3. Star Deaths (별의 죽음)
3-1 Final Stages of Stellar Evolution
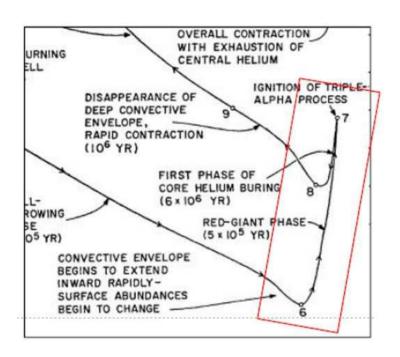(항성 진화의 마지막 단계)

김상철
(Sang Chul KIM)

© Anglo-Australian Observatory

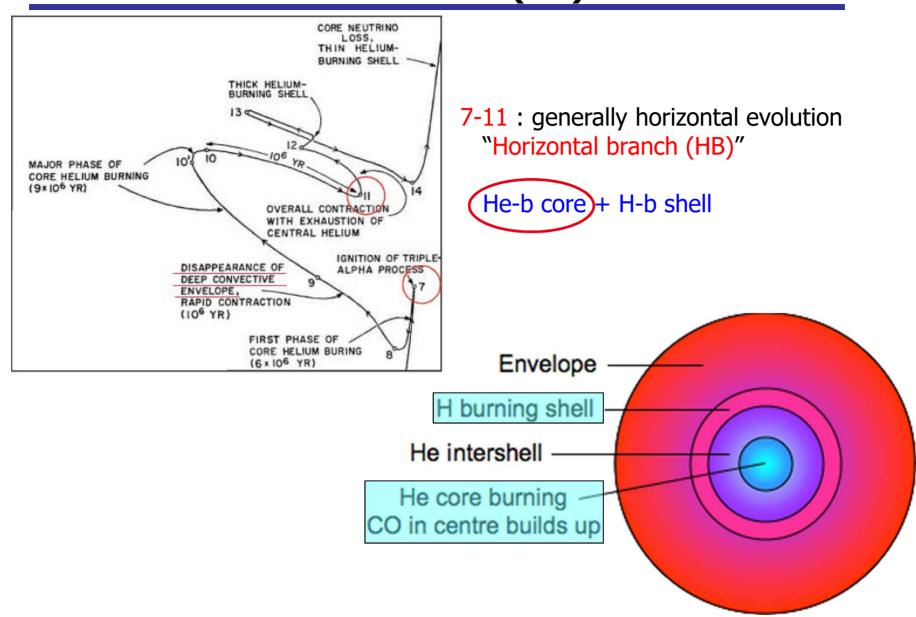# 5 $M_\odot$ star evolution after ignition of the triple-α process

- At point 7 :
- $T_c = 1.3 \times 10^8$ K, $\rho_c = 7700$ g/cm^3
- High central T and ρ
  → triple-α process begins

- Strong temperature-dependence

$$\epsilon_{3\alpha} \simeq \epsilon'_{o,3\alpha} \rho^2 Y^3 f_{3\alpha} T_8^{41.0}$$
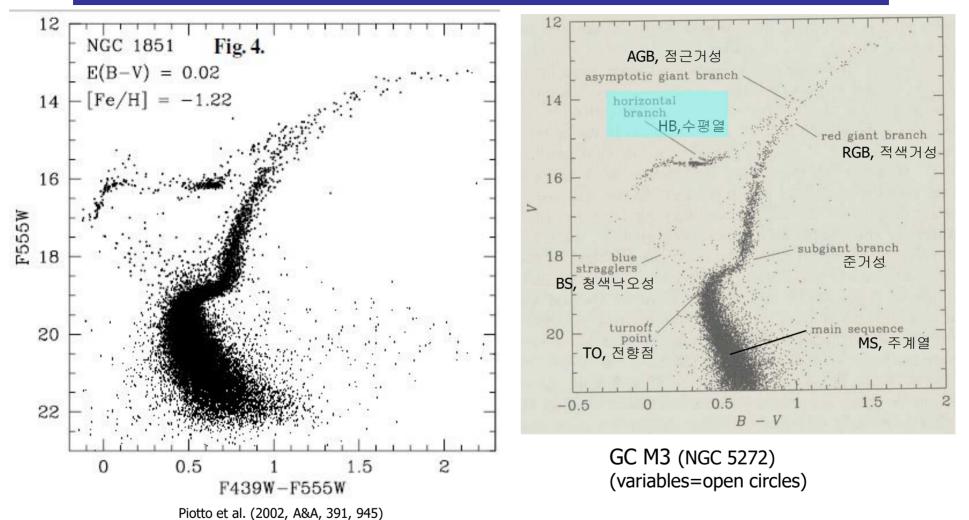
$$(T_8 \equiv T/10^8 \,\mathrm{K})$$

- (7→8)
- New E source in core → core expands → shell E-output ↓ → L↓
  Envelope contracts → T_{eff} ↑

- (8→10)
- Since envelope contraction → H-b shell compresses → shell E-output↑ → L↑

Horizontal Branch (HB) Stars

CORE NEUTRINO LOSS, THIN HELIUM-BURNING SHELL

THICK HELIUM-BURNING SHELL

13

12

10^6 YR

10' 10

MAJOR PHASE OF CORE HELIUM BURNING (9×10^6 YR)

11 14

OVERALL CONTRACTION WITH EXHAUSTION OF CENTRAL HELIUM

IGNITION OF TRIPLE-ALPHA PROCESS

DISAPPEARANCE OF DEEP CONVECTIVE ENVELOPE, RAPID CONTRACTION (10^6 YR)

9 7

FIRST PHASE OF CORE HELIUM BURING (6×10^6 YR) 8

7-11 : generally horizontal evolution
"Horizontal branch (HB)"

He-b core + H-b shell

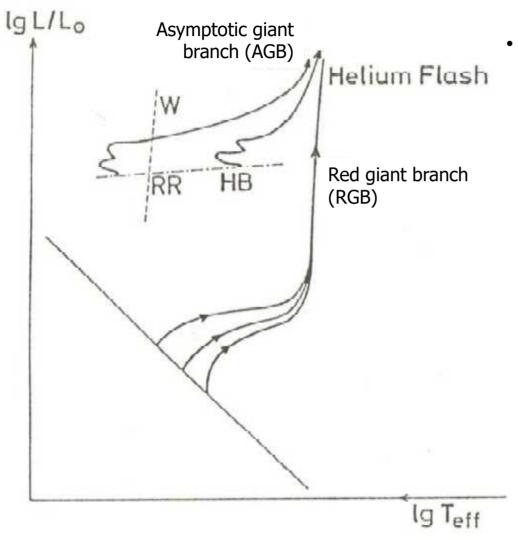
Envelope

H burning shell

He intershell

He core burning CO in centre builds up

https://astronomy.swin.edu.au/cosmos/H/Horizontal+Branch+stars

3

Color-Magnitude Diagrams for globular clusters (GCs)

NGC 1851 Fig. 4.
E(B−V) = 0.02
[Fe/H] = −1.22

Piotto et al. (2002, A&A, 391, 945)

AGB, 점근거성
asymptotic giant branch

horizontal branch
HB,수평열

red giant branch
RGB, 적색거성

blue stragglers
BS, 청색낙오성

subgiant branch
준거성

turnoff point
TO, 전향점

main sequence
MS, 주계열

GC M3 (NGC 5272)
(variables=open circles)

Post-HB Evolution – in HR diagram

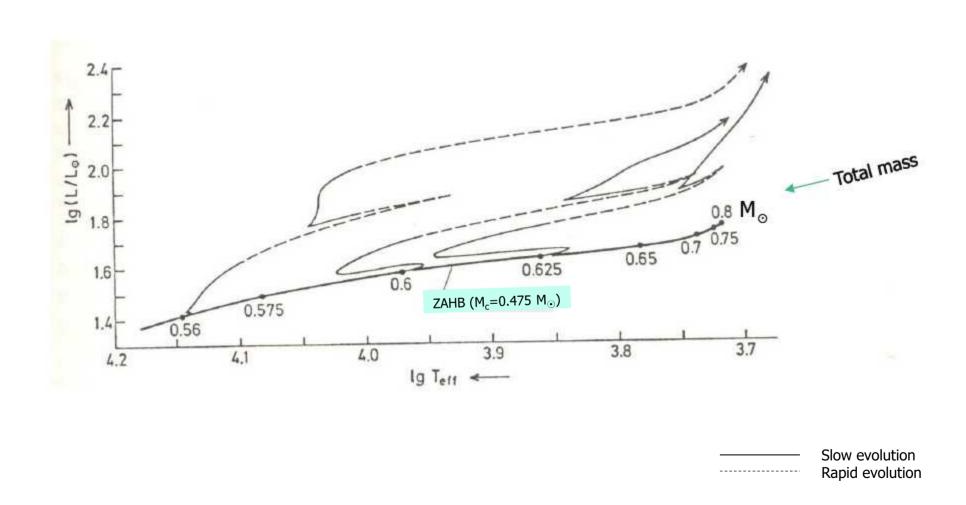- Evolution of low-mass stars, with three different masses
  (W = W Virginis stars)
  (RR = RR Lyrae stars)
  (HB = Horizontal branch stars)

Post-HB Evolution – in HR diagram

Zero-age HB (ZAHB) and evolution afterwards
(He-core M_c =0.475 $M_\odot$, H-rich envelope with X=0.699, Y=0.3)

ZAHB (M_c=0.475 $M_\odot$)

0.8 $M_\odot$

Total mass

——— Slow evolution
-------------- Rapid evolution

Pulsating Variable Stars

HB stars in the instability strip (IS) = RR Lyrae stars
→Instabilities in outer envelope
→Periodic pulsations
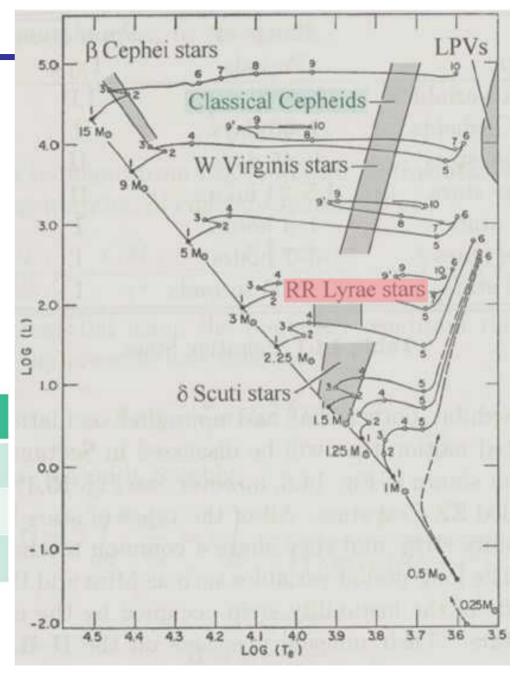→Variations in L, T, R, surface radial vel.

