Astrophysics Graduate Course
Late Stages of Stellar Evolution
(Ph. Podsiadlowski, Oxford, HT07)

1 Literature

- David Arnett, *"Supernovae and Nucleosynthesis: An Investigation of the History of Matter, from the Big Bang to the Present"*, Princeton Series in Astrophysics
- Ken Nomoto et al. 2005, *"Nucleosynthesis in Hypernovae and Population III Supernovae*, Nuclear Physics A, Vol. 758, P. 263-271 (available online)
- Ken Nomoto et al. 2003, *"Hypernovae and Other Black-Hole-Forming Supernovae"* (astro-ph/0308136)
- Alexander Heger et al. 2002, *"Massive Star Evolution Through the Ages",* in From Twilight to Highlight: The Physics of Supernovae, Hillebrandt, W. & Leibundgut, B., eds., Springer, Berlin, P. 3 (astro-ph/0211062)

2 General Issues

- *final outcomes:* white dwarf, neutron star, black hole, nothing (i.e. complete disruption)
- importance for chemical evolution: explosive nucleosynthesis (what fraction is locked up in the compact object, e.g. black hole?) → injection of heavy elements into ISM/IGM, pollution of companion stars
- supernova feedback:
  - → trigger star formation
  - → energy input into ISM/IGM (hot gas in galactic halos, clusters)
- depends on numerous uncertain factors (don't believe everything you read!)

3 White-dwarf (WD) formation

- CO WDs ($M_{\rm in} \lesssim 7\,M_\odot$); ONeMg WDs ($M_{\rm in} \simeq 7/8\,M_\odot$ for single stars, $7 - 10\,M_\odot$ in binaries [present best estimates])
- formation rate (Milky Way): $\sim 1\,{\rm yr}^{-1}$
- termination of AGB phase (formation of planetary nebula) when envelope energy becomes positive (including energy release due to recombination of H and He) (see ref. [1], somewhat controversial)
  - → energy can be ejected to infinity with small perturbation

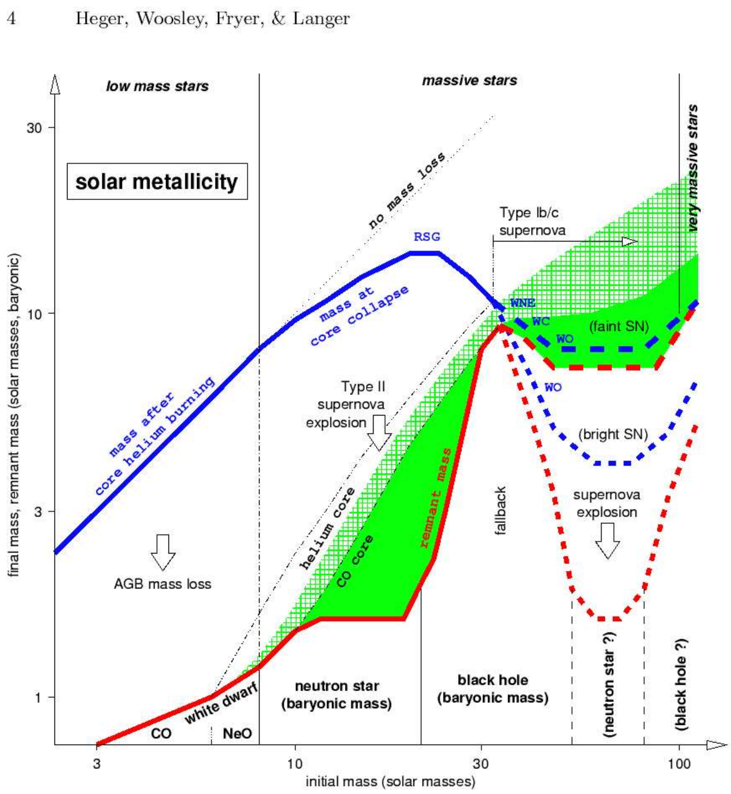
- ▷ *complication:* radiative losses → large-amplitude Mira pulsations (instead of dynamical ejection) producing a 'superwind' (with $\dot{M}_{\rm wind} \sim 10^{-4}\,M_\odot\,{\rm yr}^{-1}$; i.e. very rapid loss of envelope)

- depends on *metallicity*

  - ▷ lower Z, higher $T_{\rm eff}$ → star has to evolve further on the AGB to reach instability (→ higher WD mass)
  - ▷ also core less degenerate → reduces maximum mass for CO WDs (by about $2\,M_\odot$ for $Z = 0.001$ [1]; e.g. from 7 to $5\,M_\odot$)

- *predicted white dwarf masses [1]:* $0.59 \pm 0.02\,M_\odot$ (solar metallicity), $0.62 \pm 0.02\,M_\odot$ ($Z = 0.001$)

4 Core collapse



- *core-collapse rate (Milky Way):* $\sim 10^{-2}\,{\rm yr}^{-1}$

- *iron core collapse* leading to neutrino-driven explosion by delayed neutrino heating reviving a stalled shock after $500 - 10^3$ ms

  - ▷ present status: in the most state-of-the-art numerical models with self-consistent physics, stars do not (yet?) explode!
  - ▷ alternative ideas? E.g. magnetically driven explosions, extracting rotation energy from a rapidly rotating core. Requires large B field and rapidly rotating core (~ 1 ms)

