Chapter 10
Our Star

X-ray visible

Radius:
6.9 \times 10^8 \text{ m}
(109 times Earth)

Mass:
2 \times 10^{30} \text{ kg}
(300,000 Earths)

Luminosity:
3.8 \times 10^{26} \text{ watts}
(more than our entire world uses in 1 year!)

Why does the Sun shine?
Is it on FIRE?

- Chemical Energy Content (J)
- Luminosity (J/s = W) ~ 10,000 years

...NO

Is it on FIRE? ... NO

- Chemical Energy Content ~ 10,000 years
- Luminosity
Is it CONTRACTING?

Gravitational Potential Energy

Luminosity

~ 25 million years

Is it CONTRACTING? ... NO

Gravitational Potential Energy

Luminosity

~ 25 million years
It is powered by NUCLEAR ENERGY!

Nuclear Potential Energy (core) ~ 10 billion years
Luminosity

- Nuclear reactions generate the Sun’s heat
- But they require very high temperatures to begin with
- Where do those temperatures come from?
- They come from GRAVITY!

• The tremendous weight of the Sun’s upper layers compresses its interior
• The intense compression of its fluid interior generates temperatures >10^7 K in the innermost core
• And that’s where the nuclear reactions are
The Sun's Structure

Gravitational Equilibrium
- The compression inside the Sun generates temperatures that allow fusion.
- The fusion reactions in turn generate outward pressure that balances the inward crush of gravity.
- The Sun is in a balance between outward pressure from fusion and inward pressure from gravity.
- This is called **gravitational equilibrium**.

Solar wind:
A flow of charged particles from the surface of the Sun.
Core:
Energy generated by nuclear fusion
Temps to 15 million K

Radiation zone:
Energy transported upward by photons
Temps to 10 million K

Convection zone:
Energy transported upward by rising hot gas
Temps to 1 million K

Chromosphere:
Visible surface of Sun
Temps ~ 6,000 K

Corona:
Outermost layer of solar atmosphere
Temps ~ 1 million K

How does the Sun produce energy?

Two kinds of nuclear reactions

Big nucleus splits into smaller pieces
(Nuclear power plants)

Small nuclei stick together to make a bigger one
(Sun, stars)
• This is how the Sun produces energy
• Four hydrogen nuclei (protons) fuse into one helium nucleus.
• The protons have to touch for this to happen
• For them to touch requires temperatures > 10,000,000 K
• Why do you think it has to be so hot for them to touch?
• It’s because of their charge

• Why do high speeds require high temperatures?

\[ KE_{\text{avg}} = \frac{1}{2} kT \]

• This is a summary of the way the Sun produces its energy
• The actual reaction is more complex
• This is the complete reaction, called the proton–proton chain
• It’s interesting how long each of these steps takes...

\[ \text{IN} \\
4 \text{ protons} \\
\text{OUT} \\
\text{He nucleus} \\
6 \text{ gamma rays} \\
\text{ - not shown here}

Any ideas why?

2 positrons
- each annihilates with an e\(^{-}\) (not shown) to produce two \(\gamma\) rays
2 neutrinos

The total mass is 0.7% lower...
...which is where the energy comes from:
\[ E = mc^2 \]

• This reaction is very sensitive to temperature
• With gravitational equilibrium, this creates the "solar thermostat"...

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**Solar Thermostat**

- Core temperature drop -> fusion rate drop
- Gravity crunch exceeds pressure push
- Core compression -> temperature rise
- Original conditions restored

- Core temperature rise -> fusion rate rise
- Pressure push exceeds gravity crunch
- Core expands -> temperature drops
- Original conditions restored
How does the energy from fusion get out of the Sun?

- Gamma ray photons from fusion bounce randomly through the radiation zone
- This can take from a few hundred thousand up to a million years...

- Plasma convection takes energy to the surface of the convection zone
- This takes about a week
- The surface of the convection zone is the photosphere
This is a close-up of the photosphere of the Sun.

The brighter areas are where hot plasma reaches the photosphere.

