Structure of a White Dwarf

NO energy production

- gravity = degenerate gas pressure
- as it cools, becomes “Black Dwarf”

Mass Limit for White Dwarfs
S. Chandrasekhar (1983 Nobel Prize)
-calculated max. mass (White Dwarf)

\[ M_{wd} \leq 1.4 \, M_{\odot} \]
Chandrasekhar limit

If total mass of star < 6 to 8 \( M_{\odot} \) (core < 1.4 \( M_{\odot} \))
- star ends as a White Dwarf
  ➔ “Low Mass” star

If total mass of star > 6 to 8 \( M_{\odot} \) (core < 1.4 \( M_{\odot} \!))
  - cannot form White Dwarf !!
  ➔ “High Mass” stars
Lives of High Mass Stars
\((M_{\text{star}} > 6 - 8 M_{\odot})\)

Early life is same as a Low Mass Star:
- Formation Process / Protostar
- Main Sequence Phase

Key Differences from a Low Mass Star:
- more mass = more gravity = higher temps
- Each stage is much quicker

Supergiant (High Mass)
- Core fusion stops
  - Core collapses and heats up!
- Fusion shell begins around core
  - Next fusion starts in core
- Outer layers expand and cool
Hydrogen Fusion (Main Seq.) \(\rightarrow\) Helium Fusion \(\rightarrow\) Carbon Fusion \(\rightarrow\) Neon Fusion \(\rightarrow\) Oxygen Fusion \(\rightarrow\) Silicon Fusion \(\rightarrow\) Production of Iron

High Mass Supergiant: Onion Ring Structure

What happens:
- Core becomes 100% iron, fusion STOPS

Why?
- Iron is most stable element
- Cannot create energy from Iron
- Iron must absorb energy to fuse
- Iron must absorb energy to fission

Then...

**BANG!**
Death of High Mass Supergiant
- Iron core collapses
  - cannot form White Dwarf

Sudden Collapse of Core
- Core Collapses in 1/4 second!

- infalling material
  - moving 15% speed of light!
  - flood of neutrinos released

Collapse stops suddenly
- when neutrons crowded together
- enormous shock wave rips through star
SUPERNova EXPLOsion !!!

What happens:

- Entire envelope blasted into space
- Contains lots of heavy elements

Why?

- Excess energy from explosion allows fusion heavier than iron
Vivid View of Tycho's Supernova Remnant
Spitzer Space Telescope / Chandra / Calar Alto

North area in Tycho, MOS 1

key cts/keV/s

Energy (keV)
Supernova seen July 4, 1054 AD

Today, seen as "Crab Nebula"

X-ray Image
25 Solar Mass Star: \((\text{core mass} > 1.4 \, \text{M}_\odot)\)

What happens:

- Core becomes "Neutron Star"
- giant ball of neutrons \(~20\) miles across
- contains between \(1.4\) to \(\sim 3\) \(\text{M}_\odot\)
- rotates very fast

Why?

- Neutron degeneracy stops collapse
- Conserves angular (rotational) momentum

Can be observed as:

- \textbf{Pulsar}
- first detected in 1967

- [http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html](http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html)
35 Solar Mass Star: (core mass > 3 M☉)

What happens:

- Core collapses when fusion stops
  - NOTHING can stop collapse!!
- All matter crushed out of existence
- Becomes a “Black Hole”

Why?

- Gravity too strong for anything (even light) to escape
- Space and Time no longer exist
  - explained by Einstein's General Relativity
Einstein: General Theory of Relativity
  - Gravity is a "curvature" or distortion of Spacetime

Mass creates a "distortion" in space & time
  - "distortion" will affect anything moving through space
  - even **LIGHT** will be affected!!
Black Holes

A place where gravity is so strong:

- NOTHING, not even light, can escape
  → "BLACK"

- escape velocity > the speed of light!

A place spacetime is so distorted:

there is a "HOLE" in space & time!

Black Holes:

- made up of NOTHING!
- region of highly warped space & time

Only measurable properties of Black Hole

→ Mass, Electric Charge, Rotation
Structure of a black hole:

Singularity:
- the point where all the matter is compressed into
- place of infinite spacetime curvature

Event Horizon:
- location where $V_{\text{escape}} = c$

- inside "disconnected" from the rest of the universe
- no information can ever get out

Schwarzschild Radius:
- the radius of the event horizon
Search for Black Holes
- can look for material that is falling in
  - forms accretion disk, emits X-rays
- X-ray binary system
## Black Hole Candidates (1996)

<table>
<thead>
<tr>
<th>Object</th>
<th>Companion Star</th>
<th>Orbital Period (days)</th>
<th>Mass of Compact Object (M_☉)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyg X-1</td>
<td>O9.7 I</td>
<td>5.6</td>
<td>≥ 11</td>
</tr>
<tr>
<td>LMC X-3</td>
<td>B3 V</td>
<td>1.7</td>
<td>7.6</td>
</tr>
<tr>
<td>LMC X-1</td>
<td>O7 V</td>
<td>4.2</td>
<td>7</td>
</tr>
<tr>
<td>A 0620-00</td>
<td>K5 V</td>
<td>0.32</td>
<td>≥ 2.9</td>
</tr>
<tr>
<td>GS 2023+338</td>
<td>G9 V-K0 III</td>
<td>6.47</td>
<td>≥ 6.1</td>
</tr>
<tr>
<td>GS 1124-68</td>
<td>K0 V-K4 V</td>
<td>0.43</td>
<td>≥ 2.9</td>
</tr>
<tr>
<td>GRO J0422+32</td>
<td>M2</td>
<td>0.21</td>
<td>4.8</td>
</tr>
<tr>
<td>GRO J1655-40</td>
<td>F3-F6</td>
<td>2.60</td>
<td>≥ 3.2</td>
</tr>
<tr>
<td>GS 2000+25</td>
<td>K5 V</td>
<td>0.35</td>
<td>≥ 6.4</td>
</tr>
<tr>
<td>H1705-25</td>
<td>K3</td>
<td>0.52 (0.70)</td>
<td>≥ 3.4</td>
</tr>
</tbody>
</table>

*Astrophysical Journal Letters, 1996*

2004, Black Hole Candidates:
- 54 in binary systems
- 4 by gravitational microlensing

2013, Chandra X-ray Observatory
- 26 new candidates in Andromeda Galaxy
Supermassive Black Holes

At the center of galaxies,

- large rotating disks of stars and gas
- can calculate gravity needed to keep disk together
  \[ \Rightarrow 10^6 \text{ M}_\odot \text{ to } 10^9 \text{ M}_\odot \] !!

- size of region that provides gravity
  - much less than 1 pc
  - close to the size of our solar system !!

Galactic Nucleus:

\[ \Rightarrow \text{Supermassive Black Hole} \]

- created during formation of galaxy
- from giant regions of compressed gas and dust near the center
Disk in Galaxy NGC 7052
PRC98-22 • June 18, 1998 • ST ScI OPO
R. P. van der Marel (ST ScI), F. C. van den Bosch (University of Washington) and NASA

Galaxy NGC 6251 Nucleus
HST • FOC • WFPC2
PRC97-28 • ST ScI OPO • September 10, 1997
P. Crane and J. Vernet (European Southern Observatory) and NASA
Singularity:
- can possibly connect to another spacetime
  - Einstein-Rosen bridge or "wormhole"
A tunnel through the structure of time and space itself, and which creates a short-cut from the Bajoran Star System, to the distant Gamma Quadrant of the Galaxy.

Belgarath Silverthorn