Study Points

- What is a black hole?
- What is the end of life for low/average mass stars, for high mass stars, and for very high mass stars?
- What is the simplified statement from the Special Theory of Relativity? Has it been tested? Has it been disproved?
- According to Newton, describe how gravitational force depends on mass and distance.
- How does the universe make a black hole?
- According to Einstein, what is gravity? Explain why one mass exerts a force on a second mass. (from the General Theory of Relativity)
- Describe the basic structure of a black hole. Describe event horizon. Describe singularity.
- What is an accretion disk?
- List at least three ways astronomers detect black holes.
Black Holes

- What is a black hole?
- Special Theory of Relativity
- General Theory of Relativity
- What is gravity? How can it effect light?
- How to make a black hole
- Structure (Singularity and Event Horizon)
- How to find a black hole
What is a Black Hole?
What is a Black Hole?

- A black hole is a mass condensed so tightly that nothing, not even light, can escape from its gravitational effects.*
  - Collapsed mass > 3 $M_\odot$
  - Nothing can escape

How can that be?
Mass Of The Star Determines Its Fate

The fate of a star depends on its mass (size not to scale).

- Low to Average Mass Star
  - Mass < 1.4 $M_{\odot}$
- Large Mass Star
- Very Large Mass Star
  - 1.4 $M_{\odot}$ < Mass < 3 $M_{\odot}$
  - Possibly 3 to 8 $M_{\odot}$
  - Mass > 3 $M_{\odot}$
    - Always for > 8 $M_{\odot}$

Know This and the End of Life State (don’t need to know mass numbers)
Special Theory of Relativity
(simplified)

Nothing in the universe can travel faster than the speed of light*

SPEED LIMIT
300,000 km/s

It’s not just the limit, it’s the law!
Special Theory of Relativity
(simplified)

Tested many times in many ways.*

Never disproven.*

http://www.exphy.uni-duesseldorf.de/ResearchInst/FundPhys.html

http://math.ucr.edu/home/baez/physics/Relativity/SR/experiments.html

SPEED LIMIT

300,000 km/s
Newton & Gravity

• Weakness near speed of light

• Einstein proposed additional explanation
Gravity is a contributing factor in nearly 73 percent of all accidents involving falling objects. And yet the so-called ‘federal government’ does nothing!
Newton’s Law of Universal Gravitation

- Every mass attracts every other mass.*
- Bigger masses $\Rightarrow$ bigger force of gravity*
- Bigger separation (distance) $\Rightarrow$ smaller force of gravity*

$$F = G \frac{mM}{D^2}$$
Launch Speed

$V_{\text{Launch}} = 0$

Demo Here: http://spaceplace.nasa.gov/how-orbits-work/en/
Escape Speed

Earth

\[ V_{\text{esc}} = \sqrt{\frac{2GM}{r}} \]

\[ V_{\text{esc}} = \sim 10 \text{ km/s} \]
Escape Speed

\[ V_{esc} = \sqrt{\frac{2GM}{r}} \]

\[ V_{esc} = \sim 600 \text{ km/s} \]
The escape speed (or escape velocity) for a given object is calculated using the formula:

$$V_{esc} = \sqrt{\frac{2GM}{r}}$$

where:
- $V_{esc}$ is the escape speed,
- $G$ is the gravitational constant,
- $M$ is the mass of the object,
- $r$ is the radius of the object.

Given a mass of $3M_\odot$ (nearly 3 times the mass of the Sun) and a radius similar to the Moon, the escape speed $V_{esc}$ is approximately $15,000$ km/s.
Escape Speed

2 – 3 MILES

$V_{esc} = \sqrt{\frac{2GM}{r}}$

$V_{esc} = 300,000 \text{ km/s}$
SPEED LIMIT
300,000 km/s
Nothing Escapes.... Not even light!

I keep hitting 'escape,' but I'm still here.
How can you crush 3 $M_\odot$ into 2-3 miles?

Big Supernovas, called Hypernovas

Hypernova – explosion from very massive star collapsing into a black hole*
(how the universe makes a black hole)
Mass Of The Star Determines Its Fate

- Low to Average Mass Star
  - Large Mass Star
  - Very Large Mass Star

The fate of a star depends on its mass (size not to scale)

- mass < 1.4 M☉ → White Dwarf
- 1.4 M☉ < mass < 3 M☉ → Neutron Star
  - Possibly 3 to 8 M☉
- mass > 3 M☉ → Black Hole
  - Always for > 8 M☉

Know This and the End of Life State (don’t need to know mass numbers)
Mass Of The Star Determines Its Fate

Red Giant collapses & creates White Dwarf

- Low to Average Mass Star
- Large Mass Star
- Very Large Mass Star

Supernova II creates neutron star

sometimes Supernova Ia after white dwarf explodes

Hypernova creates black hole*

The fate of a star depends on its mass (size not to scale)
How can you crush $3 \, M_\odot$ into 2-3 miles?