The darker areas are where cool plasma sinks back down.
This is called “granulation” because of the way it looks.

Granulation is not static, and the “granules” are not small.

Motion sped up ~600X  Total actual elapsed time = 35 min
Average size of a convection cell ~1300 km (800 miles)
Speed of gas motion 1-2 km/s (2000-4000 mph)
We’ve talked about the Sun’s structure
We’ve talked about how it generates energy
But how do we know we’re right?
The next slide shows how…

• We make mathematical and computational models of the Sun
• We use them to predict things about the Sun, e.g.:
  – We predict the way the Sun vibrates based on hypotheses about internal structure and composition…
    …then observe solar vibrations
  – We predict the number of neutrinos the Sun produces based on hypotheses about the nuclear reaction mechanism…
    …then observe solar neutrinos
• We compare observations to predictions
• If observations don’t match predictions, we revise the model

Does this process sound familiar?

THE SCIENTIFIC METHOD

Patterns of vibration on the surface tell us about what the Sun is like inside.
Models of the interior of the Sun are adjusted until the vibrations of the model match the observed vibrations of the Sun
• Here is a movie made from observations of the vibrating surface of the Sun

![Movie image]

• And that’s how we test and refine our model of the internal structure

• This is how we think the Sun generates its energy

• But how can we test it?

• The proton-proton chain produces a certain number and type of neutrino

• Unlike gamma rays, neutrinos don’t interact very much with the Sun

• In fact, they fly directly through any normal matter

• Trillions of them are flying through each of us right now

• And they come straight out of the Sun to Earth

• So looking at them, and counting them, is nearly as good as looking right at the nuclear reactions going on in the core

• But at first there was a problem…

**Solar neutrino problem:**

• Early searches for solar neutrinos found only ~1/3 of the predicted number
Solar neutrino problem:

- Early searches for solar neutrinos found only ~1/3 of the predicted number.
- It took 20 years, until scientists better understood neutrino behavior, to figure out why.
- On the way to Earth from the Sun, the neutrinos changed form from the type produced in the proton-proton chain (ν_ε) to the other two types (ν_μ and ν_τ).
- When this is taken into account, the observed number matches predictions.

Types of Solar Activity

- Sunspots
- Solar flares
- Solar prominences
- Coronal mass ejections
- All related to magnetic fields
- We’re going to focus on sunspots

Sunspots...

- Cooler than other parts of the Sun’s surface (4,000 K)
- Strong magnetic fields
- How do we know?
- The Zeeman Effect
We can detect magnetic fields in sunspots by observing the splitting of spectral lines.

**The Zeeman Effect**

- The Sun's magnetic field is essentially the same as an electromagnet's field...and a planet's magnetic field
- Charged particles moving in looped paths generate the magnetic field
- Convection of the plasma beneath the surface of the Sun causes its field
- Sunspots occur where field lines poke out of the Sun's surface...we'll see why in a bit...
- And this keeps the sunspot cooler than the surrounding plasma
- Here's how...

How do magnetic fields make sunspots "cool"?

- Charged particles spiral along magnetic field lines
- Field lines "fence out" hot plasma
- Allows sunspots to exist for long periods...
Loops of bright gas often connect sunspot pairs
The gas is following magnetic field lines

All of solar activity—sunspots, flares, etc—is tied to the Sun’s magnetic field
The Sun’s magnetic field varies in a more or less regular way
The most obvious manifestation of the variation is the number of sunspots
The number of sunspots rises and falls in 11-year cycles.
One way of tracking sunspot variation is to measure the percentage of the Sun’s surface covered by sunspots

Another way is to look at where the sunspots are
• The sunspot cycle has to do with the winding and twisting of the Sun’s magnetic field
• Think of the Sun’s magnetic field as lines of bar magnets end-to-end
• The Sun’s equator rotates faster than the poles
• This eventually breaks apart magnetic linkages (like breaking apart the lines of bar magnets)
• Sunspots form where the broken magnetic fields poke out
• The global magnetic field reorganizes itself at each solar minimum
• But the polarity is opposite what it was at the previous minimum

