Astronomy 104: Stellar Astronomy

Lecture 19: Stellar Remnants (Hanging Out with the Degenerates)

Spring Semester 2013

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Things To Do

• Today and Next Time
  • Chapter 12.2 (Neutron Stars)
  • Chapter 12.3-12.4 (Black Holes)

• No Labs this week, please bring Lecture Tutorials book to lab next week.

• Field Trips start TONIGHT (Wed/Thurs/Sun/Mon/Tues).
  • Will only be cancelled if predicted weather conditions are potentially dangerous.
  • We will send out emails by around 4pm each day with the decision for that night.
Tutorial: Review of Stellar Evolution

• Do the Review of Stellar Evolution Tutorial starting on page 61
  • Do ONLY Questions 1 through 3
Last Class: The Key Point

• **KEY POINT:** How a star evolves is governed by one thing... **mass.**

• Mass determines how high a star’s core temperature can rise
  • which determines how quickly a star uses its fuel
  • and what kinds of elements it can make.
The Final Fates of Stars

- Consider the balance of forces
  - Gravity inwards
  - Pressure outwards

- Stellar corpses ("dead stars") no longer can rely on nuclear burning to supply heat for outward pressure...
  - WHAT HOLDS THEM UP AGAINST GRAVITY IS THE KEY TO THEIR FATE...
Clicker Question

Which of the remnants below will the Sun become?

a) White Dwarf
b) Neutron Star
c) Black Hole
d) Could be any of the above
White Dwarfs are Forever

• How does the temperature of a white dwarf change over time?
  a) Stays the same
  b) increases
  c) decreases

• No fusion is occurring...
• So where does the pressure come from?
Degenerate Matter
(Outside of Stars)

• **DEGENERACY PRESSURE**
  • Makes solids & liquids incompressible.
  • If all the atoms in your body are gravitationally attracted to one another ... ever wonder why gravity doesn’t collapse you?
    • Degeneracy pressure is what prevents you from “collapsing”
    • and it is what holds up stellar cores after they run out of fuel.
Electron Degeneracy Pressure

• The **Pauli Exclusion Principle**: no two electrons with similar properties can occupy the same space
  • Purely quantum mechanical physical explanation
  • Called **Electron Degeneracy Pressure**
White Dwarfs

- Cores of low mass stars, held up by electron degeneracy pressure.
- Higher mass white dwarfs are smaller.
- Density of about $10^6$ kg/cm$^3$

**QUESTION:** Is there an Upper Limit to the Mass of White Dwarfs?
Is there an Upper Limit to the Mass of White Dwarfs?

• Yes! Chandrasekhar Limit ~ 1.4M⊙
  • Quantum mechanical physics says that electrons must move faster as they are squeezed into a very small space.
  • As White Dwarf mass approaches the Chandrasekhar Limit, the electrons approach the ultimate speed limit, the speed of light.

• What does this mean? White Dwarfs can’t exceed 1.4 M⊙.
Neutron Degeneracy Pressure

- **Neutron Degeneracy Pressure:**
  neutrons also obey an exclusion principle
  - 2000 more massive than electrons
    → 2000× less exclusive

- Neutron stars are the expected result of a collapse of a high-mass stellar core to “neutron degenerate matter.”
Neutron Stars

• Cores of high mass stars, held up by neutron degeneracy pressure.

• **Density:**
  \[ \sim 10^{10} \text{–} 10^{11} \text{ kg/cm}^3 \]
What **evidence** is there for Neutron Stars? **Pulsars!**

- Don’t look in the optical... neutron stars are too faint.

- 2 radio astronomers at Cambridge (Jocelyn Bell and Tony Hewish) recording intensity of radio waves from several stars
  - CP 1919 (now known as PSR B1919+21) seen to have a period of 1.337 s.
PSR B0329+54

**Period:** 0.714519 seconds
(1.4 pulses a second)

20 Second Recording of Typical Pulsar
PSR B0833-45 (a.k.a. The Vela Pulsar, ~10,000 years old)

**Period**: 89 milliseconds
(11 pulses a second)

X-ray (Chandra) Image of Vela Pulsar region

26 Second Recording of Vela Pulsar
PSR B0531+21 (a.k.a. The Crab Pulsar)

**Period:** 33 milliseconds
(30 pulses a second)

20 Second Recording of Crab Pulsar
PSR B1937+21

**Period**: 0.00155780644887275 seconds
(642 pulses a second)

*Note:* The surface of this Pulsar moving 25% the speed of light!

10 Second Recording of 2\textsuperscript{nd} Fastest Rotating Pulsar known!
Neutron Stars could be Pulsars
Why do astronomers think Pulsars are Neutron Stars?

• Circumference of Neutron Star ~60 km

• Spin Rate of Fast Pulsars ~1000 cycles/sec

• Surface Rotation Velocity ~60,000 km/s
  • ~20% speed of light
  • ~escape velocity from neutron star

• Anything else would be torn to pieces!
Clicker Question

• A Neutron Star ______ appears to be a pulsar.
  A) always
  B) sometimes, depending on when you look
  C) sometimes, depending on your view of the neutron star
Clicker Question

• A neutron star that appear as a pulsar to other civilizations (in the galaxy) will _______ to us.