Hypernovas or Lots of gas condensing

Why doesn’t light escape from a black hole?

(or how can gravity pull on light?)
General Theory of Relativity

Gravity is

Einstein
General Theory of Relativity (simplified)

Gravity is the curvature of space-time*

This is why masses attract!*
Mass deforms space-time.

Sheet demo

http://einstein.stanford.edu/content/education/EducatorsGuide/Page7.html
A second mass simply follows the curvature of space-time.

Coin wishing well demo

http://einstein.stanford.edu/content/education/EducatorsGuide/Page7.html
Both mass and light follow the curvature of space-time.
Space is something!

Light travels at 300,000 km/s in it.

Masses warp it.
Has General Relativity been tested?

Many times – all positive
Tests of General Relativity

• Mercury’s orbit perihelion precession
• Light bent by gravity
  – Solar Eclipse in 1919
Tests of General Relativity

• Mercury’s orbit perihelion precession
• Light bent by gravity
  – Solar Eclipse in 1919
  – Gravitational lensing - focusing of light from distant galaxy or quasar by an intervening galaxy; produces multiple images
  • Quasar – energetic black hole core of a distant galaxy
Einstein’s Cross
quasar behind the center of a massive galaxy and displayed as a clover leaf
http://apod.nasa.gov/apod/ap130102.html
Tests of General Relativity

• Mercury’s orbit perihelion precession

• Light bent by gravity
  – Eclipse in 1919
  – Gravitational lensing - focusing of light from distant galaxy or quasar by an intervening galaxy; produces multiple images
    • Quasar – energetic core of a distant galaxy

• Gravitational redshift
  – Lengthening of photon wavelength due to leaving a gravity field
Tests of General Relativity

- **Gravity Probe A (1976)**
  - Clocks move slower in Earth’s orbit, so you gain more time in space

- **Radio waves sent to Viking, Mars lander (1979)**
  - Time passes slower with higher gravity

https://en.wikipedia.org/wiki/Gravitational_time_dilation#media/File:Orbit_times.svg
https://mars.nasa.gov/programmissions/missions/past/viking/
Tests of General Relativity

• Gravity Probe A (1976)
• Radio waves sent to Viking, Mars lander (1979)
• Radio waves sent to Cassini, Saturn orbiting spacecraft, on other side of Sun (2003)
  – Verified curvature of space-time around the Sun

Tests of General Relativity

• Gravity Probe A (1976)
• Radio waves sent to Viking, Mars lander (1979)
• Radio waves sent to Cassini, Saturn orbiting spacecraft, on other side of Sun (2003)
• Gravity Probe B, in Earth orbit (2011)
  – space-time is curved and twisted
A word about General Relativity

**Weak field case**
- inside solar system

**Strong field case**
- outside solar system
What happens inside a black hole?
What happens inside a black hole?

As masses get closer, gravity gets stronger!

So the tighter you cram in mass, the stronger gravity gets!
What happens inside a black hole?

Once $3 \, M_\odot$ is crammed into 2-3 miles, no known force can stop further collapse.

All the mass collapses into a point of zero size called the singularity!*
Singularity? All the mass is in 0 size?

Signal that our theories need some modification.

Quantum Gravity?
What is the structure of a Black Hole?

Singularity*

All mass condensed here
0 size?
Infinite density?

Event Horizon*

Limit!!!!!!!

• Inside here: Escape speed is greater than the speed of light*
• Nothing can escape inside the event horizon.*
How massive are black holes?

1. Stellar mass
   (3-20 $M_{\odot}$)

2. Mid-mass
   (100-10,000 $M_{\odot}$)

3. Supermassive
   (Hundreds of Thousands to Billions $M_{\odot}$)
If a black hole is black, how do you “see” one?

10 Ways to Find Black Holes*

1. Binary “stars”
   – Star and black hole orbiting each other.
   – Look for wobble in the spectral lines of a visible star.
Example of a binary system: Cygnus X-1 Star & Black Hole

Super Blue Giant: Wobble of spectral lines Indicate an unseen companion $\sim 9M_\odot$

http://imagine.gsfc.nasa.gov/docs/science/know_l2/black_holes.html
10 Ways to Find Black Holes*

1. Binary “stars”

2. Accretion Disk of gas, orbiting just outside the event horizon*
   - Disk of X-Rays or UV from colliding matter at event horizon*
Example of a binary system: Cygnus X-1 Star & Black Hole

Cygnus X-1
Dark companion ~9 $M_\odot$ → Strong X-ray source

http://imagine.gsfc.nasa.gov/docs/science/know_l2/black_holes.html
Bloated star

Black Hole

Accretion Disk

NGC 4261

X-rays!!!

