ASTR 1040 Recitation: White Dwarfs and Supernovae

Ryan Orvedahl

Department of Astrophysical and Planetary Sciences

March 10 & 12, 2014

This Week

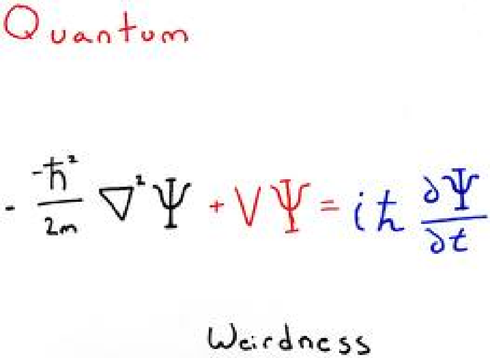
- Observing Session: Tonight Mar 10 (8:00 pm)
- MIDTERM: Thurs Mar 13 (regular class time, 9:30 am)
- Review Session: Wed Mar 12 (5:00 - 7:00 pm)

Today's Schedule

- Past / Current Homework Questions?
- White Dwarfs and Degeneracy Pressure
- Supernovae and Nuclear Reactions

“Basic” Quantum Mechanics

- Heisenberg Uncertainty Principle
- Pauli Exclusion Principle
- Planck’s Constant: $h \approx 10^{-34}$ J s or $\hbar \equiv h/(2\pi)$ J s



"Basic" Quantum Mechanics

- Heisenberg Uncertainty Principle
- $\Delta x \Delta p \geq \hbar/2$
- $\Delta t \Delta E \geq \hbar/2$
- p is momentum and E is energy

Werner Heisenberg

"Basic" Quantum Mechanics

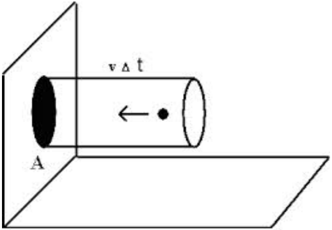
- Pauli Exclusion Principle
- No two fermions (protons, electrons, neutrons) can occupy the same quantum state
- Fermions have half-integer spin and Bosons (photons) have integer spin

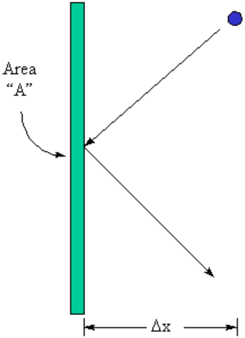
Wolfgang Pauli

Degeneracy Pressure

- White Dwarf: ∼size of Earth, ∼mass of Sun
- Supported by Electron Degeneracy Pressure
- $P_{\mathrm{NR}} = \frac{\hbar^2}{m_e} \left(\frac{Z}{A}\right)^{5/3} \left(\frac{\rho}{m_p}\right)^{5/3}$

How did you get that result?





Newton: $F = ma$

F = change in linear momentum
per unit time
$= \Delta p / \Delta t$

p = linear momentum
$= m \times v$

Before collision:

$-p_x, p_y, p_z$

After collision:

p_x, p_y, p_z

$\Delta p = 2\, p_x$
$\Delta t = 2\, (\Delta x / v_x)$

White Dwarf Mass-Radius Relationships

- *Is* there a relationship between Mass and Radius?

White Dwarf Mass-Radius Relationships

- *Is* there a relationship between Mass and Radius?

- Yes! How do we find it?

White Dwarf Mass-Radius Relationships

- *Is* there a relationship between Mass and Radius?
- Yes! How do we find it?
- Use Hydrostatic Equation (who remembers what that even means?)

White Dwarf Mass-Radius Relationships

- *Is* there a relationship between Mass and Radius?
- Yes! How do we find it?
- Use Hydrostatic Equation (who remembers what that even means?)
- Set $P_{\mathrm{HSE}} = P_{\mathrm{Deg}} \qquad \Rightarrow \qquad R \propto M^{-1/3}$

Relativistic Result

- We used $P = nvp$, what happens when $v \approx c$?

