Physics 160  
Stellar Astrophysics  
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Lecture 17

Star Evolution III: Stellar Remnants: White Dwarfs & Degenerate Matter

26 November 2013
Lecture 17: Star Evolution III:
Stellar End States and White Dwarfs
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PRELIMS
• Announcements [5 min]

MATERIAL [70 min]
• [15 min] Review
• [20 min] Stellar end states
• [10 min] White dwarfs
• [25 min] Degenerate matter

DEMONSTRATIONS/EXERCISES

MATERIALS
Review
• evolution of stars along MS: H->He, \( \mu \) changes
• continues until inert core’s mass gets too large – gravity wins over thermal + external pressure – He core collapse
  o mass limit: \( M_{\text{core}}/M_{\text{total}} = 0.37 \left( \mu_{\text{envelope}}/\mu_{\text{core}} \right)^2 \)
  o \( M_c \sim 10\% \) for Sun
• Post-MS evolution

End states of stars
• AGB phase – why mass loss? E.g. Betelguese \( v_{\text{thermal}} > v_{\text{escape}} \)
• Final state depends on mass
  o \( < 4 \) Msun => do not reach S-C mass limit for C/O core (\( \approx 0.24 \) Mtotal) => white dwarf
  o 4-8 Msun => add’l rxns occur up to Fe (list)
    ▪ alpha capture: C->O->Ne->Mg->Si
    ▪ \( T = 6e8 \) => C->O, Ne, Na, Mg
    ▪ \( T = 1e9 \) => O->Mg, Si, P, S; Si->S; S->Ar; ...
    ▪ \( T = 3e9 \) => “last reaction”: Cr->Ni
    ▪ At \( T > 1e9 \), atoms begin to disintegrate – collapse cannot be halted – Type II supernovae
  o Remnant core after SN depends on mass – neutron star, black hole or nothing!
• These endstates are increasingly influenced by the additional role of degeneracy pressure in supporting a star

White dwarfs
• Sirius B as an example – history
• Hot surface illuminates PNe – signposts of WDs
• Very common – end state of 97% of stars in Galaxy, >10k known
• Classification:
  o DA = H rich spectra
o DB = He rich spectra
o DC = no lines (why?)
o DO = He II (hot)
o DQ = C lines present
o DZ = metal lines present (accreted?)

• All supported by degeneracy pressure
Announcements

• Remote observing lab is OFF for tonight; 2 more opportunities Tuesday 12/3 and Thursday 12/5

• NO local lab – remote lab grade will be “doubled”

• Project papers deadline -> Friday at 4pm (email PDF preferred)

• Comet ISON a bust today!
We are discussing post-MS evolution of a low-mass star like the Sun.

AGB stars represent last gasps of stellar burning, accompanied with massive pulsations, from shell burning, mass loss, and eventually formation of planetary nebula.
A0B stars undergo tremendous mass loss: \( \dot{M} \approx 10^{-4} M_\odot/\text{yr} \) (episodic)

Composition is enriched due to dredge-up & material

Shells & dust go, form cold enough to form grains + dust

It produces a planetary nebulae

Goes to form ISM, next generation star

What's next?

\( M < 4 M_\odot \Rightarrow \) C/O core remains as envelope dissipates

\( \Rightarrow \) exposed core (very hot!) goes on to be a white dwarf

\( 4 < M < 8 M_\odot \Rightarrow \) add'l nucleosynthesis can occur

\[ \begin{align*}
\text{C} + \text{C} & \rightarrow \text{O} + \text{He} + \text{He} \\
(\text{T} \approx 6 \times 10^8 \text{K}) \\
\text{O} + \text{O} & \rightarrow \text{Ne} + \text{O} + \text{He} + \text{He} + \text{He} \\
(\text{T} \approx 10^9 \text{K})
\end{align*} \]

end on to

56 Fe - peak & nuclear binding energy

26 Fe - peak & nuclear binding energy
Why do AGB stars lose so much mass?

\[ T \sim 3 \times 10^4 \text{ K} \]

E.g. Betelgeuse

\[ M \sim 18 \text{ M}_\odot \sim 3.6 \times 10^{31} \text{ kg} \]

\[ R \sim 1200 \text{ R}_\odot \sim 8.4 \times 10^9 \text{ m} \]

\[ \langle \rho \rangle \sim \frac{3}{4} \frac{M}{R^3} \lesssim 10^{-5} \frac{\text{kg}}{\text{m}^3} \lesssim 10^{-8} \frac{\text{g}}{\text{cm}^3} \]

\[ (\text{cf. air} \sim 1 \frac{\text{kg}}{\text{m}^3}) \]

\[ \mathbf{g} \sim \frac{GM}{R^2} \lesssim 3.4 \times 10^{-3} \frac{\text{m}}{\text{s}^2} \quad (\text{cf. Earth} \sim 10^{-2} \text{m/s}^2) \]

\[ V_{\text{esc}} = \sqrt{2gR} \sim 80 \text{ km/s} \quad (\text{cf. Earth} \sim 11 \text{ km/s}) \]

\[ \text{Sun} \sim 600 \text{ km/s} \]

\[ \langle V^2 \rangle \sim \frac{3\mathbf{g} \rho}{M R^3} \lesssim 1.2 \times 10^{-7} \text{ cm}^2 \]

\[ \sqrt{\langle V^2 \rangle} \sim 350 \text{ km/s} \]

\[ \uparrow \]

thermal motion is enough!
A red giant contracts: 

\[ ^{14} \text{Si} \rightarrow ^{32} \text{S} \]

\[ ^{32} \text{S} \rightarrow ^{36} \text{Ar} \]

\[ ^{36} \text{Ar} \rightarrow ^{36} \text{Ar} \]

\[ 3 \times 10^9 \text{K} \rightarrow ^{56} \text{Fe} \rightarrow ^{56} \text{Fe} \rightarrow \text{SN (Type II)} \]

On the shell burning:

Why collapse? 

