Section 4. Stellar evolution

> **4.1 Virial theorem 4.2 Evolution of density and temperature**

Let's understand these questions with the words of physics

- Why are stars so luminous?
- Why do stars show $L \sim M⁴$?
- Why do stars evolve?
- Why does the destiny of stars depend on the mass?
- Why do some stars explode?
- Why don't normal star explode?
- Why does stellar core collapses?
- **Why is the energy of supernova so huge?**

Stellar life

IMAGES NOT TO SCALE

(C: Essay Web)

Black Hole

1. Massive stars

~ 10 Mem **M > 10 Msun**

Why do stars evolve??

"Evolution" = Changes in the state with time

What happens when there is no more fuel for nuclear burning

Etot: Total energy Ω: Gravitational energy U: Internal energy

$$
U=-\frac{1}{2}\Omega
$$

$$
E_{\rm tot} = U + \Omega = \frac{1}{2}\Omega = -U
$$

No nuclear burning

- **Total energy decreases**
- **Contraction (gravitational energy decreases)**
- **Temperature rises**

Heated iron stars

Gets colder

Gets hotter

Condition of H-burning

Lecture Note by Pols

Nuclear binding energy

 $Eb = [Nm_N + Zm_p - m_i]$ $c^2 > 0$

Larger binding energy = more stable

Fe has the largest Eb/nucleon

Then, all the stars produce Fe? => No Stellar material does not always behave as ideal gas

元素はいかにつくられたか(岩波書店)

Do all the stars evolve to Fe core?? => No

Equation of state is important Stellar interior is not always ideal gas state

2. Low-mass stars **M** < 10 Msun **M < 10 Msun**

Stellar Cloud with Protostars

図の大きさは天体の大きさと一致していません

(C: Essay Web)

H He

C + O

White dwarf: supported degeneracy pressure

温度がゼロでも圧力が生まれる

温度がゼロでも圧力が生まれる

P is non-zero even at T=0

星が「死ぬ」とはどういうことか (ベレ出版)

regions where radiation pressure, ideal gas pressure, non-relativistic electron degeneracy and extremely relativistic electron degeneracy dominate, for a composition of *X* = 0.7 and *Z* = 0.02. In the right panel, schematic **textbook by Pols**

Assignment 2 For those who have not taken stellar evolution in undergrad course

- **2a. Derive pressure of ideal gas from the Maxwell distribution**
- **2b. Derive pressure of degenerate electrons (both for non-relativistic case and relativistic case)**
- **2c. Derive radiation pressure from Planck function**
- **2d. Draw the regions where**
- **ideal gas pressure**
- **degenerate pressure of non-relativistic electrons**
- **degenerate pressure of relativistic electrons**
- **radiation pressure**

become dominant in the rho-T diagram.

レポート課題 **2**

学部の恒星物理学**II**をとっていない人

2a. マクスウェル分布から 理想気体の圧力の式を導け

- **2b.** 電子が非相対論的、超相対論的なときの 縮退圧の式を導き、実際に数字を入れて計算せよ
- **2c.** プランク関数から輻射圧の式を導け
- **2d.** 密度温度平面で
- 理想気体のガス圧
- 電子の縮退圧(非相対論的)
- 電子の縮退圧(超相対論的)
- 輻射圧

がそれぞれ支配的になる境界を求め、図示せよ

Please attend some part of the conference

"ELT Science in Light of JWST" at Katahira from June 3-7.

Summarize the one of the invited talks you got interested in (e.g., specification of TMT/GMT/ELT, some science cases)

about 2 pages, A4

レポート課題2 学部の恒星物理学IIをとった人

6月**3-7**日に片平キャンパスで行われる **"ELT Science in Light of JWST" (**の一部**)**に参加して 興味のある招待講演の内容をまとめる **(e.g., TMT/GMT/ELT**のスペック**,** サイエンスケース**)**

 A4で**2**ページ程度

Summary: Stellar evolution

- **• Virial theorem (for ideal gas case)**
	- Internal energy always relates with gravitational energy
	- When stars lose energy, they contract
	- Temperature rises ("negative heat capacity")
- **• Evolution of density and temperature**
	- Rise in temperature due to contraction $T \sim \rho^{1/3}$
	- Next burning stages => Onion-like structure
- **• Importance of the equation of state**
	- **Stars stop contraction if supported by degeneracy pressure** => No temperature rise => End of nuclear burning
	- The core of low mass stars become a white dwarf