Relativistic Result

- We used $P = nvp$, what happens when $v \approx c$?
- Simply replace $v \rightarrow c$
- $P_{\mathrm{R}} = \hbar c \left(\frac{Z}{A}\right)^{4/3} \left(\frac{\rho}{m_p}\right)^{4/3}$

Degeneracy Pressure with Numbers

For $Z/A = 1$ and $\rho = 1$ g/cm^{-3}

Non-Relativistic:

$$P_{\mathrm{NR}} = 9.9 \times 10^{12} \text{ dyn cm}^{-2}$$

Relativistic:

$$P_{\mathrm{R}} = 1.2 \times 10^{15} \text{ dyn cm}^{-2}$$

Short Project – Units!

Unit conversions are good for the soul, so ...

Convert dyn cm^{-2} (cgs) to SI/MKS unit of pressure: Pascal

Remember $P = F/A$ and a dyn is cgs unit of force

Short Project – Units!

Unit conversions are good for the soul, so ...

Convert dyn cm^{-2} (cgs) to SI/MKS unit of pressure: Pascal

Remember $P = F/A$ and a dyn is cgs unit of force

$$1 \text{ dyn cm}^{-1} = 0.1 \text{ Pa}$$

Short Project – Units!

Unit conversions are good for the soul, so ...

Convert dyn cm^{-2} (cgs) to SI/MKS unit of pressure: Pascal

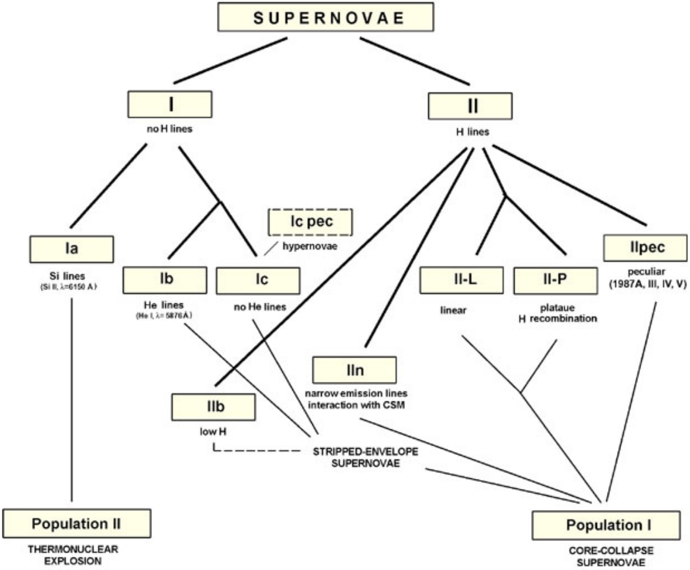
Remember $P = F/A$ and a dyn is cgs unit of force

$$1 \text{ dyn cm}^{-1} = 0.1 \text{ Pa}$$

1 dyn $\mathrm{cm}^{-2} = \frac{\mathrm{g\ cm}}{\mathrm{s}^2}\frac{1}{\mathrm{cm}^2}$

$\frac{\mathrm{g}}{\mathrm{s}^2\ \mathrm{cm}} = \frac{10^{-3}\mathrm{kg}}{\mathrm{s}^2 10^{-2}\mathrm{m}} = 0.1\ \frac{\mathrm{kg}}{\mathrm{s}^2\mathrm{m}} = 0.1\ \frac{\mathrm{kg\ m}}{\mathrm{s}^2}\frac{1}{\mathrm{m}^2} = 0.1\ \mathrm{Pa}$

Classifying Supernovae – It's Complicated



SUPERNOVAE

I

no H lines

II

H lines

Ia

Si lines

(Si II, λ=6150 Å)

Ib

He lines

(He I, λ= 5876 Å)

Ic

no He lines

Ic pec

hypernovae

II-L

linear

II-P

plataue

H recombination

IIpec

peculiar

(1987A, III, IV, V)