- min max min max min

• There are 11 years between maxima, but the full cycle lasts 22 years

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• The Sun is one of 100s of billions of stars in the Milky Way
• And there are a hundred billion times that many in the universe
• They are all similar to the Sun in what they're made of
• But the way they live their lives can be quite different…
  ...depending on their mass
• A good tool for comparing stars is the Hertzsprung-Russell diagram…

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**Hertzsprung-Russell Diagram**

- Luminosity versus surface temperature or spectral type
- Gives a lot of information
  - Put a star on the H-R diagram, and you will know if it's a giant, a main sequence star, or a white dwarf
  - You will have estimates of its mass, radius, and main sequence lifetime
  - MS lifetime depends on star mass because that affects how long it takes to use up core hydrogen
  - More massive stars don't stay on the main sequence as long as low mass stars
  - And there are limits on the masses stars can have
Upper Limit on a Star’s Mass

- The upper limit on star mass is due to luminosity
- Photons exert a slight amount of pressure when they strike matter
- Very massive stars are so luminous that the collective pressure of photons blows them apart
- Models of star formation suggest an upper mass limit of around 150$M_{\odot}$

Those models are supported by the scarcity of stars larger than 150$M_{\odot}$... only a few have been observed
- Three of these are in the "knot" at the lower right of the third panel below
- They are in the R136 cluster in the Large Magellanic Cloud
  - Masses range from 180-315$M_{\odot}$
  - Simulations suggest they formed in unusual ways
- In any case, "supermassive" stars are very uncommon

Lower Limit on a Star’s Mass

- The lower limit on star mass is due to “degeneracy pressure”
- Degeneracy pressure is a quantum effect
- It acts like a pressure
- But it is very different from thermal pressure
- To understand it, let's back up a little...
When an interstellar molecular cloud collapses, it gets hot.
The heat creates thermal pressure.
But thermal pressure caused by the gravitational collapse cannot stop the collapse.
If, however, the cloud is massive enough that its core $T \geq 10^7$ K, the collapse will stop.
Fusion in the core generates enough thermal pressure to stop the collapse of the protostar with gravitational equilibrium—and that’s how all stars are born.

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**Star Formation in General**

**Lower Limit on a Star’s Mass**

- But if the collapsing cloud is not massive enough to heat its core to $10^7$ degrees
- Fusion never ignites
- And it keeps on collapsing
- But not forever
- Enter degeneracy pressure

- Degeneracy pressure comes from the quantum nature of matter
- Two quantum particles—electrons, nuclei, etc.—cannot be in the same place at the same time
- So when a protostar has contracted to the point where it can’t contract anymore without particles being in the same place… it stops contracting
- That’s degeneracy pressure
- Like thermal pressure, it counteracts gravity, but does not depend on temperature
Thermal Pressure

- Depends on temperature
- Higher temperature → faster particles → higher pressure
- Temperature in stars depends on the weight of material above
- If there is enough mass to generate $10^7$K, fusion energy will stop contraction
- Otherwise, contraction will continue
- And that's where degeneracy pressure comes in

Degeneracy Pressure

- Does NOT depend on temperature, only on density
- Imagine if the lotto machine's globe could get smaller...
- It would keep getting smaller until the balls touched
- Similarly, if a protostar is too small and thus too cool for fusion
- Cloud collapse continues until particles "touch"
- Then degeneracy pressure stops the contraction

Brown Dwarfs – Below the Limit

So if there is not enough mass to compress the core enough to achieve $10^7$ K before electrons "touch"...
- "Electron degeneracy pressure" kicks in...
- Collapse, and heating, stops...
- Fusion never starts...
- And the protostar never becomes a hydrogen-fusing star
- This happens for protostars with mass <0.08$M_{\odot}$
- Such objects are called "brown dwarfs"
Size Limits on Stars

Stars can’t be bigger than ~150M_{Sun} or they blow themselves apart.