Appendix

1a. H-burning (pp chain) $4^1H \rightarrow 4He + 2e^+ + 2v$ sured in the laboratory and is only known from theory. quently three different branches are possible to complete the chain towards 4He: possible towards 4He: possible

$4 \text{ }^1\text{H} \rightarrow \text{ }^4\text{He} + 2 \text{ e}^+ + 2 \text{ v}$

twice. The alternative process require process require only one 3He nucleus and an already existing 4He nucleus an **Textbook by Pols**

 $(per gram)$ always necessary for hydrogen burning. This can take place in two distinct ways: either distinct ways: either d
This can take place in two distinct ways: either distinct fusion of two distinct fusions of the can take place of protons via the *p-p chain*, or by using already present CNO-nuclei as catalysts in the *CNO cycle*. Hydrogen burning in stars takes place at temperatures ranging between 8 [×] 106 K and 5.⁰ [×] 107 K, **Energy production rate q ~ ρT4**

^H ⁺ ^e⁺ ⁺ ^ν or p ⁺ ^p [→] ^D ⁺ ^e⁺ ⁺ ^ν . (6.45) This involves the simultaneous β-decay of one of the protons during the strong nuclear interaction. **T ~ 4 x 106 K**This is very unlikely and the p-p reaction the p-p reaction the p-p reaction the p-p reaction, about 10−2000 μ

Textbook by Prialnik

 $T_{\rm{c}}$ branch requires two 3He nuclei, so the first two reactions in the chain have to take place twice. The alternative police require only one 3He nucleus and an already existing 4He nucleus and an already existing \sim

1b. H burning (CNO cycle) The CNO cycle IF SOME C, N, and O is also also we allowed the gas of which a starting the temperature of the temperature o is sufficiently high, hydrogen fusion can take place via the so-called *CNO cycle*. This is a cyclical **T ~ 1.5 x 107 K** sequence of reactions that typically starts with a proton capture by a proton capture by a 12C nucleus, as follows: **E production rate q ~ ρT16**

$$
{}^{12}C + {}^{1}H \rightarrow {}^{13}N + \gamma
$$

\n
$$
{}^{13}N \rightarrow {}^{13}C + e^{+} + \gamma
$$

\n
$$
{}^{13}C + {}^{1}H \rightarrow {}^{14}N + \gamma
$$

\n
$$
{}^{14}N + {}^{1}H \rightarrow {}^{15}O + \gamma
$$

\n
$$
{}^{15}O \rightarrow {}^{15}N + e^{+} + \gamma
$$

\n
$$
{}^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He
$$

\n
$$
\rightarrow {}^{16}O + \gamma
$$

\n
$$
{}^{16}O + {}^{1}H \rightarrow {}^{17}F + \gamma
$$

\n
$$
{}^{17}F \rightarrow {}^{17}O + e^{+} + \gamma
$$

\n
$$
{}^{17}O + {}^{1}H \rightarrow {}^{14}N + {}^{4}He
$$

TEAH - 1H AS 'FAST' REFERS TO THE DIFFERENCE IN CALCULATION FACTORS AND NOT TO THE NUMBER OF REACTIONS PER SECTIONS PE **Textbook by Prialnik**

Textbook by Pols

2. He-burning (triple alpha) H_{eff} is the function of the fusion of \mathbb{R}^n in the function of \mathbb{R}^n temperatures *^T* [∼] > 108 K. Such high temperatures are needed because (1) the Coulomb barrier for 2 He-hurning (trinle alnha

⁴He + ⁴He
$$
\leftrightarrow
$$
 ⁸Be
\n⁸Be + ⁴He \rightarrow ¹²C^{*} \rightarrow ¹²C + γ
\n¹²C + ⁴He \rightarrow ¹⁶O + γ ,

the second reaction 8Be(α, γ) **Energy production rate (per gram) q ~ ρ2T40**

$\mathbf{r} \approx \mathbf{4} \mathbf{r} \approx \mathbf{4} \mathbf{0}$ **T ~ 1.5 x 108 K**

Textbook by Prialnik

3. C-burning 3. C-bu **Neon burning** The next nuclear burning cycle might be expected to be oxygen fusion, but already at somewhat lower temperature (*T*⁹ ≈ 1.5) a process called 'neon burning' is initiated by the photo-

$$
{}^{12}\text{C} + {}^{12}\text{C} \rightarrow {}^{24}\text{Mg}^* \rightarrow {}^{20}\text{Ne} + \alpha
$$
\n
$$
\rightarrow {}^{23}\text{Na} + \text{p}
$$
\nT² 7 x 10⁸ K