Instability strip
 : narrow (~600 – 1000K wide)

Stars evolve horizontally along the IS
→Enters : starts pulsating
→Leaves : cease pulsating

Type	Periods	Population	Comments
Classical Cepheids	1-50 days	I	Radial Pulsation
W Virginis stars (Pop II Cep)	2-45 days	II	Radial Pulsation
RR Lyrae stars	1.5 – 24 hours	II	Radial Pulsation

These stars are distance indicators !

An Introduction to Modern Astrophysics (2nd edition), Bradley W. Carroll & Dale A. Ostlie (1996), p. 547

7

RR Lyrae stars

- Periodic variable stars
- P = 1.5 to 24 h (~12 h), Peak $M_V \sim$ 0-1 mag, spectra A2 to F6
- Current mass ~ 0.8 $M_\odot$ (original MS mass ~ 1 $M_\odot$), old, relatively metal-poor
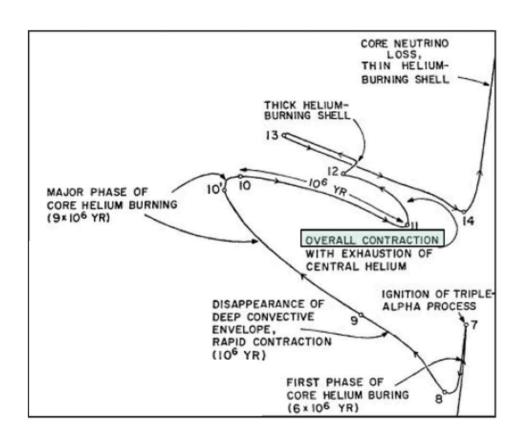- In GCs and in low-metallicity systems (population II) – But, some have high metallicity

$M_V(RR) = +0.71 \pm 0.12$ at $\langle [Fe/H] \rangle = -1.61$ for the halo (162 stars)

$M_V(RR) = +0.79 \pm 0.30$ at $\langle [Fe/H] \rangle = -0.76$ for the thick disk (51 stars)

Layden et al. (1996, AJ, 112, 2110)

$$\langle M_V \rangle = (0.16 \pm 0.03)[Fe/H] + 1.02 \pm 0.03 \qquad (5.24)$$

$$\langle M_K \rangle = -(2.3 \pm 0.2)\log(P/1\,d) - 0.88 \pm 0.06 \qquad (5.25)$$

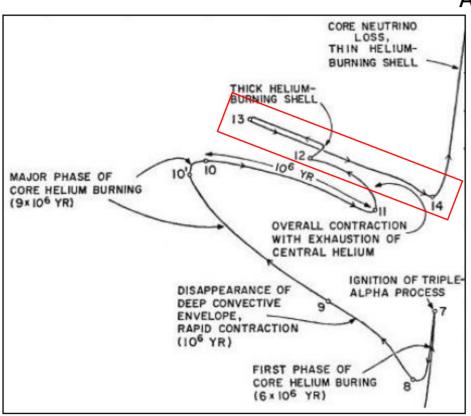$$\langle M_K \rangle = -(2.0 \pm 0.3)\log(P/1\,d) + (0.06 \pm 0.04)[Fe/H] - 0.7 \pm 0.1 \qquad (5.26)$$

Post-HB, early-AGB (E-AGB)

- At point 11 : core He exhausted
  → entire star contracts
  → core T ↑

- At near 12
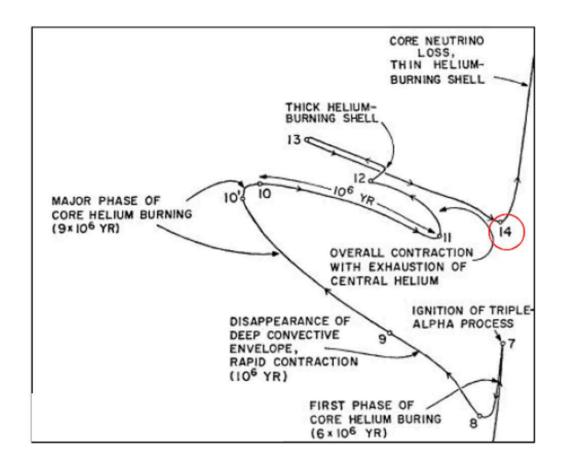 : thick He-b shell develops

Asymptotic giant branch (AGB) stars

Early-AGB (E-AGB)

After point 12

- He-b shell produces more E
- Envelope expands + cools

- T_{eff} ↓ → convective envelope deepens again (extending downward to the chemical discontinuity between the H-rich outer layers and the He-rich region above the He-b shell)
→ Mixing = **second dredge-up**
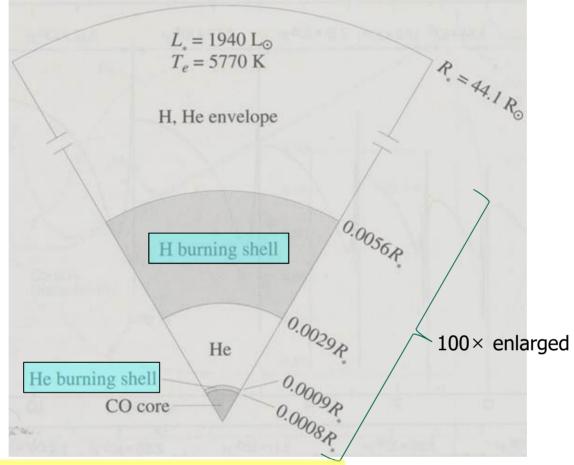→ Increases He-, N-content of the envelope

Early-AGB (E-AGB)

CORE NEUTRINO
LOSS,
THIN HELIUM-
BURNING SHELL

THICK HELIUM-
BURNING SHELL

13

12

10^6 YR

10' 10

MAJOR PHASE OF
CORE HELIUM BURNING
(9×10^6 YR)

11

14

OVERALL CONTRACTION
WITH EXHAUSTION OF
CENTRAL HELIUM

DISAPPEARANCE OF
DEEP CONVECTIVE
ENVELOPE,
RAPID CONTRACTION
(10^6 YR)

IGNITION OF TRIPLE-
ALPHA PROCESS

9

7

FIRST PHASE OF
CORE HELIUM BURING
(6×10^6 YR)

8

At point 14 :
$T_c \sim 2 \times 10^8$ K, $\rho_c \sim 10^6$ g/cm^3

Interior structure →

Inert CO core +
Two shell sources
(not to scale)

$L_* = 1940\ L_\odot$
$T_e = 5770\ K$

H, He envelope

$R_* = 44.1\ R_\odot$

H burning shell

$0.0056 R_*$

$0.0029 R_*$

He

He burning shell

$0.0009 R_*$

CO core

$0.0008 R_*$

100× enlarged

H shell burning : begins to turn-on and -off periodically
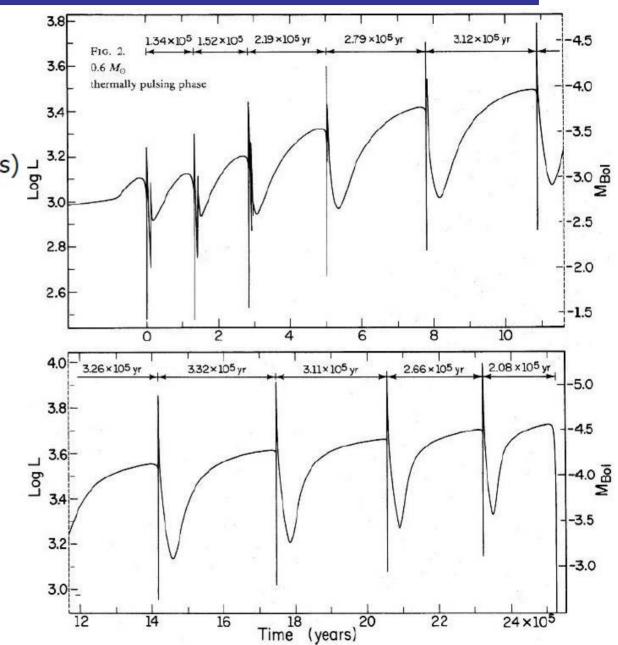
H-b shell dumps He onto the He-layer → He-layer mass↑, becomes slightly degenerate
  → He-layer T↑ → He-shell flash (similar to the core He flash of low-mass stars, but much less energetic)
  → Drives H-b shell outward → cool, turn-off for a time

He-shell burning diminishes → contract, T↑ → H-shell burning recovers → repeats → **thermally pulsing AGB**

Thermally pulsing AGB (TPAGB)

- 0.6 $M_\odot$

- Pulse period = f(stellar mass)
  : from 10^3 years (~5 $M_\odot$)
   to 10^5 years (~0.6 $M_\odot$)

- Pulse amplitude grows
  w/successive event

FIG. 2.
0.6 $M_\odot$
thermally pulsing phase
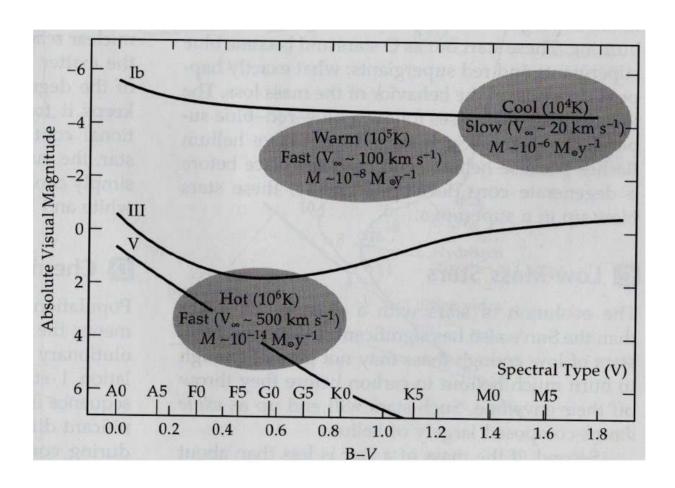
Iben 1982 (ApJ, 260, 821 – Low mass AGB evolution. I.)