Stars can’t be smaller than ~0.08M_{Sun} or they don’t ignite fusion.

If they are in between, they can take their place on the main sequence.

After the Main Sequence - Broken Thermostat

- While a star is on the main sequence, it has a core thermostat, like our Sun’s solar thermostat.
- It keeps the rate of H→He fusion constant.
- And that fusion supports the core and the star through gravitational equilibrium.
- When hydrogen is used up, H→He fusion turns off.
- The core is now all helium, no hydrogen.
- The star is dying.

On the main sequence, the "core thermostat" works.

But when core hydrogen is gone, the core thermostat can’t function.
After the Main Sequence - Broken Thermostat

- As hydrogen burns in the shell it deposits He "ash" on the core.
- It turns out that degeneracy pressure is a little squishy...
- So the He ash compresses the core even more...
- ...and the compression continues to heat it up.
- Eventually the temperature reaches 100 million K.
- This is hot enough for He to fuse to carbon...
- ...and the star becomes a "helium-burning star"...

But when core hydrogen is gone, the core thermostat can't function.

- The helium burning star experiences something like a second main sequence.
- This is because the core thermostat is temporarily fixed due to He→C fusion in the core.
- There is also hydrogen still burning in a shell, but the helium fusing in the core expands the core.
- This generates less energy than in the red giant, but more than on the main sequence.
- No helium burning stars are in between in size.
- But eventually, the helium gets used up just like the core hydrogen did (but more quickly).
- This leaves behind a carbon core.

Double-Shell Burning

- After core helium fusion stops, the carbon core collapses (like the He core) and heats.
- Meanwhile hydrogen continues to burn in a shell around the carbon core, depositing a shell of helium on the core.
- The shell of helium fuses to carbon while the hydrogen shell above it fuses to helium.
- The star has become a red giant again, this time called a "double-shell burning star".
Double-Shell Burning

- This double-shell-burning stage is unsteady...
- ...the fusion rate periodically spikes upward in a series of thermal pulses.
- With each pulse, carbon gets dredged up from the core and transported into the overlying "envelope".
- Soon that carbon will enrich the interstellar medium...
- The carbon core continues to shrink and get hotter.
- For "low mass stars":
  - Carbon atoms "touch" before it gets hot enough (600 million K) to fuse carbon.
  - And degeneracy pressure kicks in again.

Life stages of a low-mass star like the Sun

Planetary Nebulae and White Dwarfs

- Double-shell burning ends with a pulse (or pulses) that ejects the gas envelope into space as a planetary nebula.
Planetary Nebulae and White Dwarfs

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- The core left behind becomes a white dwarf.
- White dwarfs are inert balls of carbon and oxygen (from fusion of helium and carbon).
- They might also have a little residual H/He atmosphere.

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- They might also have a little residual H/He atmosphere.
- They are about the size of Earth.
- Some even contain gigantic diamonds!

For more information about the diamond star, see http://www.cfa.harvard.edu/news/archive/pr0407.html
Planetary Nebulae and White Dwarfs

- The planetary nebulae surrounding white dwarfs come in a variety of shapes and sizes.
Planetary Nebulae and White Dwarfs

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Life Stages of High-Mass Stars

• Main-sequence life of high-mass stars is similar to low-mass stars:
  — Hydrogen core fusion (main sequence), but faster

CNO Cycle

• High-mass main-sequence stars fuse H to He at much higher rates than low-mass stars.
• This is partly because their higher mass means higher core temperatures.
• But it’s also because they use carbon, nitrogen, and oxygen as catalysts.
• The “CNO cycle” is shown at left.
Life Stages of High-Mass Stars

- Main-sequence life of high-mass stars is similar to low-mass stars:
  - Hydrogen core fusion (main sequence), but faster
- Early stages after main sequence are similar for high-mass stars and low-mass stars:
  - Hydrogen shell burning (as a supergiant)
  - Helium core fusion (as a supergiant)
- But high-mass stars can go beyond that and do “advanced nuclear burning”

