Lecture 22: Extreme Stars: White Dwarfs & Neutron Stars

Readings: 22-2, 22-4, 23-1, 23-3, 23-4, 23-5, 23-8, 23-9

Key Ideas

White Dwarf

Remnant of a low-mass star
Supported by Electron Degeneracy Pressure
Maximum Mass ~1.4 M_{Sun} (Chandrasekhar Mass)

Neutron Star

Remnant of a massive star
Supported by Neutron Degeneracy Pressure
Pulsar=rapidly spinning neutron star
Maximum Mass ~2-3 M_{Sun}

The Stellar Graveyard

Question:
What happens to the cores of dead stars?

Answer:
They continue to collapse until either:

A new pressure law halts further collapse & they settled into hydrostatic equilibrium
If too massive, they collapse to zero radius and become a black hole.

Degenerate Gas Law

At high density, 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
Compression does give higher density=greater pressure

Allows cold objects to exist in hydrostatic equilibrium

White Dwarfs

Remnant cores of stars with $M < 8\ M_{Sun}$

Held up by Electron Degeneracy Pressure

$M < 4M_{Sun}$: C-O white dwarfs

M between 4-8 M_{Sun}: O-Ne-Mg white dwarfs

Properties

Mass < 1.4 M_{Sun} (reflects large amount of mass loss in planetary nebula phase)

Radius ~ R_{earth} (<0.02 R_{Sun})

Density~$10^{5\text{-}8}$ g/cc

Escape Speed: 0.02 c (2% speed of light)

Shine by residual heat: no fusion or contraction

Example: Sirius B

M=1.0 M_{Sun}

R=5800 km

V_{esc}=0.02c

Chandrasekhar Mass

Mass-Radius Relation for White Dwarfs

Larger Mass=Smaller Radius

Different than Normal Matter, such as Chocolate Cake

Larger Mass=Higher Gravitational Force=Larger Pressure=Higher Density=Smaller Volume

Chandrasekhar Mass

Maximum Mass for White Dwarf

M_{Sun}=1.4 M_{Sun}

Calculated by S. Chandrasekhar in the 1930s

Above this mass, electron degeneracy fails and the star collapses

Evolution of White Dwarfs

White dwarfs shine by leftover heat

No sources of new energy (no fusion)

Cool off and fade away slowly

Ultimate State: A *Black Dwarf*

Old, cold white dwarf

Takes ~10 Trillion years to cool off

Age of Universe ~ 13.7 billion years < 10 trillion years, so
Galaxy is not old enough for Black Dwarfs

Not to be confused with "Black Holes"

Black dwarfs are black=do not shine because they are the same temperature as their surroundings

Black holes do not shine because light cannot escape.

Path of White Dwarfs on H-R Diagram: Cool quickly at first , then gradually approach the temperature of empty space

The Other Supernova

What happens mass is added to the white dwarf and $M > 1.4M_{Sun}$

Electron degeneracy falls, star collapses

Ignites C-O fusion at high density

Generates heat, but no pressure because degeneracy pressure is independent of temperature

Greater heat=greater fusion=greater heat…..

Runaway nuclear explosion:

Fusion of light elements into Iron & Nickel

White Dwarf detonates as a Type Ia Supernova

Leaves behind no remnant (total disruption)

Mass Transfer in a Binary

See Figure 21-18b

A white dwarf can exceed the Chandrasekhar mass by getting mass from a companion. If the mass transferred (mostly hydrogen & helium) is less than the Chandrasekhar mass, a runaway nuclear reaction can happen, but it will be much less energetic and not disrupt the star. This is a *nova*.

Type I and Type II Supernovae

Type I	Type II
White dwarf binary	High Mass Star
Runaway fusion of light elements	Core bounce/neutrino emission
Peak $L \sim 10^{10} L_{Sun}$	Peak $L \sim 10^{8}$-$10^{9} L_{Sun}$
Standard Candle	Not standard

Neutron Stars

Remnant cores of massive stars:

- $8 < M < 18 M_{Sun}$
- Leftover core of core-bounce supernova

Held up by Neutron Degeneracy Pressure:

- Mass: $\sim 1.2 - 2 M_{Sun}$, Radius: ~ 10 km
- Density 10^{14} g/cc
- Escape Speed ~0.7c (70% speed of light)

Shine by residual heat: no fusion or contraction

Radiation

- Very hot at beginning, but very small
- Low luminosity
- Emit in X-rays
- ~6 isolated neutron stars seen. Otherwise we see them with their supernova remnants.