AGB stars

- AGB stars – strong wind + rapid mass-loss $\dot{M} \sim 10^{-4} M_\odot \ yr^{-1}$ "superwind"

Cool (effective T ~3,000 K)

→ dust grains exist in the matter expelled

- O-rich environment → Silicate grains form
- C-rich environment → Graphite grains form

- Stellar initial masses evolving to AGB : $0.89 \leq M/M_\odot \leq 5.0$

(Vassiliadis & Wood 1993, ApJ, 413, 641 : Evolution of low- and intermediate-mass stars to the end of the AGB with mass loss)

- Evolution afterwards
- depends on initial mass and mass-loss
- massive stars – burnings up to form Fe → neutron stars (NSs), black holes (BHs)
- low-mass stars – white dwarfs (WDs) + planetary nebulae (PNe)
- dividing mass ~ 8 $M_\odot$

Mass Loss Rates

- Solar mass loss rate (via wind) : 10^{-14} $M_\odot$/yr
- RGB and supergiants, massive O-type stars : $10^{-7} \sim 10^{-6}$ $M_\odot$/yr

Thermonuclear Energy Generation Stages

Process	Fuel	Major products	Temperature (K)	Minimum mass ($M_\odot$)
H-burning	H	He	$1\text{-}3\times10^7$	0.1
He-burning	He	$^{12}_{6}$C, $^{16}_{8}$O	2×10^8	1
C-burning	C	$^{16}_{8}$O, $^{20}_{10}$Ne, $^{23}_{11}$Na, $^{23}_{12}$Mg, $^{24}_{12}$Mg	8×10^8	1.4
Ne-burning	Ne	$^{16}_{8}$O, $^{24}_{12}$Mg	1.5×10^9	5
O-burning	O	$^{24}_{12}$Mg, $^{27}_{13}$Al, $^{28}_{14}$Si, $^{31}_{15}$P, $^{32}_{16}$S	2×10^9	10
Si-burning	Mg to S	near Fe	3×10^9	20

Thermonuclear Energy Generation Stages

Table 1 Evolution of a 15-solar-mass star.

Stage	Timescale	Fuel or product	Ash or product	Temperature (10^9 K)	Density (gm cm^{-3})	Luminosity (solar units)	Neutrino losses (solar units)
Hydrogen	11 Myr	H	He	0.035	5.8	28,000	1,800
Helium	2.0 Myr	He	C, O	0.18	1,390	44,000	1,900
Carbon	2000 yr	C	Ne, Mg	0.81	2.8×10^5	72,000	3.7×10^5
Neon	0.7 yr	Ne	O, Mg	1.6	1.2×10^7	75,000	1.4×10^8
Oxygen	2.6 yr	O, Mg	Si, S, Ar, Ca	1.9	8.8×10^6	75,000	9.1×10^8
Silicon	18 d	Si, S, Ar, Ca	Fe, Ni, Cr, Ti, . . .	3.3	4.8×10^7	75,000	1.3×10^{11}
Iron core collapse*	~1 s	Fe, Ni, Cr, Ti, . . .	Neutron star	>7.1	$>7.3 \times 10^9$	75,000	$>3.6 \times 10^{15}$

* The pre-supernova star is defined by the time at which the contraction speed anywhere in the iron core reaches 1,000 km s^{-1}.

Stellar lifetimes

Table 1 Stellar lifetimes[a] for a selection of solar-metallicity ($Z = 0.014$) models (using models from Karakas 2014)

Mass/$M_\odot$	Main sequence		RGB		Core He burning		AGB		Total[b]
1.0	9685	79%	2360	19%	118.3	1%	21.35	0.1%	12,186
2.0	874.5	74%	162.3	14%	130.9	11%	18.21	2%	1185.9
5.0	80.03	74%	3.053	3%	23.07	21%	1.997	2%	108.15
8.0	29.12	80%	0.484	1%	6.475	18%	0.435	1%	36.519

[a]Lifetimes are in Myr (10^6 years)
[b]The total stellar lifetimes includes all nuclear burning phases but does not include the post-AGB or white dwarf cooling phases
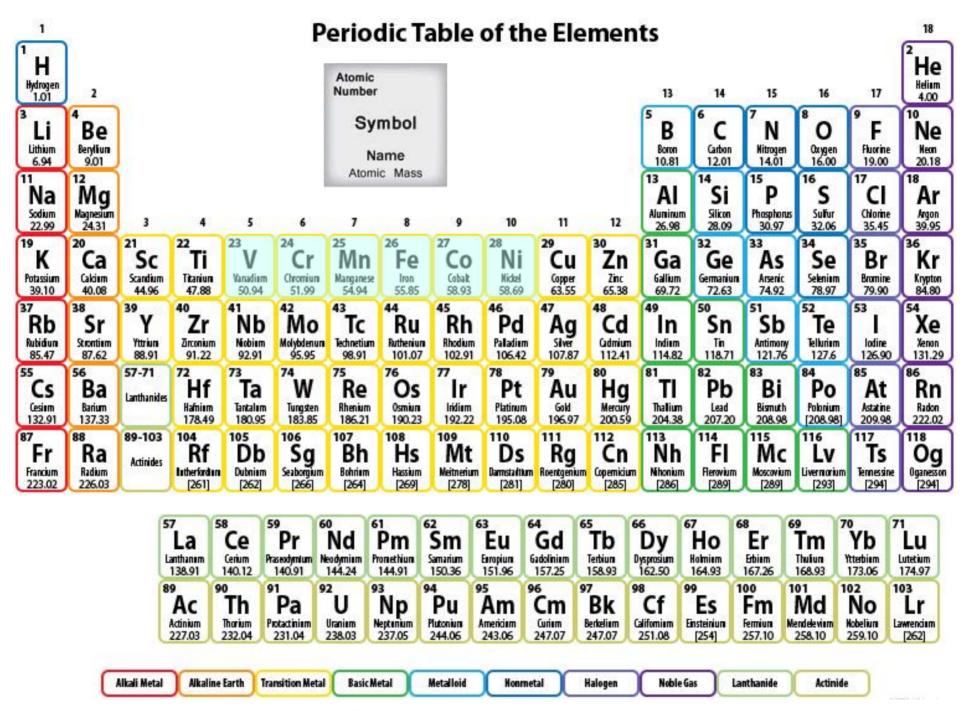
Evolving up the AGB (asymptotic giant branch)

- **Early-AGB (E-AGB)** : He shell burning
  Radius increases (up to 1 AU ~215 $R_\odot$)

- **Thermally pulsing AGB (TP-AGB)** :
  when He shell runs out of fuel → H shell burning
  when He builds up → He-shell ignites explosively (He-shell flash)

- He-b shell converts more and more of the He into C and then into O
  → CO core mass ↑ / core contracts slowly, ρ_c↑
  → electron degeneracy pressure begins to dominate

- Similar to the development of an electron-degenerate He-core
  in a low-mass star during its rise up the RGB

Massive (M ≥ 8 $M_\odot$) star evolution

- He-b shell → add ash to the CO core
- CO core continues to contract
- $^{12}_{6}C$-burning starts
- By-products : $^{16}_{8}O$, $^{20}_{10}Ne$, $^{23}_{11}Na$, $^{23}_{12}Mg$, $^{24}_{12}Mg$

- NeO core
- $^{16}_{8}O$-burning starts
→ Making $^{28}_{14}Si$-dominated (and $^{32}_{16}S$) core

At T~3×10^9 K → Si-burning starts

Making iron($^{56}_{26}Fe$)-peak elements, like $^{54}_{26}Fe$, $^{56}_{26}Fe$, $^{56}_{28}Fe$, and finally iron-core
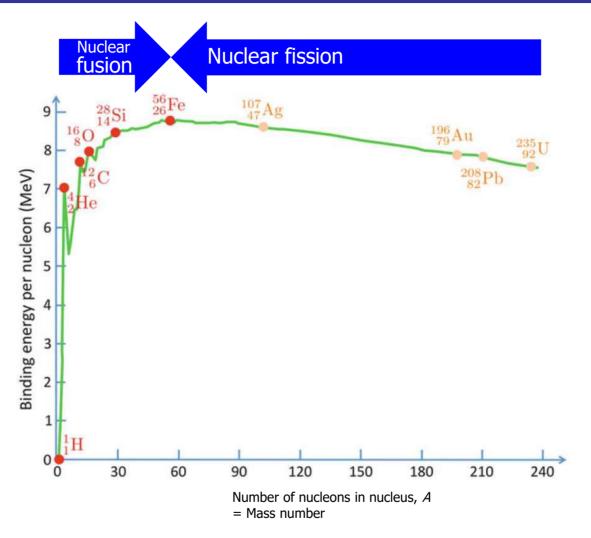
$50 \le A \le 62$

(Atomic mass)

