Assignments

• For Mon. Nov. 02
  – **Read Ch. 15** + **Do** Online Exercise 12 ("Black holes" tutorial)

– No lab next week: Tues. UD holiday for election.

– Video of Jocelyn Bell Burnell colloquium on Wed. now available via Canvas link
Life Track of a Sun-Like Star
How do high-mass stars make the elements necessary for life?
Advanced Nuclear Burning

Core temperatures in stars with $>8M_{\text{Sun}}$ allow fusion of elements as heavy as iron.
Advanced reactions in stars make elements such as Si, S, Ca, and Fe.
Multiple Shell Burning

- Advanced nuclear burning proceeds in a series of nested shells.
Iron is a dead end for fusion because nuclear reactions involving iron do not release energy. (Fe has lowest mass per nuclear particle.)
Evidence for helium capture:

Higher abundances of elements with even numbers of protons.
What element has the most stable nucleus, meaning either its fission or fusion would require adding energy?

A. Hydrogen
B. Helium
C. Carbon
D. Iron
E. Uranium
What element has the most stable nucleus, meaning either its fission or fusion would require adding energy?

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How does a high-mass star die?
Supernova Explosion

- Core degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos.

- Neutrons collapse to the center, forming a neutron star.
Supernova Remnant

- Energy released by the collapse of the core drives outer layers into space.

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

- Big Bang fusion
- Dying low-mass stars
- Exploding massive stars
- Cosmic ray fission
- Merging neutron stars
- Exploding white dwarfs
How are the lives of stars with close companions different?
Thought Question

The binary star Algol consists of a $3.7 M_{\text{Sun}}$ main-sequence star and a $0.8 M_{\text{Sun}}$ subgiant star.

What’s strange about this pairing?

How did it come about?
Stars in Algol are close enough that matter can flow from the subgiant onto the main-sequence star.
The star that is now a subgiant was originally more massive.

As it reached the end of its life and started to grow, it began to transfer mass to its companion (mass exchange).

Now the companion star is more massive.
Chapter 14
The Bizarre Stellar Graveyard
White Dwarfs

- White dwarfs are the remaining cores of dead low-mass stars.

- Electron degeneracy pressure supports them against gravity.
White dwarfs cool off and grow dimmer with time.
White dwarfs with the same mass as the Sun are about the same size as Earth.

Higher-mass white dwarfs are smaller.
The White Dwarf Limit

• 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 (also known as the Chandrasekhar limit).
What can happen to a white dwarf in a close binary system?
A star that started with less mass gains mass from its companion.

Eventually, the mass-losing star will become a 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.
Nova

• The temperature of accreted matter eventually becomes hot enough for hydrogen fusion.

• Fusion begins suddenly and explosively, causing a nova.
Nova

- The nova star system temporarily appears much brighter.

- The explosion drives accreted matter out into space.
What happens to a white dwarf when it accretes enough matter to reach the $1.4M_{\text{Sun}}$ limit?

A. It explodes.
B. It collapses into a neutron star.
C. It gradually begins fusing carbon in its core.
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Two Types of Supernova

**Massive star supernova:**

Iron core of massive star reaches white dwarf limit and collapses into a neutron star, causing an explosion.

**White dwarf supernova:**

Carbon fusion suddenly begins as white dwarf in close binary system reaches white dwarf limit, causing a total explosion.
One way to tell supernova types apart is with a light curve showing how luminosity changes with time.
Nova or Supernova?

- Supernovae are MUCH MUCH more luminous than novae (about 10 million 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 Types:
Massive Star or White Dwarf?

• Light curves differ

• Spectra differ (exploding white dwarfs don’t have hydrogen absorption lines)
What is a neutron star?
A neutron star is the ball of neutrons left behind by a massive-star supernova.

The degeneracy pressure of neutrons supports a neutron star against gravity.
Electron degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos.

Neutrons collapse to the center, forming a *neutron star*. 
A neutron star is about the same size as a small city.
Discovery of Neutron Stars

- 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.

Pulses are precisely 1.337301 seconds apart.