Advanced Nuclear Burning

- Advanced nuclear burning proceeds in a series of nested shells.
- It’s during this process—and afterwards—that stars synthesize most of the chemical elements
- If the star is massive enough (> ~8 MSun), Tcore is high enough to make very large nuclei fuse
- In these stars, a variety of different fusion reactions in the nested shells can make elements all the way up to iron

- But iron is a dead end for fusion because nuclear reactions involving iron do not release energy
  - This is because iron has the lowest energy per nuclear particle of all elements
  - Elements smaller than iron can fuse with a release of energy
  - Elements larger than iron can fission with a release of energy
- But iron cannot fuse to anything larger, or fission to anything smaller
- So iron cannot generate any energy to support the core
- And when iron appears, the star’s death is imminent
• Advanced nuclear burning beyond that possible for a low mass star proceeds in a series of nested shells until iron appears.
• Once iron appears, the dying star’s fate is sealed.
• The iron can’t fuse, so the core collapses in a matter of milliseconds!

Supernova Explosion

• Why does this cause a supernova?
• The collapse heats the core to the point that the iron nuclei dissociate into protons and neutrons.
• The protons then combine with free electrons to produce more neutrons and neutrinos.
• With the loss of the electrons, electron degeneracy pressure disappears.
• The core collapses to a ball of neutrons, supported by neutron degeneracy pressure.

Supernova Remnant

• The energy released by the collapse of the core, the “bounce,” when neutron degeneracy pressure kicks in, and the massive production of neutrinos drives outer layers into space.
• It also drives synthesis of chemical elements up to uranium.
• Left behind is either a **neutron star** or, if the core is massive enough to “break” the neutron degeneracy pressure, a **black hole**.
• The outer envelope of the star moves out into space, forming a **nebula**.
• The Crab Nebula is the remnant of the supernova seen in A.D. 1054.
A star’s mass determines its entire life story by determining its core temperature.

High-mass stars have short lives... they get hot enough to make iron... and go supernova.
Low-mass stars have long lives... don't get hot enough to fuse carbon... and become white dwarfs.

A Different Kind of Supernova

- Algol is a binary star system consisting of a 0.8 $M_\odot$ red giant and a 3.7 $M_\odot$ main-sequence star.
- What’s wrong with that?...
- Binary stars formed from the same cloud and should be the same age.
- The more massive star should have become a red giant first.
- This is the “Algol paradox.”
• The stars in the Algol system are separated by less than 20% of the distance between Mercury and the Sun, about 0.05 AU.
• This is close enough that matter can be pulled by gravity off the subgiant onto the main-sequence star.
• And this "mass transfer" explains the Algol paradox.

The star that is now a subgiant was originally the most massive.
As it reached the end of its life and expanded into a red giant, it began to transfer mass to its companion.
And the companion star, originally less massive, grew to be more massive.

Close Binaries and White Dwarf Supernovae
• If the giant star in a system like Algol has a low enough mass, it will eventually become a white dwarf.
• When this happens, the direction of mass transfer can be reversed.
• And this can lead to a "white dwarf supernova" (also known as a "type Ia supernova").
• These were instrumental in the discovery in the 1990s that the expansion of the universe is accelerating.
• Here's how a white dwarf supernova happens...
Once the white dwarf forms, the main-sequence companion can no longer siphon away hydrogen and helium. So the main-sequence companion lives out its main-sequence lifetime, and becomes a red giant. And now it’s the white dwarf’s turn to siphon...

Hydrogen and helium siphoned from the red giant swirls in an "accretion disk" around the white dwarf. H and He falls onto the surface of the white dwarf, which is still very, very hot. A layer of hydrogen and helium builds up over time. And this leads, not to a supernova, but to a "nova"...