Periodic Table of the Elements

1																	18
1 H Hydrogen 1.01	**2**											**13**	**14**	**15**	**16**	**17**	**2** He Helium 4.00
3 Li Lithium 6.94	**4** Be Beryllium 9.01											**5** B Boron 10.81	**6** C Carbon 12.01	**7** N Nitrogen 14.01	**8** O Oxygen 16.00	**9** F Fluorine 19.00	**10** Ne Neon 20.18
11 Na Sodium 22.99	**12** Mg Magnesium 24.31	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13** Al Aluminum 26.98	**14** Si Silicon 28.09	**15** P Phosphorus 30.97	**16** S Sulfur 32.06	**17** Cl Chlorine 35.45	**18** Ar Argon 39.95
19 K Potassium 39.10	**20** Ca Calcium 40.08	**21** Sc Scandium 44.96	**22** Ti Titanium 47.88	**23** V Vanadium 50.94	**24** Cr Chromium 51.99	**25** Mn Manganese 54.94	**26** Fe Iron 55.85	**27** Co Cobalt 58.93	**28** Ni Nickel 58.69	**29** Cu Copper 63.55	**30** Zn Zinc 65.38	**31** Ga Gallium 69.72	**32** Ge Germanium 72.63	**33** As Arsenic 74.92	**34** Se Selenium 78.97	**35** Br Bromine 79.90	**36** Kr Krypton 84.80
37 Rb Rubidium 85.47	**38** Sr Strontium 87.62	**39** Y Yttrium 88.91	**40** Zr Zirconium 91.22	**41** Nb Niobium 92.91	**42** Mo Molybdenum 95.95	**43** Tc Technetium 98.91	**44** Ru Ruthenium 101.07	**45** Rh Rhodium 102.91	**46** Pd Palladium 106.42	**47** Ag Silver 107.87	**48** Cd Cadmium 112.41	**49** In Indium 114.82	**50** Sn Tin 118.71	**51** Sb Antimony 121.76	**52** Te Tellurium 127.6	**53** I Iodine 126.90	**54** Xe Xenon 131.29
55 Cs Cesium 132.91	**56** Ba Barium 137.33	**57-71** Lanthanides	**72** Hf Hafnium 178.49	**73** Ta Tantalum 180.95	**74** W Tungsten 183.85	**75** Re Rhenium 186.21	**76** Os Osmium 190.23	**77** Ir Iridium 192.22	**78** Pt Platinum 195.08	**79** Au Gold 196.97	**80** Hg Mercury 200.59	**81** Tl Thallium 204.38	**82** Pb Lead 207.20	**83** Bi Bismuth 208.98	**84** Po Polonium [208.98]	**85** At Astatine 209.98	**86** Rn Radon 222.02
87 Fr Francium 223.02	**88** Ra Radium 226.03	**89-103** Actinides	**104** Rf Rutherfordium [261]	**105** Db Dubnium [262]	**106** Sg Seaborgium [266]	**107** Bh Bohrium [264]	**108** Hs Hassium [269]	**109** Mt Meitnerium [278]	**110** Ds Darmstadtium [281]	**111** Rg Roentgenium [280]	**112** Cn Copernicium [285]	**113** Nh Nihonium [286]	**114** Fl Flerovium [289]	**115** Mc Moscovium [289]	**116** Lv Livermorium [293]	**117** Ts Tennessine [294]	**118** Og Oganesson [294]

Atomic Number
Symbol
Name
Atomic Mass

57 La Lanthanum 138.91	**58** Ce Cerium 140.12	**59** Pr Praseodymium 140.91	**60** Nd Neodymium 144.24	**61** Pm Promethium 144.91	**62** Sm Samarium 150.36	**63** Eu Europium 151.96	**64** Gd Gadolinium 157.25	**65** Tb Terbium 158.93	**66** Dy Dysprosium 162.50	**67** Ho Holmium 164.93	**68** Er Erbium 167.26	**69** Tm Thulium 168.93	**70** Yb Ytterbium 173.06	**71** Lu Lutetium 174.97
89 Ac Actinium 227.03	**90** Th Thorium 232.04	**91** Pa Protactinium 231.04	**92** U Uranium 238.03	**93** Np Neptunium 237.05	**94** Pu Plutonium 244.06	**95** Am Americium 243.06	**96** Cm Curium 247.07	**97** Bk Berkelium 247.07	**98** Cf Californium 251.08	**99** Es Einsteinium [254]	**100** Fm Fermium 257.10	**101** Md Mendelevium 258.10	**102** No Nobelium 259.10	**103** Lr Lawrencium [262]

Alkali Metal | Alkaline Earth | Transition Metal | Basic Metal | Metalloid | Nonmetal | Halogen | Noble Gas | Lanthanide | Actinide

Massive (M ≥ 8 $M_\odot$) star evolution

Onion-like interior → (not to scale)

H, He envelope

He rich — Hydrogen burning

C rich — Helium burning

O rich — Carbon burning

Si rich — Oxygen burning

Silicon burning

Iron core

To surface
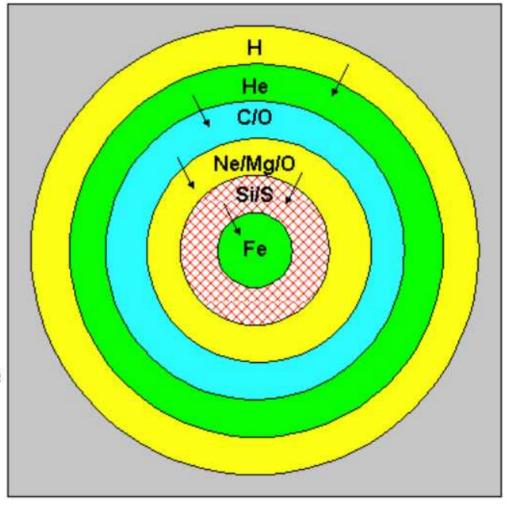
Binding energy per nuclear particle

$^{56}_{26}$Fe : The largest binding energy
    The most stable element
    The final product of both nuclear fusion and nuclear fission

End of Massive stars → Core-Collapse Supernovae (CCSNe)

https://www.astro.umd.edu/~richard/ASTR680/A680_SNR_2019_lec1.pdf

- Iron core collapse
  → shock wave propagates outward
  → outer layers (envelope) follows collapse
  → explosion!

- (expansion velocity ~a few 10^4 km/s)

- Final stage of the evolution of massive stars
  - Outer part → SN explosion → interstellar media
  - Inner part → neutron stars (pulsars) or black holes

Supernova SN 1987A (in Large Magellanic Cloud, LMC)

SN 1987A (II peculiar, LMC)

Tarantula Nebula

d~49.97 kpc (Pietrzynski+ 13 Nature 495 76)

1987 Feb 23.316 (UT)

B3 I (supergiant)
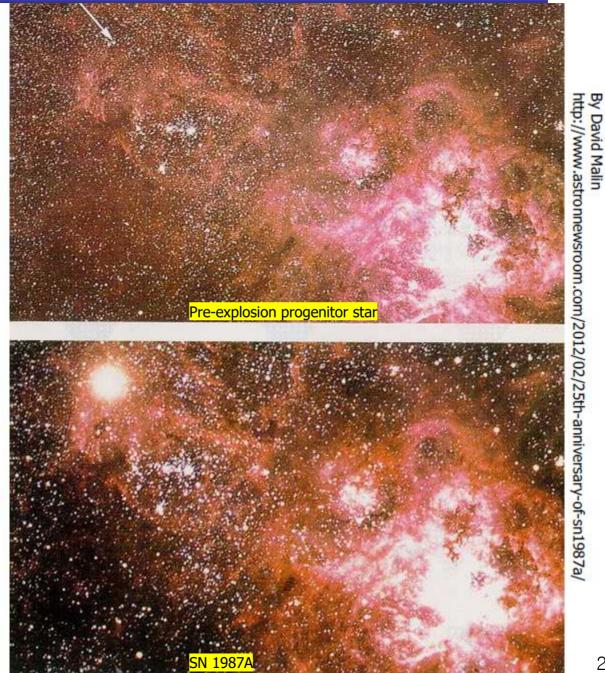
Peak : +2.9 mag

$(B-V) = +0.085$

$T_{eff} = 16,000$ K

$L \geq 10^5 L_\odot$

$\rightarrow M_{initial} \sim 20 M_\odot$ (N. Smith 2007 AJ 133 1034)

Pre-explosion progenitor star

SN 1987A

By David Malin http://www.astronnewsroom.com/2012/02/25th-anniversary-of-sn1987a/

Yearly numbers of reported SN discoveries

Table 1 Yearly numbers of reported SN discoveries. Numbers in parentheses are that of confirmed and announced SNe on IAUCs/CBETs

Year	Discovery						
1981	11	1989	32	1998	163(162)	2007	607(572)
1982	27	1990	38	1999	206(201)	2008	520(261)
1983	28	1991	64	2000	185(184)	2009	475(390)
1984	22	1992	73	2001	307(305)	2010	586(337)
1985	21	1993	38	2002	338(334)	2011	902(298)
1986	16	1994	41	2003	426(335)	2012	1045(322)
1987	20	1995	58	2004	373(251)	2013	1457(228)
1988	35	1996	96	2005	377(367)	2014	1632(136)
		1997	163	2006	554(551)	2015	3412(61)

Naming convention : SN + year

SN 185, SN 386, SN 393, SN 1006, SN 1054, SN 1181, SN 1572, SN 1604

M1 (Crab nebula)   Tycho   관상감, Kepler

since 1885 → SN + year + A-Z

aa, ab, …

aaa, aab, aac, …

https://www.supernovae.net/

Supernova (SN) types

- **Brightest objects in galaxies (M_V = -14 ~ -22)**

- **Typical types**
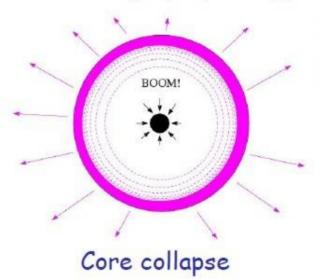
No H lines (pop II) → Type Ia Ib Ic   H lines (pop I) → Type II

WD + Giant/MS/He *   WD + WD   Core collapse
(Single Degenerate, SD)   (Double Degenerate, DD)

SNe Ia (thermonuclear stellar explosion)   CC SNe
(WD originated SNe)
백색왜성 기원 초신성   핵붕괴 초신성

Supernova (SN) types

- **Brightest objects in galaxies ($M_V = -14 \sim -22$)**

- **Typical types**

No H lines (pop II) → Type Ia

H lines (pop I) → Type II

Ib
Ic

WD + Giant/MS/He *
(Single Degenerate, SD)

WD + WD
(Double Degenerate, DD)

Core collapse

SNe Ia (thermonuclear stellar explosion)
(WD originated SNe)
백색왜성 기원 초신성

CC SNe

핵붕괴 초신성

Supernovae taxonomy

Type	Sub-types			
I No H	**Ia** Si II (6150 Å) absorption near peak light			
	Ib/c Weak/no Si absorption	**Ib** He I (5876 Å) emission		
		Ic Weak/no He		
II H	**II-P/L/n**	**II-P/L** No narrow lines	**II-P** Plateau in light curve(LC: mag vs time)	
			II-L Linear decrease in LC	
		Some narrow lines	**IIn** : H lines	
			Ibn : He lines	
	IIb : Spectrum changes to become like type Ib			