![Graph showing pulsations over time](image)
Pulsars

A pulsar is a neutron star that beams radiation along a magnetic axis that is not aligned with the rotation axis.
Pulsar at center of Crab Nebula pulses 30 times per second
X rays

Visible light

Crab Nebula Movie-CHANDRA
Pulsars

The radiation beams sweep through space like lighthouse beams as the neutron star rotates.
Why Pulsars Must Be Neutron Stars

Circumference of Neutron Star = \(2\pi \text{ (radius)} \sim 60 \text{ km}\)

Spin Rate of Fast Pulsars \(\sim 1000 \text{ cycles per second}\)

Surface Rotation Velocity \(\sim 60,000 \text{ km/s}\)
\(\sim 20\% \text{ speed of light}\)
\(\sim \text{escape velocity from NS}\)

*Anything else would be torn to pieces!*
Pulsars spin fast because the core’s spin speeds up as it collapses into a neutron star.

Conservation of angular momentum
Thought Question

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

A. Yes
B. No
Thought Question

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

A. Yes
B. No
What can happen to a neutron star in a close binary system?
Matter falling toward a neutron star forms an accretion disk, just as in a white dwarf binary.
Accreting matter adds angular momentum to a neutron star, increasing its spin.

Episodes of fusion on the surface lead to X-ray bursts.
X-Ray Bursts

- Matter accreting onto a neutron star can eventually become hot enough for helium to fuse.

- The sudden onset of fusion produces a burst of X rays.
Neutron Star Limit

- Quantum mechanics says that neutrons in the same place cannot be in the same state.

- Neutron degeneracy pressure can no longer support a neutron star against gravity if its mass exceeds about \(3M_{\text{Sun}}\).
13.3 Black Holes: Gravity’s Ultimate Victory

Our goals for learning:

- What is a black hole?
- What would it be like to visit a black hole?
- Do black holes really exist?
What is a black hole?
What is a black hole?

A black hole is an object whose gravity is so powerful that not even light can escape it.

Some massive star supernovae can make a black hole if enough mass falls onto the core.
Remnant mass:

\[ < 1.3 \, M_{\text{sun}} \Rightarrow \text{white dwarf (electron degen)} \]
\[ 1.3-3 \, M_{\text{sun}} \Rightarrow \text{neutron star (neutron degen)} \]
\[ >3 \, M_{\text{sun}} \Rightarrow \text{black hole (singularity)} \]

Stellar mass:

\[ < 8 \, M_{\text{sun}} \Rightarrow \text{Planetary nebula} \Rightarrow \text{white dwarf} \]
\[ 8-20 \, M_{\text{sun}} \Rightarrow \text{Supernova} \Rightarrow \text{neutron star} \]
\[ > 20 \, M_{\text{sun}} \Rightarrow \text{Supernova} \Rightarrow \text{black hole} \]
Black hole escape velocity

\[
\text{initial kinetic energy} = \text{final gravitational potential energy}
\]
\[
\frac{(\text{escape velocity})^2}{2} = \frac{G (\text{mass})}{(\text{radius})}
\]

Black hole has escape velocity = speed of light \( c \)

\[
R_{bh} = 3 \text{ km} \frac{M}{M_{\text{Sun}}}
\]
The event horizon of a $3M_{\text{Sun}}$ black hole is also about as big as a small city.
Surface of a Black Hole

- The “surface” of a black hole is the radius at which the escape velocity equals the speed of light.

- This spherical surface is known as the event horizon.

- The radius of the event horizon is known as the Schwarzschild radius.

\[ R_{bh} = 3 \, \text{km} \frac{M}{M_{\text{Sun}}} \]
What would be the radius of a Black Hole with a mass of 10 Msun?

A. 3 km
B. 30 km
C. 10 Rsun
D. 30 Rsun
E. 1/10 Rsun
A black hole’s mass strongly warps space and time in the vicinity of the event horizon.
Thought Question

How does the radius of the event horizon change when you add mass to a black hole?

A. It increases.
B. It decreases.
C. It stays the same.
Thought Question

How does the radius of the event horizon change when you add mass to a black hole?

A. It increases.
B. It decreases.
C. It stays the same.
What would it be like to visit a black hole?
If the Sun shrank into a black hole, its gravity would be different only near the event horizon.

Black holes don’t suck!
Tidal forces near the event horizon of a $3M_{\text{Sun}}$ black hole would be lethal to humans.

Tidal forces would be gentler near a supermassive black hole because its radius is much bigger.
Do black holes really exist?
Some X-ray binaries contain compact objects of mass exceeding $3M_{\text{Sun}}$ that are likely to be black holes.
One famous X-ray binary with a likely black hole is in the constellation Cygnus.
Masses in the Stellar Graveyard

in Solar Masses

LIGO-Virgo Black Holes

X-ray Binary Black Holes

Known Neutron Stars

LIGO-Virgo Neutron Stars