20Ne + γ Φερτικά του Αγγελία του Αγγελί
20Ne + γ Φερτικά του Αγγελία του Αγγ

12C(p, γ)

$$
{}^{20}\text{Ne} + \gamma \leftrightarrow {}^{16}\text{O} + \alpha
$$

$$
{}^{20}\text{Ne} + \alpha \rightarrow {}^{24}\text{Mg} + \gamma
$$

T ~ 1.5 x 10⁹ K

4. Ne-burning the contract of in the mixture, from 12C to 24Mg. Examples are 23Na (p, α) and 23Na (p, α) and 23Na (p, α) and 23Na (p, α) and 13C(α, n)16O, where the neutron will immediately react further. The overall energy disintegration of 20Ne. At this temperature a sufficient number of photons have energies in the MeV of photons
At this temperature a sufficient number of photons have energies in the MeV of photons have energies in the Me immediately followed by the capture of the capture of the a particle by another 20Ne nucleus, thus: thus: thus: T_{C} reaction is equal to $\frac{16}{160}$ + 24 Mg $\frac{16}{160}$

T ~ 1.5 x 109 K

C burning the overall composition has a 'neutron excess' (n/p > 1, or µ*^e* > 2). The first reaction is endothermic, but effectively the two reactions combined \mathcal{L} 5. O-burning the contract of t Oxygen burning At an al-T9 ≈ 2.0 million of 16O nuclei sets in many ways and ways and ways and ways and ways a
The contract of 16O nuclei sets in many ways and ways an

95% by mass fraction).

$$
{}^{16}O + {}^{16}O \rightarrow {}^{32}S^* \rightarrow {}^{28}Si + \alpha
$$
\n
$$
\rightarrow {}^{31}P + p
$$
\nT ~ 2-3 x 10⁹ K

 \rightarrow ²⁸Si + α **T** ~ 2-3 x 10⁹ K **T ~ 2-3 x 109 K**

6. Si-burning (Nuclear statistical equilibrium) T > 4 x 109 K the Coulomb barrier for 28Si + 28Si fusion is prohibitively high. Instead silicon burning proceeds by a series of photo-disintegration (γ, ^α) and ^α-capture (α, ^γ) reactions when *^T*⁹ [∼] *^Q* [≈] 16 MeV. Since some of the side reactions involve ^β+-decays and electron captures, the neutron e. SPDUITHING (INUCIEDI SLAUSL 6 Si-hurning (Nuclear statistical equilibrium) *C* is the station station capture in the side of the side of the neutron capture in the neutron capture i excess of the final mixture is further increased.

High temperature => photo-dissociation

$$
^{28}\text{Si}(\gamma,\alpha)^{24}\text{Mg}(\gamma,\alpha)^{20}\text{Ne}(\gamma,\alpha)^{16}\text{O}(\gamma,\alpha)^{12}\text{C}(\gamma,\alpha)2\alpha
$$

28Si (γ, α) 24 Mg (γ, α) 24 Mg (γ, α) 200 Mg (γ, α) 2α του 2α a series of photo-disintegration (γ, ^α) and ^α-capture (α, ^γ) reactions when *^T*⁹ [∼] 'melts' into lighter nuclei, while another part captures the released 4He to make heavier nuclei: while another part captures the released 4He to make heavier nuclei: while another part capture \mathcal{A}

$$
^{28}\text{Si}(\alpha,\gamma)^{32}\text{S}(\alpha,\gamma)^{36}\text{Ar}(\alpha,\gamma)^{40}\text{Ca}(\alpha,\gamma)^{44}\text{Ti}(\alpha,\gamma) \dots^{56}\text{Ni}
$$

 \Rightarrow equilibrium of many reactions

$$
(\mathsf{Ex.})
$$

'melts' into lighter nuclei, while another part captures the released 4He to make heavier nucleicher part capt
'melts' into lighter nucleis the released 4He to make heavier nucleicher nucleicher nucleicher nucleicher nucl

$$
= 2 \text{ equilibrium on many reductions}
$$
\n
$$
2^8 \text{Si} + \gamma \leftrightarrow 2^4 \text{Mg} + \alpha,
$$

6.5 Neutrich Executives entre Nuclei with high binding energy tend to be produced (Fe, Co, Ni) where the most abundant nuclei are those with the lowest binding energy, constrained by the lowest binding energy, constrained by the total strained by the lowest binding energy, constrained by the total strained by the to