SNII-P

SNII-L

Peculiar SNe

Ic-BL : sometimes associated with GRBs and/or hypernova (broad lines : $(2\text{-}3)\times10^4$ km/s)
ultra-bright type II : $\sim 10^{51}$ erg radiation energy
.Ia : changing rapidly
Superluminous SNe, pair-instability SNe, Superluminous Ia
Subluminous SNe, Subluminous Ia
Super-Chandrasekhar Ia : mass > Chandrasekhar limit
Ia-IIn : CSM
Iax : Ia w/lower L, less E, less ejecta mass
Kilonova/macronova, SN imposters, magnetar
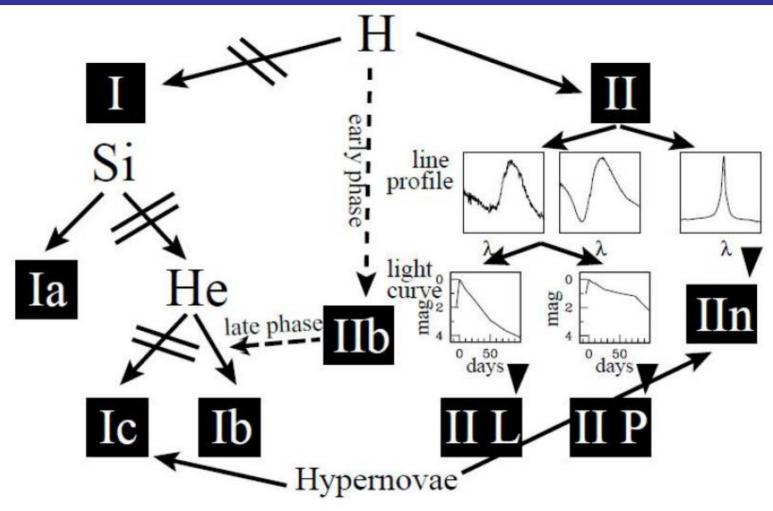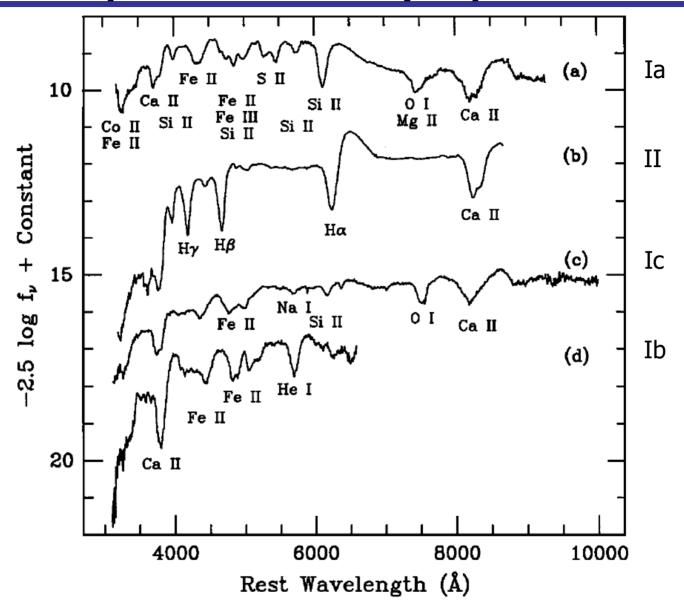
Supernova taxonomy

Cappellaro & Turatto (2000) Figure 2

https://arxiv.org/abs/astro-ph/0012455

Supernova taxonomy - spectra
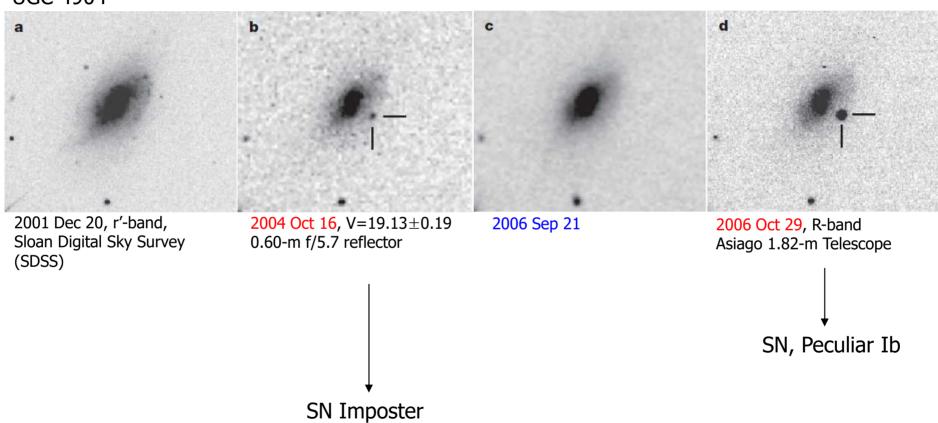
Filippenko 1997 (ARA&A 35 309)

Supernova imposters

UGC 4904

a — 2001 Dec 20, r'-band, Sloan Digital Sky Survey (SDSS)

b — 2004 Oct 16, V=19.13±0.19 0.60-m f/5.7 reflector

c — 2006 Sep 21

d — 2006 Oct 29, R-band Asiago 1.82-m Telescope

SN Imposter

SN, Peculiar Ib

Supernova(SN) Ia light curve (LC)

M_B

Correction (luminosity-decline rate relation)

Luminosity ($L_\odot$)

10^{11}

10^{10}

10^9

Luminous SN fade slowly

Less luminous SN fade fast

corrected luminosities & durations

-20   0   20   40   60

0   20   40   60

Time from peak (days)

LC width
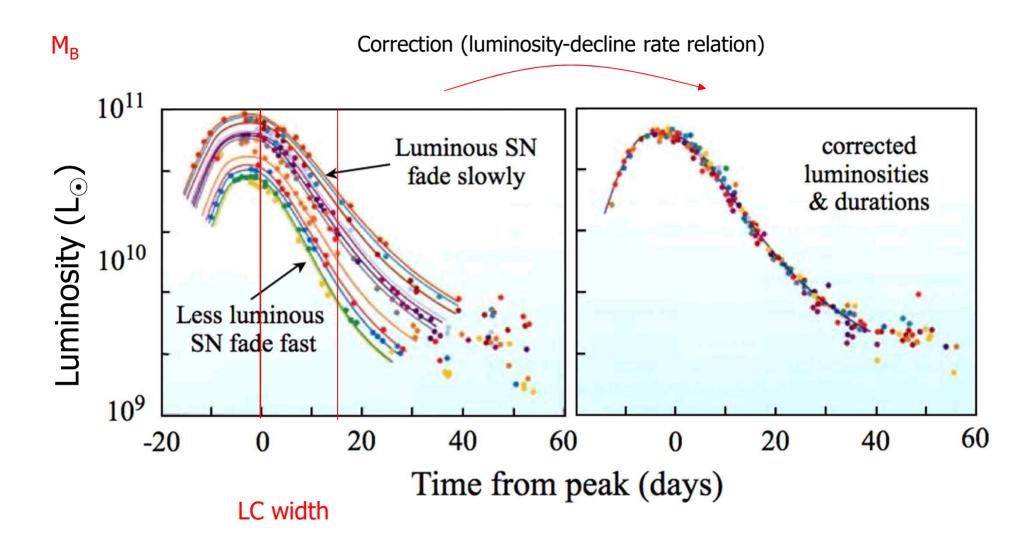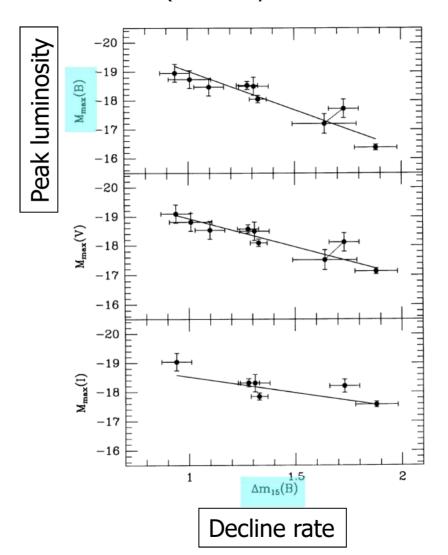
Supernova(SN) Ia light curve (LC)
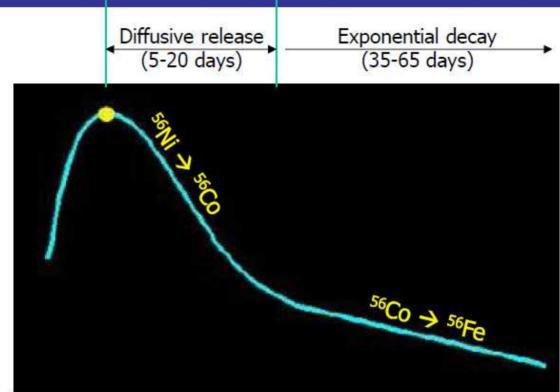
Correction (luminosity-decline rate relation)

Phillips Relation
(Phillips 1993 ApJL 413, L105)

Peak luminosity

Decline rate

: Mag decrease
from the peak mag
for 15 days

Supernova(SN) Ia light curve (LC)

Diffusive release (5-20 days) | Exponential decay (35-65 days)