  A) definitely appear as a pulsar
  B) definitely NOT appear as a pulsar
  C) might or might not appear as a pulsar
Can Neutron Degeneracy Pressure fail?

• Not as clear an answer.
  • Suggested limits between 2.0 and 3.3 M☉
  • So any truly massive stellar core, more massive than limit of neutron degeneracy pressure, must collapse...

• If Neutron Degeneracy Pressure fails... no known force can stop gravity.
  • Gravity crushes all the matter into a single point known as a singularity.
Clicker Question

• What happens to the escape velocity of an object if you shrink it?
  A) It increases.
  B) It decreases.
  C) It remains the same.

Hint:

\[ F_g = G \frac{M_1 M_2}{d^2} \]
What is a Black Hole?

- A Black Hole is an object whose gravity is so strong that its escape velocity exceeds the speed of light.
  - Since nothing can travel faster than the speed of light... not even light can escape!
• The “surface” of a black hole is where the escape velocity equals the speed of light.

• Known as the event horizon.
  • The radius of the event horizon is known as the Schwarzschild radius.
  • ~3 km per solar mass.

3 $M_\odot$
Black Hole
What evidence is there for Stellar Mass Black Holes?

- **Stellar Mass** Black Holes (obviously) are not visible in “visible light”...
  - But if the black hole is in a binary star system, the debris falling into them heats up... a lot and should glow in X-rays!
What evidence is there for Stellar Mass Black Holes? II

X-Ray Image of Cygnus X-1 from EXOSAT Satellite

Gamma-Ray Image of Cygnus X-1 from Integral Satellite
Review of Stellar Remnants

• The possibilities for Stellar Remnants
  • White Dwarfs ($M_{\text{core}} < 1.4 \, M_{\odot}$)
  • Neutron Stars ($1.4 \, M_{\odot} < M_{\text{core}} < 2-3.3 \, M_{\odot}$)
  • Black Hole ($M_{\text{core}} > 2 - 3.3 \, M_{\odot}$)

• A neutron star is the left-over core of a high-mass star
  • High density, small size (~30km)
  • Detected as pulsar

• Black hole is so massive nothing can escape from it.
  • Form from core collapse of very high mass stars.
The Fates of Binary Stars

"Sometimes having a neighbor makes a big difference."
Interesting White Dwarf Behavior

• White Dwarfs by themselves are pretty boring... they just cool off as time goes on.

• But place the White Dwarf in a close binary star system and explosive stuff can happen.
Mass Transfer to White Dwarfs

- Conservation of angular momentum prevents material from falling straight into White Dwarf, so material pulled off larger star orbits the white dwarf in an accretion disk.

- Friction between orbiting rings of matter in the disk causes the disk to heat up and glow.
Nova

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

- Fusion begins suddenly on the surface of the white dwarf causing a nova.

- The nova causes the binary star system to temporarily be much more luminous.
Clicker Question

• What happens if the white dwarf accumulates enough mass to become more massive than the Chandrasekhar Limit?
  A) It explodes.
  B) It collapses into a neutron star.
  C) It gradually begins fusing carbon in its core.
Another Way to Supernova

White Dwarf Deflagration

Resolution: 6 km
Initial Bubble Radius: 18 km
Ignition Offset: 42 km

Variable 1: Density [1.5e+07 - 2.0e+07]
Variable 2: Reaction Progress [0.0 - 1.0]

• UNEXPECTED RESULT!!! It turns out just before it can reach the Chandrasekhar limit, a White Dwarf will get hot enough to trigger Carbon fusion....

• Since degenerate matter happens to transmit heat very quickly, the entire White Dwarf detonates!

• This releases as much energy as a core-collapse Supernova, so also called a Supernova!

First 3-dimensional SN1a simulation from ASC / Alliances Center for Astrophysical Thermonuclear Flashes
SN2011fe in M101
data from MSUM
White Dwarf: Nova vs. Supernova

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

- **Supernova**: complete explosion of white dwarf
  - *nothing left behind.*
  - Supernovae are MUCH MUCH more luminous!!! (about 10 million times)
At least Two Types of Supernova

• **Type Ia Supernova** - White Dwarf Supernova:
  
  • Carbon fusion suddenly begins as white dwarf in close binary system reaches white dwarf limit, causing total explosion.
  
  • **NO HYDROGEN.**

• **Type II Supernova** - Massive Star (Core Collapse) Supernova:
  
  • Iron core of massive star reaches white dwarf limit and collapses into a neutron star, causing explosion.
  
  • **HYDROGEN FROM OUTER LAYERS OF STAR IS SEEN.**
Tutorial Time

• Please do Question 4 on *A Review of Stellar Evolution* Tutorial on page 61-63...