Thought question
- Binaries
- Spin up
- Thought question

Read: S3, Chap 18
White dwarfs with same mass as Sun are about same size as Earth

Higher mass white dwarfs are smaller (why?)
Quantum mechanics says that electrons must move faster as they are squeezed into a very small space.

As a white dwarf’s mass approaches $1.4M_{\text{Sun}}$, its electrons must move at nearly the speed of light.

Because nothing can move faster than light, a white dwarf cannot be more massive than $1.4M_{\text{Sun}}$, the white dwarf limit (or Chandrasekhar limit).
White dwarf binary

- Star that started with less mass gains mass from its companion
- Eventually the mass-losing star will become a white dwarf
- Next the companion star evolves, transferring mass to the white dwarf
- What happens next?
White dwarf binary

- Star that started with less mass gains mass from its companion
- Eventually the mass-losing star will become a white dwarf
- Next the companion star evolves, transferring mass to the white dwarf
- What happens next?
Star that started with less mass gains mass from its companion
Eventually the mass-losing star will become a white dwarf
Next the companion star evolves, transferring mass to the white dwarf
What happens next?
Accretion disks

- Mass falling toward a white dwarf from its close binary companion has some angular momentum
- The matter therefore orbits the white dwarf in an accretion disk
Accretion disks

Friction between orbiting rings of matter in the disk transfers angular momentum outward and causes the disk to heat up and glow.
What would gas in disk do if there were no friction?

(A) It would orbit indefinitely.

(B) It would eventually fall in.

(C) It would blow away.
Thought question

What would gas in disk do if there were no friction?

(A) It would orbit indefinitely.

(B) It would eventually fall in.

(C) It would blow away.
The temperature of accreted matter eventually becomes hot enough for hydrogen fusion.

Fusion begins suddenly and explosively, causing a nova.
The nova star system temporarily appears much brighter.
The explosion drives accreted matter out into space.

b Hubble Space Telescope image showing blobs of gas ejected from the nova T Pyxidis. The bright spot at the center of the blobs is the binary star system that generated the nova.
What happens to a white dwarf when it accretes enough matter to reach the $1.4 \, M_{\text{Sun}}$ limit?

(A) It explodes  
(B) It collapses into a neutron star  
(C) It gradually begins fusing carbon in its core
What happens to a white dwarf when it accretes enough matter to reach the $1.4 M_{\text{Sun}}$ limit?

(A) **It explodes**

(B) **It collapses into a neutron star**

(C) **It gradually begins fusing carbon in its core**
Two types of supernova

- **Massive star supernova**
  - Iron core of massive star reaches white dwarf limit and collapses into a neutron star, causing explosion

- **White dwarf supernova**
  - Carbon fusion suddenly begins as white dwarf in close binary system reaches white dwarf limit, causing total explosion

**Announcements**
- Stellar death
- Supernova remnant
- Role of Mass
- White dwarfs
- White dwarf limit
- White dwarf binary
- Accretion disks
- Thought question
- Nova
- Thought question

**Thought question**
- 2 types of SN
- Nova or supernova?
- Standard candles
- Neutron stars
- Discovery
- Crab pulsar
- Pulsars
- Pulsars are NS!
- Magnetic fields
- Thought question
- Binaries
- Spin up
- Thought question

Read: S3, Chap 18

10/30/12 – slide 19
Two types of supernova

- Light curves differ (how luminosity changes with time)
- Spectra differ (exploding white dwarfs don’t have hydrogen absorption lines)

Read: S3, Chap 18
Nova or supernova?

- Supernovae are MUCH MUCH more luminous!!! (about 10 thousand times)

- Nova: H to He fusion of a layer of accreted matter, white dwarf left intact

- Supernova: complete explosion of white dwarf, nothing left behind
Supernova as \textit{standard candles}

\textbf{Standard candle:} an object whose luminosity is known and reveals its distance by a brightness measurement

- Data suggests that white-dwarf light curves are always similar
- Good \textit{standard candles}

Read: S3, Chap 18
What is a neutron star?

- A neutron star is the ball of neutrons left behind by a massive-star supernova.
- Degeneracy pressure of neutrons supports a neutron star against gravity.

Read: S3, Chap 18
What is a neutron star?

- Electron degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos
- Roughly $10^{57}$ neutrinos created in the iron core as protons are converted to neutrons
- Neutrons collapse to the center, forming a neutron star
- Approx. 10 km in radius (size of Amherst!)
- *Strong* magnetic fields
Using a radio telescope in 1967, Jocelyn Bell noticed very regular pulses of radio emission coming from a single part of the sky. The pulses were coming from a spinning neutron star—a **pulsar**.
Crab pulsar

Announcements
Stellar death
Supernova remnant
Role of Mass
White dwarfs
White dwarf limit
White dwarf binary
Accretion disks
Thought question
Nova
Thought question
2 types of SN
Nova or supernova?
Standard candles
Neutron stars
Discovery

Crab pulsar
Pulsars
Pulsars are NS!
Magnetic fields
Thought question
Binaries
Spin up
Thought question

Read: S3, Chap 18
Crab pulsar

Observable in X-ray

- \( R = 10 \, \text{km} = 0.000014 \, R_{\odot} \)
- \( T = 10^6 \, \text{K} = 170 \, T_{\odot} \)
- Wien’s law \( \Rightarrow \) x-ray
Crab pulsar

Observable in X-ray

- $R = 10 \text{ km} = 0.000014 R_\odot$
- $T = 10^6 \text{ K} = 170 T_\odot$
- Wien’s law $\Rightarrow$ x-ray

How much luminosity?

$$L_n/L_\odot = \left( \frac{R_n}{R_\odot} \right)^2 \left( \frac{T_n}{T_\odot} \right)^4 = 0.2$$
A pulsar is a neutron star that beams radiation along a magnetic axis that is not aligned with the rotation axis.