^{56}Ni → ^{56}Co

^{56}Co → ^{56}Fe
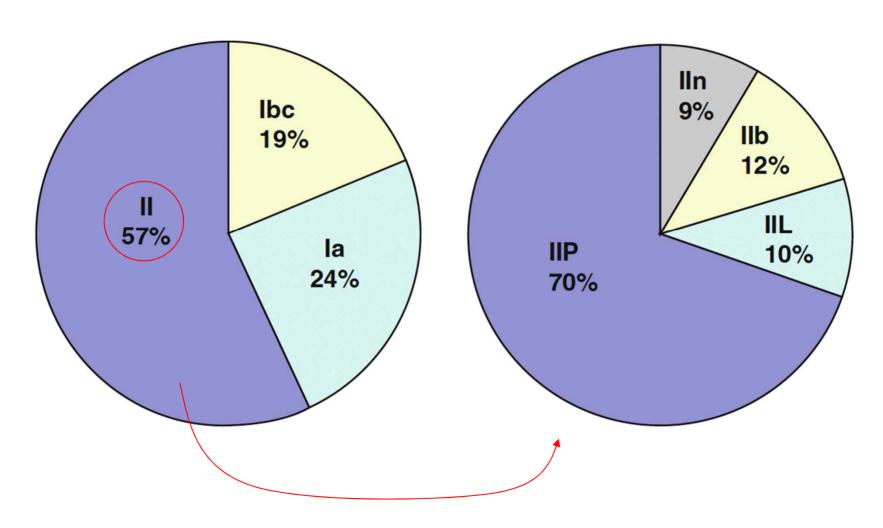
Radioactive decay of ^{56}Ni → ^{56}Co → ^{56}Fe
(Colgate & McKee 69 ApJ 157 623; Arnett 82 ApJ 253 785)

half life
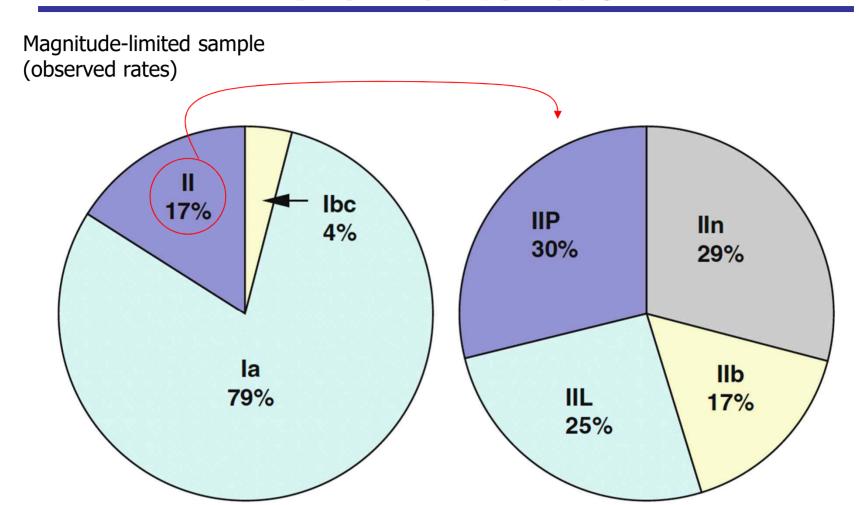
$$^{56}_{28}\mathrm{Ni} \rightarrow {}^{56}_{27}\mathrm{Co} + e^+ + \nu_e + \gamma$$ 6.10 d, E=1.72 MeV

$$^{56}_{27}\mathrm{Co} \rightarrow {}^{56}_{26}\mathrm{Fe} + e^+ + \nu_e + \gamma$$ 78.8 d, E=3.59 MeV

SNe – number ratio

Volume-limited sample
(Intrinsic rates)

Li et al. 2011 (MN 412 1441)

SNe – number ratio

Magnitude-limited sample
(observed rates)
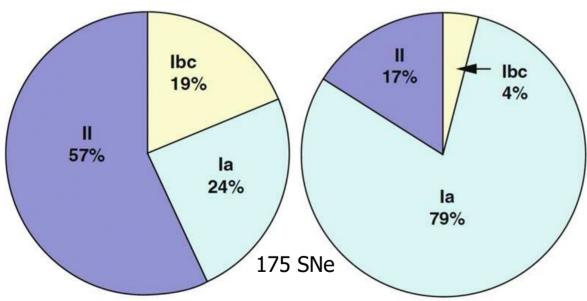
SNe Ia – distance indicator

- SN Ia : maximum brightness (peak luminosity)
  $M_V \sim -19.30 \pm 0.03 + 5 \log (H_0/60)$
- Rising time ~ 20 days

Number ratio

Ia : CC = 24 : 76

Ia : CC = 79 : 21

Ibc 19%

II 57%

Ia 24%

II 17%

Ibc 4%

Ia 79%

175 SNe
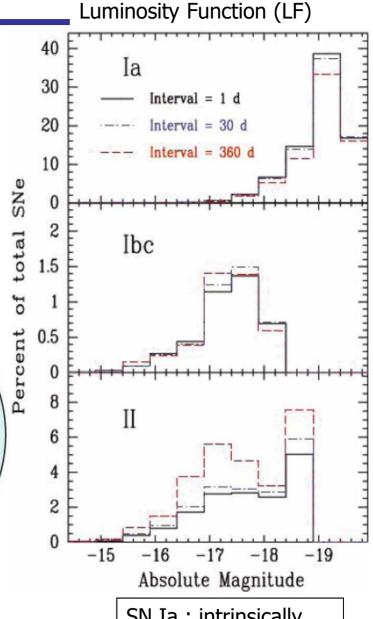
Volume-limited sample
D ≤ 60 Mpc (CC SNe)
D ≤ 80 Mpc (SNe Ia)
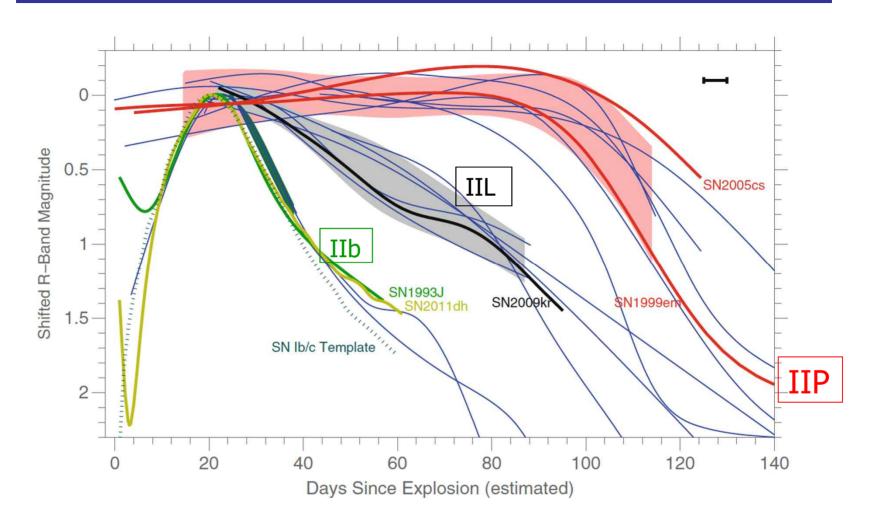
Magnitude-limited sample

Ia

— Interval = 1 d
—·—· Interval = 30 d
– – – Interval = 360 d

Ibc

II

Percent of total SNe

Absolute Magnitude
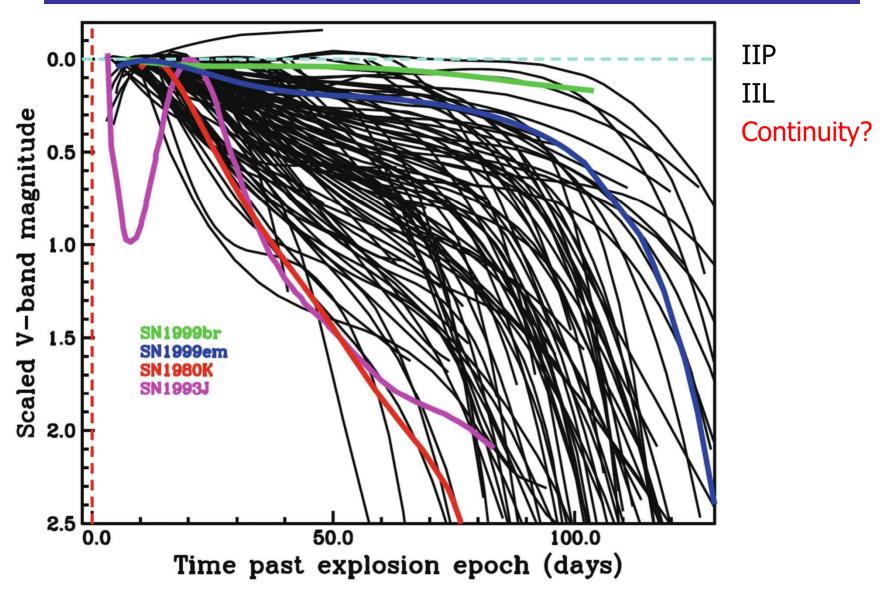
SN Ia : intrinsically brighter than CC SNe

Li et al. 2011, MNRAS 412 1441

Type II – Light Curves (LCs)

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Type II – Light Curves (LCs)

IIP

IIL

Continuity?

SN1999br
SN1999em
SN1980K
SN1993J

CC SNe vs. SNe Ia
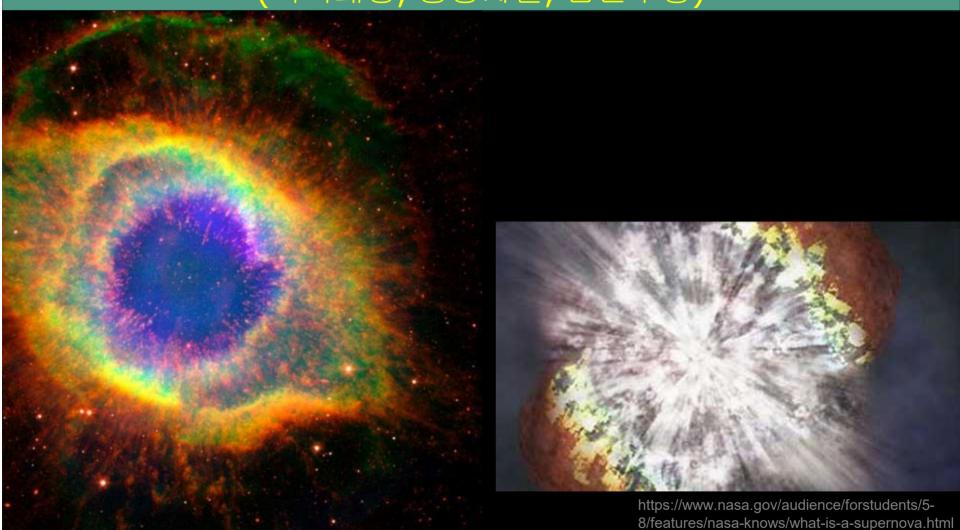
- CC SNe : not in early-type galaxies, Spiral galaxies – spiral arms
- SN Ia : all types of galaxies (Spiral galaxies – no spatial preference)