IIn

narrow emission lines

interaction with CSM

IIb

low H

STRIPPED-ENVELOPE SUPERNOVAE

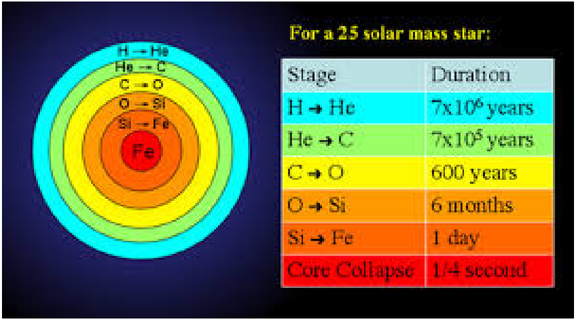
Population II

THERMONUCLEAR EXPLOSION

Population I

CORE-COLLAPSE SUPERNOVAE

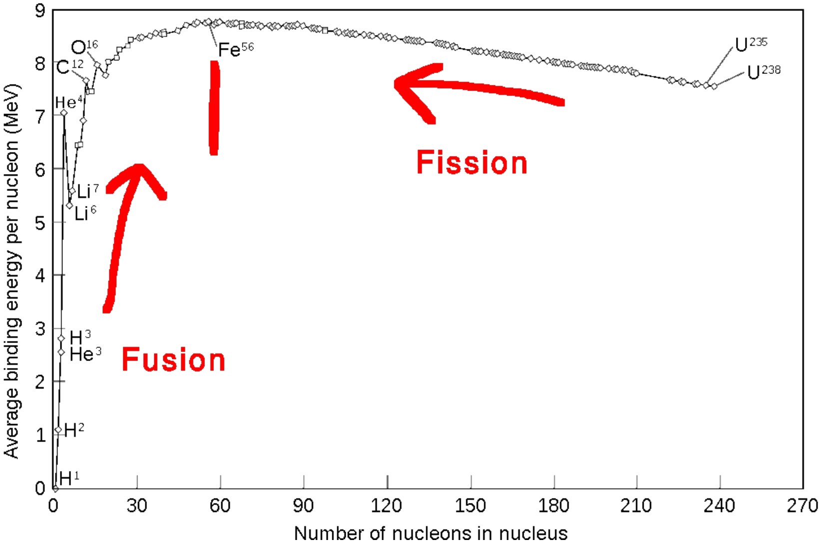
Supernova Onion Shell Burning



For a 25 solar mass star:

Stage	Duration
H → He	7x10^6 years
He → C	7x10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second

Why Stop at Iron ($Z = 26$)?



Naturally Occurring Elements with $Z > 26$ Exist!

- For high Z elements it is hard to get another charged particle close due to the high Coulomb potential barrier
- Not for neutrons: ${}^{A}_{Z}X + n \rightarrow {}^{A+1}_{Z}X + \gamma$
- Results in more massive nucleii that are stable or unstable against beta-decay: ${}^{A+1}_{Z}X \rightarrow {}^{A+1}_{Z+1}X + ?$

Naturally Occurring Elements with $Z > 26$ Exist!

- For high Z elements it is hard to get another charged particle close due to the high Coulomb potential barrier
- Not for neutrons: ${}^{A}_{Z}X + n \rightarrow {}^{A+1}_{Z}X + \gamma$
- Results in more massive nucleii that are stable or unstable against beta-decay: ${}^{A+1}_{Z}X \rightarrow {}^{A+1}_{Z+1}X + ?$
- ${}^{A+1}_{Z}X \rightarrow {}^{A+1}_{Z+1}X + e^{-} + \bar{\nu}_e + \gamma$

Neutron Processes

If beta-decay half-life is short compared to timescale for neutron capture

slow process or s-process reactions

tends to produce stable nucleii

If beta-decay half-life is long compared to timescale for neutron capture

rapid process or r-process reactions

tends to produce neutron rich nucleii

Neutron Processes

s-process tend to occur in normal phases of stellar evolution

r-process can occur during a supernova

Neither process plays a significant role in energy production

Accounts for abundances of nucleii with $A \gtrsim 60$, $(Z \gtrsim 26)$