ASTR 400/700: Stellar Astrophysics

Stephen Kane
Supernovae and GRBs
Chapter 15
Summary of Post-Main-Sequence Evolution of Stars

M $>$ 8 $M_{\text{sun}}$

- Fusion proceeds; formation of Fe core.

M $<$ 2 $M_{\text{sun}}$

- Fusion stops at formation of C,O core.

Subsequent ignition of nuclear reactions involving heavier elements.

Supernova
Fusion of Heavier Elements

Final stages of fusion happen extremely rapidly: Si burning lasts only for ~ 2 days.

\[ ^{12}\text{C} + ^{4}\text{He} \rightarrow ^{16}\text{O} + \gamma \]
\[ ^{16}\text{O} + ^{4}\text{He} \rightarrow ^{20}\text{Ne} + \gamma \]
\[ ^{16}\text{O} + ^{16}\text{O} \rightarrow ^{28}\text{Si} + ^{4}\text{He} \]

Onset of Si burning at \( T \sim 3 \times 10^9 \) K

\rightarrow \text{formation of S, Ar, \ldots;}
\rightarrow \text{formation of } ^{54}_{26}\text{Fe and } ^{56}_{26}\text{Fe}
\rightarrow \text{iron core}
The Life “Clock” of a Massive Star (> 8 M\textsubscript{sun})

Let’s compress a massive star’s life into one day…

**Life on the Main Sequence**

+ Expansion to Red Giant: 22 h, 24 min.
  
  H burning

**He burning:**

(Horizontal Branch) 1 h, 35 min, 53 s
H → He
He → C, O
C → Ne, Na, Mg, O

C burning:
6.99 s

Ne → O, Mg

Ne burning:
6 ms
C → Ne, Na, Mg, O
Ne → O, Mg
O → Si, S, P
Si → Fe, Co, Ni

O burning:
3.97 ms

The final 0.03 msec!!
Iron is a dead end for fusion because nuclear reactions involving iron do not release energy.

(Fe has lowest mass per nuclear particle.)
Supernovae can easily be seen in distant galaxies.

Total energy output:

\[ \Delta E_v \sim 3 \times 10^{46} \text{ J} \]
\[ \sim 100 \, L_0 \, t_{\text{life},0} \]
\[ \Delta E_{\text{kin}} \sim 10^{44} \text{ J} \]
\[ \Delta E_{\text{ph}} \sim 10^{42} \text{ J} \]

\[ L_{pk} \sim 10^{36} \text{ J/s} \sim 10^9 L_0 \]
\[ \sim L_{\text{galaxy}} ! \]
Type I and II Supernovae

Core collapse of a massive star:
- Type II Supernova
- Type Ia Supernova

Type I: No hydrogen lines in the spectrum
Type II: Hydrogen lines in the spectrum

Type Ib: He-rich
Type Ic: He-poor

Light curve shapes dominated by delayed energy input due to radioactive decay of $^{56}_{28}$Ni

Collapse of an accreting White Dwarf exceeding the Chandrasekhar mass limit → Type Ia Supernova.
The Famous Supernova of 1987:  
SN 1987A

Unusual type II Supernova in the Large Magellanic Cloud in Feb. 1987

Progenitor: Blue supergiant (denser than normal SN II progenitor)

20 solar masses;
lost ~ 1.4 – 1.6 $M_\odot$ prior to SN

Evolved from red to blue ~ 40,000 yr prior to SN
The Remnant of SN 1987A

Ring due to SN ejecta catching up with pre-SN stellar wind; also observable in X-rays.

\[ v_{ej} \sim 0.1 \, c \]

Neutrinos from SN1987 have been observed by Kamiokande (Japan)

Escape before shock becomes opaque to neutrinos → before peak of light curve
Gamma-Ray Bursts (GRBs)

Short (sub-second to minutes) flashes of gamma-rays
General Properties

- Random distribution in the sky
- Approx. 1 GRB per day observed
- No repeating GRB sources
Afterglows of GRBs

Most GRBs have gradually decaying afterglows in X-rays, some also in optical and radio.

X-ray afterglow of GRB 970228

(GrBs are named by their date: Feb. 28, 1997)
Optical afterglows of GRBs are extremely difficult to localize:

Very faint (~ 18 – 20 mag.); decaying within a few days.

Optical afterglow of GRB 990510 (May 10, 1999)
Optical Afterglows of GRBs

Long GRBs are often found in the spiral arms (star forming regions!) of very faint host galaxies.

Optical afterglow of GRB 990123, observed with Hubble Space Telescope (HST/STIS)
Models of GRBs (I)

There’s no consensus about what causes GRBs. Several models have been suggested, e.g.:

**Hypernova:**
- Supernova explosion of a very massive (> 25 M$_{\text{sun}}$) star
- Iron core collapse forming a black hole;
- Material from the outer shells accreting onto the black hole
- Accretion disk => Jets => GRB!
Models of GRBs (II)

Black-hole – neutron-star merger:

Black hole and neutron star (or 2 neutron stars) orbiting each other in a binary system

Neutron star will be destroyed by tidal effects; neutron star matter accretes onto black hole

=> Accretion disk
=> Jets => GRB!

Model works probably only for short GRBs.