- spiral arms = short-lived massive stars
→ CC SNe = massive stars
    SN Ia = not that massive stars

- Total energy emitted in neutrinos 3×10^{53} erg
- Total kinetic energy $\sim 10^{51}$ erg = f.o.e. = foe

~1% of total kinetic energy comes in photons $\sim 10^{49}$ erg
    (peak luminosity $\sim 10^{43}$ erg/s, $\sim 10^{9}$ $L_{\odot}$, ~brightness of an entire galaxy)

CC SNe vs. SNe Ia

- Total energy emitted in neutrinos 3×10^{53} erg
- Total kinetic energy $\sim 10^{51}$ erg = f.o.e. = foe

$\sim 1\%$ of total kinetic energy comes in photons $\sim 10^{49}$ erg
(peak luminosity $\sim 10^{43}$ erg/s, $\sim 10^9$ $L_\odot$, $\sim$brightness of an entire galaxy)

foe 미국식 ['foʊ] 🔊 영국식 🔊

명사 an enemy

foe 미국식 [foʊ] 🔊 영국식 [fəʊ] 🔊   https://endic.naver.com/
[명사] (구식 또는 격식) 적(敵)

적² 敵
(원수) (the) enemy, (literary) foe

원수¹ 怨讐
(적)enemy, (literary) foe

© © NASA/JPL-Caltech/Corbis
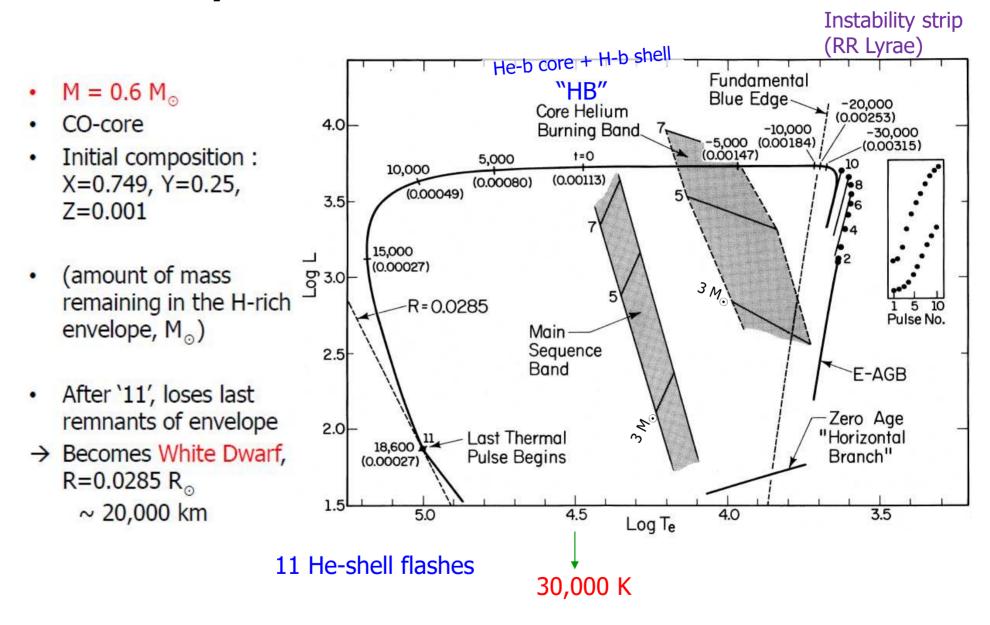
Helix Nebula in the Aquarius

https://www.nasa.gov/audience/forstudents/5-8/features/nasa-knows/what-is-a-supernova.html

https://www.dailymail.co.uk/sciencetech/article-3517714/The-dying-star-rewrite-know-stellar-evolution-White-dwarf-bizarre-atmosphere-oxygen.html

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1. Planetary nebula evolution in the CMD

- **M = 0.6 M$_\odot$**
- CO-core
- Initial composition : X=0.749, Y=0.25, Z=0.001

- (amount of mass remaining in the H-rich envelope, M$_\odot$)

- After '11', loses last remnants of envelope
- → Becomes White Dwarf, R=0.0285 R$_\odot$
  ~ 20,000 km

Instability strip (RR Lyrae)

He-b core + H-b shell
"HB"

11 He-shell flashes

30,000 K

WDs - general

RG

Extremely low-mass ($M_i \leq 0.2\ M_\odot$) → no He-b → He WD

$M_i \leq 8\ M_\odot$, $T_c < 10^9$ K, No C-burning → CO-core + PN
   → CO WD

$8 < M_i < 10.5\ M_\odot$ → C-b, but no Ne-b
   → ONeMg WD
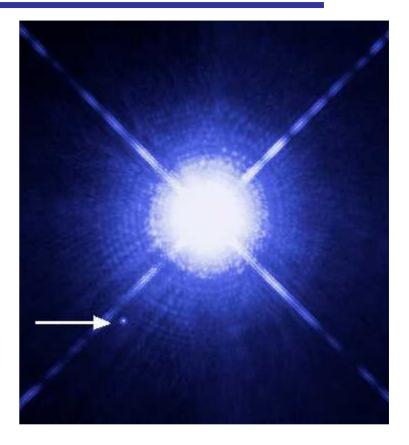
No fusion reactions, supported by electron degenerate pressure

(Current) Mass : 0.55 – 0.6 $M_\odot$
 - min mass ~ 0.4 $M_\odot$
 - max mass for a non-rotating WD = Chandrasekhar mass
     ~1.4 $M_\odot$
Typical density ~ 10^6 g/cm^3
Typical B ~ 10^6 Gauss (2×10^3 - 10^9 Gauss)

Binary – mass transfer from a companion → CO WD mass
approaches the Chandrasekhar mass → C-detonation → SN Ia

Evolution : hot WD → E decreases, color reddens → black
dwarf (timescale > 13.8 Gyr)
   → no black dwarf yet formed

Sirius A, Sirius B (WD) - HST

★ 1 Tesla = 10^4 Gauss
※ Sun : $B_\odot$~1-2 Gauss, mean density~1.408 g/cm^3
※ Earth : $B_\oplus$~0.1 Gauss
※ Magnetic Resonance Imager : B~1 Tesla~$10^5\,B_\oplus$
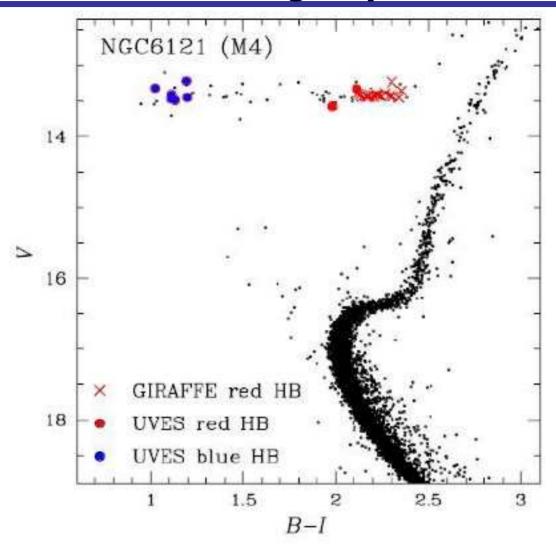   (MRI, 자기공명영상)
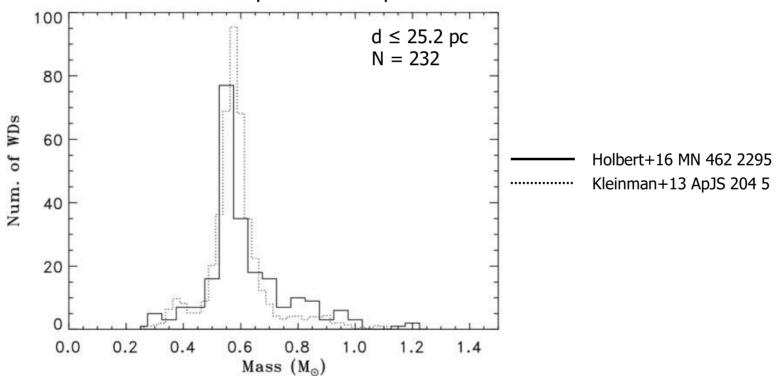
WD catalog

- Villanova Catalogue of Spectroscopically identified WDs
  (McCook & Sion 99 ApJS 121, 1-130, N=2249)

  https://heasarc.gsfc.nasa.gov/w3browse/all/mcksion.html

- Sloan Digital Sky Survey (SDSS) Catalog of Spectroscopically confirmed WDs
  (DR4, Eisenstein et al. 06 ApJS 167, 40, N=9316)

- Volume-limited WD sample within 25 pc : Holbert+16 MN 462 2295

d ≤ 25.2 pc
N = 232

——————— Holbert+16 MN 462 2295
·················· Kleinman+13 ApJS 204 5

WD – cooling sequence

NGC6121 (M4)

GIRAFFE red HB
UVES red HB
UVES blue HB

Marino+11 (ApJ 730 L16 - Sodium-Oxygen Anticorrelation Among HB Stars in the GC M4)

VLT 8.2m

WD – cooling sequence
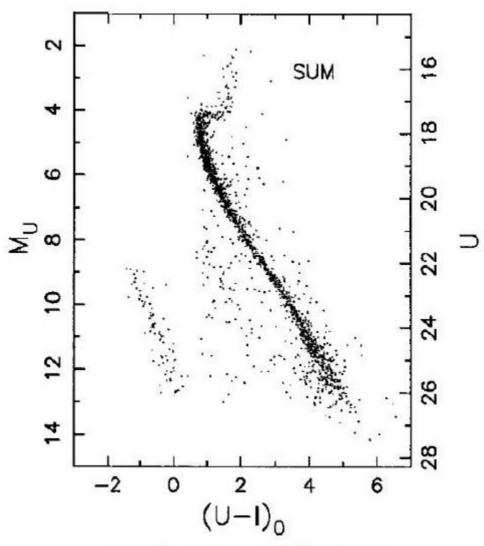
- **WD cooling line** of the GC M4
  - : bluest stars
  - : U = 22 – 26 mag

$$\boxed{L \propto T_{eff}^4} \quad \text{or}$$

$$M_{bol} = -10 \log T_{eff} + const.$$

- **Constant radius** line
- Roughly parallel to the MS
- Stretched not by mass, but by age (young → old)