- Fe photodisintegrates:
  \[ ^{56} \text{Fe} + \gamma \rightarrow ^{13} \text{C} + ^{4} \text{He} + 4 \nu \]

- \[ ^{4} \text{He} + \gamma \rightarrow ^{1} \text{p} + ^{3} \text{He} \]

Very high energy photons:

\[ \text{loss of } \text{Fe + } ^{3} \text{He degeneracy} \]

\[ T > 10^9 \text{K} \rightarrow \text{loss of pressure support} \]

How much energy released?

- 10 Me star \rightarrow 1.3 Me core for Fe photodisintegration to start

\[ U \]

\[ \rho \sim 10^{13} \text{ kg/m}^3 \Rightarrow R \cong \left( \frac{3 \times 10^{5} \text{ m}}{4 \pi \rho} \right) \approx 4 \times 10^{5} \text{ m} \approx 0.1 \text{ R}_\odot \]

\[ \text{E} \gamma \text{ potential} \sim -\frac{3}{5} \frac{6m^2}{R} \approx -7 \times 10^{44} \text{ J} \]

- collapses to \approx 50 km ball = \[ U \sim -\frac{3}{5} \frac{6m^2}{R_{50}} \approx -10^{46} \text{ J} \approx \text{~10^{48} J lost} \]

About right energy: scale for SN explosion.
Planetary Nebulae imaged by the Hubble Space Telescope
White Dwarf

For low-mass stars (M < 0.5M\(_\odot\)), no SN explosion occurs; envelope is dissipated through stellar winds ⇒ left with a neon core & C/O, shell & H/He that is very hot

![Diagram of a white dwarf with important parameters and core properties.]

Shell & gas created by high energy photons ⇒ planetary nebula

\[ T \sim 10^5 \text{K} \Rightarrow \lambda_{\text{peak}} = 30 \text{nm} \]

⇒ UV

Core is extremely compact: \[ M \approx M_{\text{Me}} \]

\[ \frac{M}{R_{\odot}} \approx \frac{M}{R_{\odot}} \]

(Sirius B core)

\[ \langle \rho \rangle = \frac{3 M}{4 \pi R^3} \approx 2 \times 10^9 \text{ kg/m}^3 \]

\[ \approx 2 \times 10^6 \text{ g/cm}^3 \]

⇒ Lead \approx 11 \text{ g/cm}^3

Osmium \approx 22.6 \text{ g/cm}^3

\[ P_c = \frac{GM^2}{R^4} \approx 1.4 \times 10^{23} \text{ N/m}^2 \approx 2 \times 10^{18} \text{ bar} \]

\[ \tau \sim \text{core} \ ⇒ \ \text{sun} \ P \sim 10^{36} \text{ N/m}^2 \]

\[ \frac{dT}{dR} = \frac{-3}{4 \pi c} \frac{\epsilon \rho L R}{T^3 \ 4\pi R^2} \]

⇒ 0.02 \text{W/kg} for e\(^-\) scattering

\[ T_c \sim \frac{l_{\text{sun}}^2}{2 \pi} \frac{3}{6\pi} \frac{\epsilon \rho L}{c T_c^3 R^2} \]

⇒ 0.03 L\(_\odot\) for Sirius B

\[ T_c \sim \left( \frac{2}{6\pi} \frac{\epsilon \rho L}{c R} \right)^{1/4} \sim 7 \times 10^7 \text{ K} \]

⇒ hot enough to fuse H!

⇒ no H inside

White dwarfs are supported by the physics of degenerate matter
Example of a WD: \( \text{Sirius B} \)

1844 - Russell figured out Sirius had companion due to "astrometric wobble" (pull on Sirius by companion) \( M_B \approx 1 \, M_\odot \)

1862 - Alvan Clark detected Sirius B at angular 0.10" very faint: \( L_B \approx 0.03 \, L_\odot \)

\( \Rightarrow \) should be a cool \( M \)-type dwarf.

1917 - Walter Adams obtained spectrum, found Sirius B to be a hot blue star, \( T_B \approx 27,000 \, \text{K} \) \( \text{(vs.} T_\odot \approx 6,000 \, \text{K}) \)

\( \Rightarrow \) \( L = \frac{4\pi}{3} R^2 T^4 \rightarrow \frac{L}{4\pi (0.03 \, L_\odot)^4} \approx 5.5 \times 10^6 \, M_\odot \approx 0.9 \, R_{\text{Earth}} \)

Sirius B is a solar-mass star packed into an object the size of the Earth!