Extreme Stars: White Dwarfs and Neutron Stars
The Stellar Graveyard

• Q: What happens to the cores of dead stars?
• A: They continue to collapse until either:
  – A new pressure law takes hold to halt further collapse & they settle into equilibrium.
  – If too massive they collapse to zero radius and become a Black Hole.
Degenerate Gas Law

• At high densities, a new gas law takes over:
  – Pack many electrons into a tiny volume
  – These electrons fill all low-energy states
  – Only high-energy = high-pressure states left

• Result is a “Degenerate Gas”:
  – Pressure is independent of Temperature.
  – Compression does not lead to heating.
White Dwarfs

- Remnant cores of stars with $M_* < 8 \, M_{\odot}$.
- Held up by **Electron Degeneracy Pressure**.
- **Properties:**
  - Mass $< 1.4 \, M_{\odot}$
  - Radius $\sim R_{\text{earth}} (<0.02 \, R_{\odot})$
  - Density $\sim 10^{5-6} \, \text{g/cc}$
  - No nuclear fusion or gravitational contraction
Sirius B
White Dwarf

Sirius B
Chandrasekhar Mass

- Mass-Radius Relation for White Dwarfs:
  - Larger Mass = Smaller Radius
- Maximum Mass for White Dwarf:
  - $M_{ch} = 1.4 \, M_{\text{sun}}$
    - Calculated by Subrahmanyan Chandrasekhar in the 1930s.
    - Above this mass, electron degeneracy pressure fails & the star collapses.
Evolution of White Dwarfs

• White dwarfs only shine by leftover heat.
  – No sources of new energy (no fusion, nothing)
  – Cools off and fades away slowly.

• Ultimate State: A “Black Dwarf”:
  – Old, cold white dwarf
  – Takes ~ 10 Tyr to cool off
  – Galaxy is not old enough to see Black Dwarfs.
Neutron Stars

• Remnant cores of massive stars:
  – $8 < M_* < 18 \, M_{\text{sun}}$ (??)
  – Leftover core of a core-bounce supernova

• Held up by Neutron Degeneracy Pressure:
  – Mass $\sim 1.2 - 2 \, M_{\text{sun}}$ (???)
  – Radius $\sim 10$ km (small city)
  – Density $\sim 10^{14}$ g/cc
Structure of a Neutron Star

• At densities > $2 \times 10^{14}$ g/cc:
  – nuclei melt into a sea of subatomic particles.
  – protons & electrons combine into neutrons.

• Surface is cooler:
  – Solid, crystalline crust.

• Inside is exotic matter:
  – superfluid neutrons, superconducting protons...
Inside a Neutron Star

- Superconducting Protons
- Neutron Superfluid
- Crystalline Iron Crust
Surface of a Neutron Star

• What is it like on a neutron star’s surface?
  – Surface gravity: \( \sim 10^{11} \) g’s
  – Escape velocity: \( \sim 0.5 \) c
  – Temperature: \( \sim 1 \) Million K
  – Magnetic Field Strength: \( \sim 10^{12} \) Gauss
    – (Earth is \( \sim 0.5 \) Gauss)
  – Rotation Rate: 6000 rpm (100 rotations/second)
• You would be squashed flat and vaporized.
First predicted by theory

• **1934:**
  Baade & Zwicky propose that supernovae are stars transforming into neutron stars.
  Most observers thought this was crazy.

• **1938:**
  Oppenheimer & Serber (US) and Landau (USSR) calculate the properties of neutron stars.
  Most theorists were dubious, too.
Accidental Discovery

• **1967:**
  Jocelyn Bell (Cambridge grad student) & Anthony Hewish (her advisor) discover pulsating radio sources while looking for something else.

• “**Pulsars**” = Pulsating Radio Sources
  Emitted 0.001 sec-long pulses every second.
Pulsars

• Rapidly spinning, magnetized neutron stars.

• **Lighthouse Model:**
  – Spinning magnetic field generates a strong electric field.
  – Electric field rips electrons off the surface & accelerates them along the magnetic poles.

• **Result:** twin beams of radiation
Pulsar Evolution

• Pulsars spin slower as they age.
  – lose rotational energy

• Young neutron stars:
  – fast spinning pulsars.
  – found in supernova remnants (e.g., Crab pulsar)

• Old neutron stars:
  – cold and hard to find.
Isolated Neutron Star RX J185635-3754

PRC97-32 • ST ScI OPO • September 25, 1997
F. Walter (State University of New York at Stony Brook) and NASA
Over the top?

- What if the remnant core is very massive?
  - $M_{\text{core}} > 2-3 \, M_{\odot}$
- (original star had $M > 18 \, M_{\odot}$)
  - Neutron degeneracy pressure fails.
  - Nothing can stop gravitational collapse.
  - Collapses to zero radius and infinite density.
- Becomes a Black Hole.
Summary:

• **White Dwarf:**
  – Remnant of a star <8 $M_{\text{sun}}$
  – Held up by Electron Degeneracy Pressure
  – Maximum Mass $\sim 1.4$ $M_{\text{sun}}$

• **Neutron Star:**
  – Remnant of a star < 18 $M_{\text{sun}}$
  – Held up by Neutron Degeneracy Pressure
  – Pulsar = rapidly spinning neutron star
Questions:

• Do we see white dwarfs?
• Do we see neutron stars?
• Do we see black holes?
• What happens if you add mass to a White Dwarf?