Structure of a Neutron Star

At densities > 2×10^{14} g/cc

- Nuclei melt into a sea of subatomic particles (protons & neutrons)
- Protons & electrons combine into neutrons

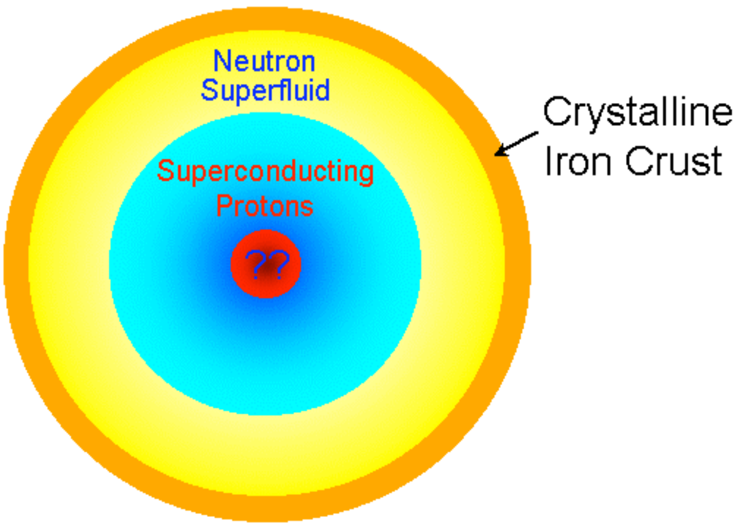
Surface is cooler

- Solid crystalline crust

Inside is exotic matter

Superfluid of neutrons, superconducting protons, and weirder stuff.

Subject of much current research



Accidental Discovery of Pulsars

1967:

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

Pulsars=Pulsating Radio Sources

Emit sharp millisecond-long pulses every second

Cannot be normal stars or white dwarfs. Strong evidence for neutron stars.

Pulsars

Rapidly spinning, magnetized neutron stars

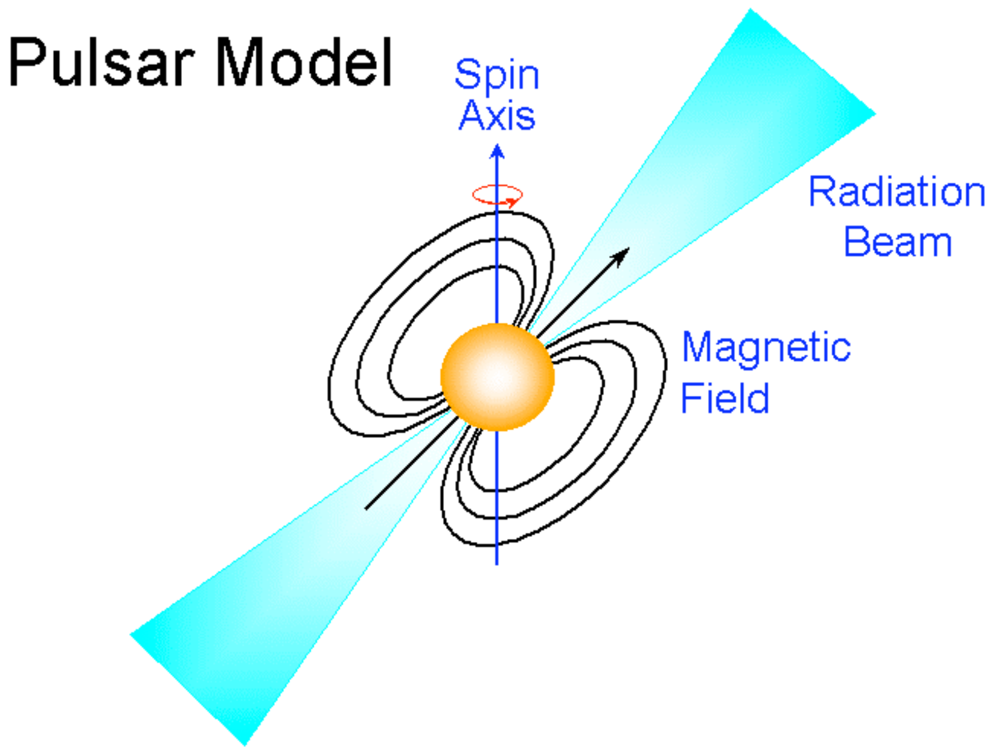
Lighthouse Model:

Spinning magnetic field generates a strong electric field.

Electric field rips electrons off the surface

Magnetic field accelerates them along the poles.

Result: twin beams of intense radiation



Example: Crab Nebula Pulsar

Pulsar Evolution

Pulsars spin slower as they age

- Radiating energy, so that energy must be coming from somewhere (not fusion!)
- Lose rotational energy

Young neutron stars

- *Fast spinning* pulsars
- Found in supernova remnants (e.g. Crab Pulsar, Vela Pulsar)

Old neutron stars:

- Cold and hard to find

Over the top?

What if the remnant core is *very* massive?

- $M_{core} > 2\text{-}3\ M_{Sun}$ (original star had $M > 18\ M_{Sun}$)
- First forms neutron star, but material keeps falling on it
- Neutron degeneracy pressure fails
- Nothing can stop gravitational collapse
- Collapse to a <u>singularity</u>: zero radius and infinite density

Becomes a BLACK HOLE, Gravity's final victory.