The layer of hydrogen and helium on the surface of the white dwarf gets more and more compressed as material continues to rain down. And the compression heats it. Eventually it reaches the hydrogen fusion temperature. Fusion begins suddenly and explosively throughout the layer. The white dwarf temporarily appears much brighter. This is a "nova".
• Nova explosions typically recur every few thousands or tens of thousands of years
• Each time, much of the surface material is blown into space
• But not all of it
• So after each nova, the white dwarf is a little more massive
• This continues until the white dwarf’s mass approaches 1.4 solar masses
• Electron degeneracy pressure, which prevents white dwarfs from collapsing, can support no more than 1.4 solar masses
• Let’s delve a little deeper into that…

Size of a White Dwarf

• White dwarfs with the same mass as the Sun are about the size of Earth
• Higher-mass white dwarfs are smaller
• This is because of the greater compression of the interior

Size of a White Dwarf

• Electron degeneracy pressure supports them, but it’s “squishy”
• They can still contract as more mass is added
• But due to the quantum nature of matter, not indefinitely
The White Dwarf Limit

- Quantum mechanics says that electrons must move faster as they are squeezed into a very small space — This is the “Heisenberg Uncertainty Principle”
- 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)

Close Binaries and White Dwarf Supernovae

- So when the mass of the white dwarf reaches 1.4 solar masses, electron degeneracy pressure fails...
- ...It’s like the lotto globe contracts until it crushes the balls...
- ...and the white dwarf collapses, compressing the carbon/oxygen core

Close Binaries and White Dwarf Supernovae

- The compression heats the white dwarf to the carbon fusion temperature
- And the whole white dwarf explodes in a frenzy of carbon fusion
- A white dwarf supernova is even brighter than a massive star’s core-collapse or “type 2 supernova”
- The white dwarf is obliterated
- Nothing is left behind
Close Binaries and White Dwarf Supernovae

- Since white dwarf supernovae always occur when the 1.4-solar-mass limit is reached...
- ...the luminosities of different white dwarf supernovae are almost the same
- This is not true for massive star supernovae, whose brightness depends on the mass of the star that produced them
- But because white dwarf supernovae are very bright and have a known luminosity, they can be used as "standard candles" to measure very large cosmic distances.

White Dwarf Supernovae and Cosmology

- In the 1990s, scientists measured the distances to a number of white dwarf supernovae in galaxies billions of light years away
- Because a white dwarf supernova occurs at a mass of 1.4 M_{Sun}, they have a known luminosity
- The apparent brightness is easily measured
- And the distance can then be calculated using the "inverse square law for light"
The scientists compared the distances to predicted distances based on how the universe is expanding. The supernova data was only consistent with a model where the universe is expanding at an accelerating rate.

This was a surprise, because the general view was that the expansion rate was constant or even slowing down. Still somewhat controversial...but it might turn out to be one of the greatest scientific discoveries of all time...it netted the Nobel Prize in 2011. Among other things, it led to the proposal of "dark energy" as the reason for the acceleration, and greatly expanded our understanding of the cosmos.

Neutron Stars
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.

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

Here are some others
Pulsars

The radiation beams sweep through space like lighthouse beams as the neutron star rotates.

Black Holes

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.
“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:

\[ R_g = \frac{3.0}{M} \frac{M_{\text{Sun}}}{\text{km}} \]

The event horizon of a \( 3 M_{\text{Sun}} \) black hole is about as big as a small city.

A black hole’s mass strongly warps space and time in the vicinity of the event horizon.
No Escape

- Nothing can escape from within the event horizon because nothing can go faster than light.
- No escape means there is no more contact with something that falls in.
- It increases the hole’s mass, changes its spin or charge, but otherwise loses its identity.

Light waves take extra time to climb out of a deep hole in spacetime leading to a *gravitational redshift*.

Time passes more slowly near the event horizon.
Tidal forces near the event horizon of a 3 $M_{\odot}$ 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?

Black Hole Verification

- Need to measure mass
  - Use orbital properties of companion
  - Measure velocity and distance of orbiting gas

- It’s a black hole if it’s not a star and its mass exceeds the neutron star limit (~3 $M_{\odot}$).
Some X-ray binaries contain compact objects of mass exceeding $3M_{\odot}$ which are likely to be black holes.

One famous X-ray binary with a likely black hole is in the constellation Cygnus.