The radiation beams sweep through space like lighthouse beams as the neutron star rotates.
Why pulsars must be neutron stars

- Circumference of NS $= 2\pi (\text{radius}) \approx 60 \text{ km}$
- Spin Rate of Fast Pulsars $\approx 1000$ cycles per second
- Surface Rotation Velocity $\approx 60,000 \text{ km/s}$
  - $\approx 20\%$ speed of light
  - $\approx$ escape velocity from NS!

Read: S3, Chap 18
Why pulsars must be neutron stars

- Circumference of NS = $2\pi(r)$ ≈ 60 km
- Spin Rate of Fast Pulsars ≈ 1000 cycles per second
- Surface Rotation Velocity ≈ 60,000 km/s
  - ≈ 20% speed of light
  - ≈ escape velocity from NS!

Pulsars are NS!
Why pulsars must be neutron stars

- Circumference of NS = $2\pi r \approx 60$ km
- Spin Rate of Fast Pulsars $\approx 1000$ cycles per second
- Surface Rotation Velocity $\approx 60,000$ km/s
  - $\approx 20\%$ speed of light
  - $\approx$ escape velocity from NS!

Read: S3, Chap 18
Why pulsars must be neutron stars

- Circumference of NS $= 2\pi (radius) \approx 60$ km
- Spin Rate of Fast Pulsars $\approx 1000$ cycles per second
- Surface Rotation Velocity $\approx 60,000$ km/s
  - $\approx 20\%$ speed of light
  - $\approx$ escape velocity from NS!

Anything else would be torn to pieces!
Magnetic fields: review

Magnetic fields are produced by electric currents

- Currents in wires
- Currents caused by electrons in atomic orbits

A \textit{permanent magnet} is a collection of atoms whose internal currents are lined up in a single direction on average

A magnet will tend to try to align itself with a magnetic field

We call that direction a \textit{field line}
How magnetic fields work

- **Current in a straight wire**
- **The magnetic field lines are concentric circles**

![Magnetic field diagram](image)

Read: S3, Chap 18
How magnetic fields work

- Electric current in a circular loop
- Magnetic field concentrated in the center of the loop
- Stacking multiple loops concentrates the field; solenoid or electromagnet

Electric current in a circular loop

Magnetic field concentrated in the center of the loop

Stacking multiple loops concentrates the field; solenoid or electromagnet

[Image of magnetic field in a loop]

Read: S3, Chap 18
How magnetic fields work

- Electric current in a circular loop
- Magnetic field concentrated in the center of the loop
- Stacking multiple loops concentrates the field; solenoid or electromagnet

The magnetic field is concentrated into a nearly uniform field in the center of a long solenoid. The field outside is weak and divergent.

Magnetic fields

Thought question

Spin up

Thought question

Read: S3, Chap 18
How magnetic fields work

- Electric current in a circular loop
- Magnetic field concentrated in the center of the loop
- Stacking multiple loops concentrates the field; solenoid or electromagnet

Read: S3, Chap 18
Circulating electric currents in the Earth’s molten metallic core generate a magnetic field

Current loop

Similar in Sun
Announcements
Stellar death
Supernova remnant
Role of Mass
White dwarfs
White dwarf limit
White dwarf binary
Accretion disks
Thought question
Nova
Thought question
2 types of SN
Nova or supernova?
Standard candles
Neutron stars
Discovery
Crab pulsar
Pulsars
Pulsars are NS!

- **Magnetic fields**
- Thought question
- Binaries
- Spin up
- Thought question

---

**Rapidly rotating:**

- Frequency: 1000 rotations/second
  (1 rotation/month for the Sun)
- Due to conservation of ang mom (recall skater)
Magnetic fields in neutron stars

- **Rapidly rotating:**
  - Frequency: 1000 rotations/second
    - (1 rotation/month for the Sun)
  - Due to conservation of ang mom (recall skater)

- **Strongly magnetized:**
  - $10^{12}$ Gauss (1 and 0.5 Gauss for the Sun & Earth)
  - Why? Magnetic field lines are conserved and compressed as star collapses.

---

Read: S3, Chap 18
Magnetic fields in neutron stars

- **Rapidly rotating:**
  - Frequency: 1000 rotations/second (1 rotation/month for the Sun)
  - Due to conservation of ang mom (recall skater)

- **Strongly magnetized:**
  - $10^{12}$ Gauss (1 and 0.5 Gauss for the Sun & Earth)
  - Why? Magnetic field lines are conserved and compressed as star collapses.

- **Very hot:**
  - $10^6$ K at surface after collapse (5800 K for Sun)

---

Read: S3, Chap 18
Thought question

Could there be neutron stars that appear as pulsars to other civilizations but not to us?

(A) Yes
(B) No
Could there be neutron stars that appear as pulsars to other civilizations but not to us?

(A) Yes

(B) No
Could there be neutron stars that appear as pulsars to other civilizations but not to us?

(A) Yes

(B) No
Why do some neutron stars rotate much more rapidly than 1000 times per second?
Matter falling toward a neutron star forms an accretion disk, just as in a white-dwarf binary.
Accretion of matter adds angular momentum to a neutron star, increasing its spin.
According to conservation of angular momentum, what would happen if a star orbiting in a direction opposite the neutron star rotation fell onto a neutron star?

(A) The neutron stars rotation would speed up

(B) The neutron stars rotation would slow down

(C) Nothing, the directions would cancel each other out
According to conservation of angular momentum, what would happen if a star orbiting in a direction opposite the neutron star rotation fell onto a neutron star?

(A) The neutron stars rotation would speed up

(B) The neutron stars rotation would slow down

(C) Nothing, the directions would cancel each other out