U-(U-I) CMD of GC M4 (NGC 6121)
HST
Richer et al. 1995 (ApJ 451 L17 - HST Observations of WDs in the GC M4)

WD – cooling sequence
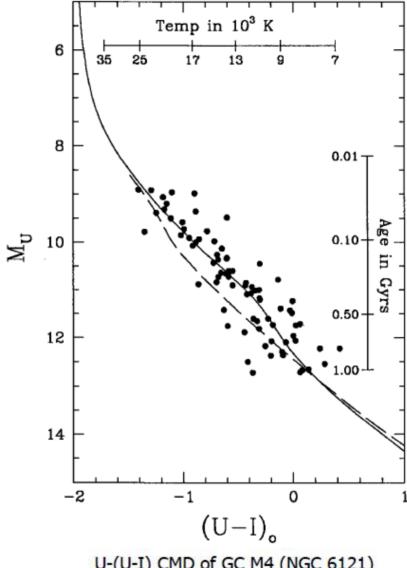
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U-(U-I) CMD of GC M4 (NGC 6121)
HST
Richer et al. 1995 (ApJ 451 L17 - HST
Observations of WDs in the GC M4)

- $M_i \geq 8 \, M_\odot$

- $M_f > 1.4 \, M_\odot \rightarrow$ degenerate electron gas pressure cannot hold off gravity
  → matter is crushed to very high densities → inverse-β decay occurs :

$$p^+ + e^- \rightarrow n + \nu_e$$

(protons and electrons are squeezed into neutrons)

- Degenerate neutron gas → provides internal pressure

- Mass : $1.1 - 2 \, M_\odot$ (upper limit $\sim 3 \, M_\odot$)

Typical mass $\sim 1.4 \, M_\odot$
Typical radius ~ 10 km
Typical density $\sim 4 \times 10^{14}$ g/cm^3
  (400,000 ton/mm^3)
$B \sim 10^{12}$ Gauss
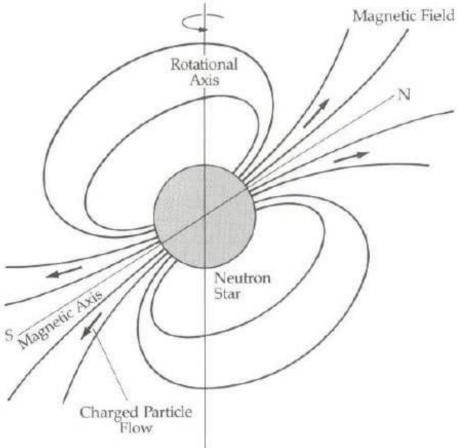Surface temp $\sim 6 \times 10^5$ K
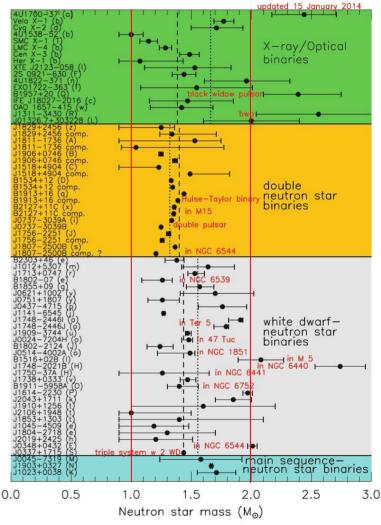
Horvath & Valentim 2017, Handbook of Supernovae, Volume 2, p. 1317

2-1. Pulsars (펄사)

- pulsating star = pulsar = rotating neutron stars
- 1967 discovered by Jocelyn Bell Burnell and Anthony Hewish (1974 Nobel prize)
  Radio pulses coming every 1.33730113s (at 81.5 MHz)+ 3 more objects
- Now, N~2300, P~1.6×10^{-3} to 4.0 s (average 0.65 s)

- Strong magnetic field
  → Synchrotron radiation along the magnetic
  dipolar axis

- Lighthouse model : transforms the
  rotational energy into electromagnetic
  energy → emits through the magnetic axes
  → pulse period = rotation period

- If the Sun becomes a NS → R = 7 km

TABLE 17-1	Properties of Selected Pulsars		
Name (PSR)	Period (s)	dP/dt (10^{-15} s/s)	DM(pc/cm³)
1937 + 21	0.001557	1.07×10^{-4}	71.2
1855 + 09	0.005362	46421	13.3
0531 + 21 (Crab)	0.033326	421	56.8
0833 − 45 (Vela)	0.089234	124	69.1

magnetic axis is inclined with respect to the rotation axis

2-1. Pulsars (펄사)

- Dispersion : a given pulse arrives at the Earth later as we look at lower frequencies
  - Due to a slowing down of the photon velocity by electrons in the line-of-sight (los)
  - Longer λ are slowed down more
  - Observations can tell us the mean electron density in the los
- If pulses of ν_1 and ν_2 ($\nu_1 > \nu_2$) are emitted at time t_0 → they arrive at t_1 and t_2, respectively
- Then, $t_1 - t_0 = \dfrac{d}{v_1}$ and $t_2 - t_0 = \dfrac{d}{v_2}$

- We can measure $t_2 - t_1$ → equal to $\left(\dfrac{1}{v_2} - \dfrac{1}{v_1}\right)d$

- Velocities depend on the electron density → if we know the electron density, we can get the distance

- Dispersion Measure (DM) = integrated electron density : $\mathrm{DM} = \displaystyle\int_0^d n_e\,dl$

TABLE 17-1 Properties of Selected Pulsars			
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Introductory Astronomy and Astrophysics (4th edition)
Michael Zeilik & Stephen A. Gregory (1998), p. 339-340

Binary pulsars (쌍성 펄사)

- First binary pulsar, PSR B1913+16 : 1974 at Arecibo by Joseph H. Taylor, Jr. (조세프 테일러, b. 1941), Russell Hulse (러셀 헐스, b. 1950)
- "Hulse-Taylor binary pulsar"

- Einstein's theory of general relativity → two NSs would emit gravitational waves as they orbit a common center of mass
- Gravitational waves carry away orbital energy → cause the two stars get closer → orbital P ↓

The Nobel Prize in Physics 1993

Russell A. Hulse and Joseph H. Taylor Jr. "for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"

https://www.nobelprize.org/prizes/lists/all-nobel-prizes-in-physics/

https://en.wikipedia.org/wiki/Binary_pulsar

3. Black Holes (BHs, 검은구멍)

- A region of spacetime in which gravity is so strong that nothing (incl. light) can escape it
- Minimum mass ~ 3 $M_\odot$
- Theoretically zero volume and infinite density → "singularity" (breakdown of the laws of physics)
- An object with escape speed v_{esc} at the surface of the BH :

$$\text{Total Energy = KE + PE} = \frac{mv_{esc}^2}{2} - \frac{GmM}{R} = 0$$

- Assuming max escape velocity = c

$$\boxed{R = \frac{2GM}{c^2} = 3M \text{ km}}$$ Schwarzshild radius
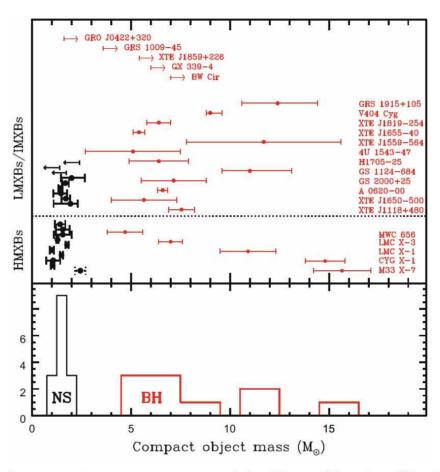
- If the Sun becomes a BH → density ~10^{16} g/cm³ (~nucleus of an atom)

- If an object cross the Schwarzshild radius, it crashes into a singularity (zero volume)

black_hole_baird.jpg
http://sciencequestionswithsurprisinganswers.org/20
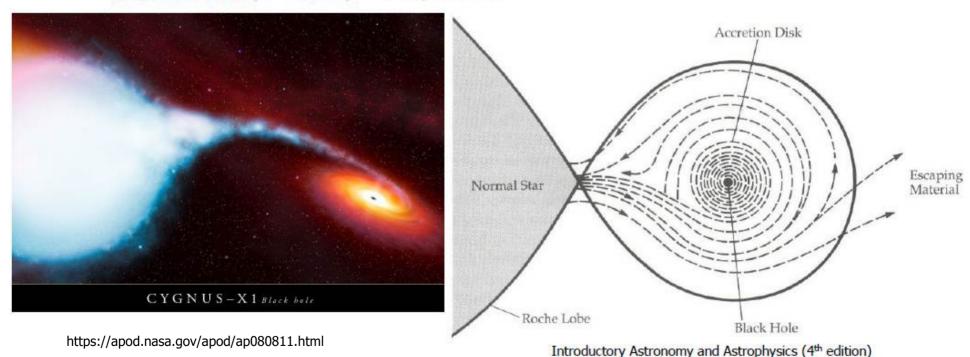13/06/18/can-you-go-fast-enough-to-get-enough-
mass-to-become-a-black-hole/

3. Black Holes (BHs, 검은구멍)

Fig. 2 *Top*: compact remnant masses measured in X-ray binaries. Neutron stars and black holes are indicated in *black* and *red colors*, respectively. 4U 1700-37 is plotted in *dotted-style line* because the nature of the compact star is uncertain. The *horizontal dotted line* divides LXMBs/IMXBs from HMXBs. *Bottom*: observed distribution of neutron stars and black hole masses

3. Black Holes (BHs, 검은구멍)

- How to observe/find a BH?
- not for an isolated BH → but for a BH in a binary system (interactions with other material)
- matter falling toward a BH - gains kinetic energy → heats up, becomes ionized → emits electromagnetic radiation
- If T reaches a few $\times 10^6$ K → emits X-rays
- accreted material + initial angular momentum → form a disk around the BH : accretion disk (강착원반) = X-ray source

CYGNUS-X1 *Black hole*

https://apod.nasa.gov/apod/ap080811.html

Introductory Astronomy and Astrophysics (4th edition)
Michael Zeilik & Stephen A. Gregory (1998), p. 348

- X-ray sources : good candidates for BHs