Visible Image

http://chandra.harvard.edu/photo/2003/ngc4261/ngc4261_scale.jpg
Scientists Spot Doughnut-Shaped Cloud With a Black Hole Filling

2004 Artist’s Rendition (not actual image)

10 Ways to Find Black Holes

1. Binary “stars”
2. Accretion Disk of X-rays or UV
3. Jets
   - Perpendicular to accretion disk
   - Radio waves
Artist’s Rendition
http://apod.nasa.gov/apod/ap130312.html
Core of Galaxy NGC 4261
Hubble Space Telescope
Wide Field / Planetary Camera

Ground-Based Optical/Radio Image

HST Image of a Gas and Dust Disk

Black Hole Jets

http://www.nasa.gov/centers/goddard/images/content/96922main_ngc4261_hubble_m.jpg
X-Rays in Accretion Disk & Radio Jets of Black Hole in NGC4696

Composite Image:

- X-ray in red
- Radio in blue
- Infrared in green

M87 galaxy center

Black Hole Jet

Centaurus A Galaxy M83

55 million solar mass black hole, about 12 million LY away

https://www.eso.org/public/images/eso0903a/
Hercules A Galaxy (small center bright object) with huge Plasma Radio Jets

1000 times the size of the Milky Way with a black hole at the center 1000 times our black hole at the center of the Milky Way

Hubble image https://apod.nasa.gov/apod/ap121205.html
10 Ways to Find Black Holes

1. Binary “stars”
2. Accretion Disk
3. Perpendicular Jets
4. Gas & dust swirling around black hole (much further out than the accretion disk)
   - Doppler Effect to measure speed
   - Kepler’s Laws to calculate mass
Galaxy M84 Nucleus

Hubble Space Telescope

WFPC2

STIS

Gas & Dust

https://www.spacetelescope.org/images/opro9712a/
Sombrero Galaxy

~100,000 ly

~100 billion stars
Inner 2000 LY Contain 1 billion $M_\odot$

With swirling gas & dust further out

Sombrero Galaxy
Milky Way Galaxy

Toward Sagittarius is our SMBH (super massive black hole)
Milky Way Galaxy

Toward Sagittarius is our SMBH (super massive black hole) named Sagittarius A*
Swirling gasses imply ~4 million $M_\odot$ at center

Milky Way Galaxy

Toward Sagittarius is our SMBH (super massive black hole)
Andromeda Galaxy (similar to Milky Way)

Inner 10 LY contain 20 million $M_\odot$
10 Ways to Find Black Holes

1. Binary “stars”
2. Accretion Disk
3. Perpendicular Jets
4. Gas & dust swirling around black hole
5. Star near center of Milky Way
   - Using Doppler and Kepler to verify
Star near center of Milky Way
Watch video clip of S2 star orbit around a black hole at Milky Way center:

http://www.youtube.com/watch?v=u_gggKHvfGw

Article here:

https://www.universetoday.com/136740/stars-orbiting-supermassive-black-hole-show-einstein-right/
Star S2 near central black hole in Milky Way

- S2 orbit is 15 years at 5000 km/s
- Implies central black hole of 3.7 million $M_\odot$
10 Ways to Find Black Holes

1. Binary “stars”
2. Accretion Disk
3. Perpendicular Jets
4. Gas & dust swirling around black hole
5. Star near center of Milky Way
6. Binary black holes merging
   2 Black Holes on right
   25,000 ly separation
   Moving at 1200 km/s (tails)
Binary Black Holes Merging

Watch Animation:
http://chandra.harvard.edu/photo/2006/a400/animations.html
10 Ways to Find Black Holes

1. Binary “stars”
2. Accretion Disk
3. Perpendicular Jets
4. Gas & dust swirling around black hole
5. Star near center of Milky Way
6. Binary black holes merging
7. Clumps of hot iron gas orbiting at 30,000 km/s

10 Ways to Find Black Holes

1. Binary “stars”
2. Accretion Disk
3. Perpendicular Jets
4. Gas & dust swirling around black hole
5. Star near center of Milky Way
6. Binary black holes merging
7. Clumps of hot iron gas
8. Star ripped apart by black hole

http://chandra.harvard.edu/photo/2004/rxj1242/
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9. **Space-time dragging & twisting**

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9. Space-time dragging & twisting
10. Gravitational Waves from black holes merging

LIGO instruments sensed gravitational waves coming from 2 black holes merging in 2015

http://www.space.com/17661-theory-general-relativity.html
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Simulations of Black Holes

There are no actual pictures of black holes.

1979 image created by Jena Pierre Luminet
https://www.engadget.com/2017/04/19/black-hole-image-jean-pierre-luminet/

2014 image created for the movie Interstellar
BIG NEWS:
First Image of a Black Hole

- Released last spring, April 10, 2019
- At the center of M87, Virgo galaxy

Watch: https://www.youtube.com/watch?v=S_GVbuddri8 (5:28)
Black Hole Power

- NASA Accidentally Discovered Giant Black Holes
- Watch at home: https://www.youtube.com/watch?v=lfG2-FFL6fY