- *electron-capture supernova* for $M \simeq 7 - 10\,M_\odot$ (in binaries?)
  - ▷ occurs when *degenerate* ONeMg WD reaches critical core density (at $M \simeq 1.36\,M_\odot$)
  - ▷ capture of electrons onto Mg causes loss of hydrostatic support (reduced e pressure) and ultimately dynamical collapse
  - ▷ smaller core masses → easier ejection (but few heavy elements and probably no supernova kick)

- *black-hole formation* (for single stars more massive than $\sim 22 - 25\,M_\odot$)

  prompt (spherical) collapse

  → the whole star collapses
  - ▷ does not necessarily produce a supernova (faint SN?)
  - ▷ the 'normal' fate of massive stars?[1]

  collapsar models and GRBs for rapidly rotating stellar cores
  - ▷ collapsing material forms disk → sudden accretion → GRB jet → hypernova

5 Thermonuclear explosions

Type Ia supernova

- degenerate carbon ignition in Chandrasekhar CO WD ($\sim 1.38\,M_\odot$) leading to complete disruption of white dwarf
- Milky Way rate: $\sim 2 - 3 \times 10^{-3}\,\mathrm{yr}^{-1}$
- unsolved progenitor questions
  - ▷ *single-degenerate (SD) models* (CO WD grows by accreting matter from a companion star) or *double-degenerate (DD) models* (i.e. merging of two CO WD with combined mass $> 1.38\,M_\odot$)

  problems:
  - ▷ SD models require serious fine-tuning (limits overall rate): accretion rate too high → mass is lost from system; accretion rate too low → nova explosions ejecting transferred matter explosively
  - ▷ DD models: rates o.k., but may produce *core collapse* (i.e. form neutron stars)
- use as *cosmological probes* (dark energy!)
  - ▷ good relation between peak supernova brightness and lightcurve width (Phillips relation) → 'standardizable' candle
  - ▷ relies on existence of a 1-parameter family of lightcurves
  - ▷ *caution:* numerous exceptions are now known; metallicity *must* be an important 2nd parameter

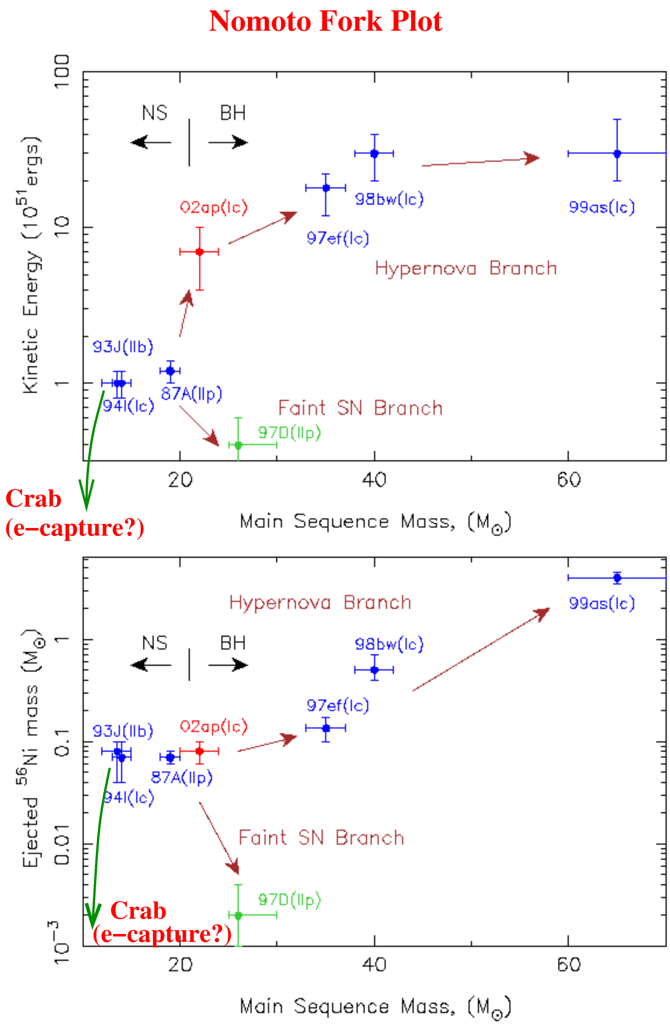
[1] Note: in the literature it is often stated that these produce a Type Ib/Ic supernova; this is probably not correct; those most likely originate from lower-mass star which have lost their H/He envelopes by mass transfer in a binary system, while prompt collapses may form a new supernova subtype.

- *pair-instability supernovae:* during oxygen burning in very massive stars

  $\longrightarrow$ complete disruption of star

  ▷ predicted chemical signature appears not consistent with observational constraints ($\rightarrow$ do they exist in Nature?)

6 Energy input



- standard core-collapse supernova energy: $\sim 10^{51}$ ergs
- hypernovae: $> 10^{52}$ ergs (but probably a range $10^{51} - 3(5) \times 10^{52}$ ergs)

  ▷ hypernova signature: broad lines $\rightarrow$ high velocities/kinetic energy $\rightarrow$ proxy for large explosion energy (but not always reliable)

▷ supernova dichotomy for stars more massive than $\sim 20\,M_\odot$ (black-hole formation? [2])

▷ if hypernovae were dominant at low metallicity/early during galaxy formation → potentially important energy input in ISM/IGM (Silk)

7 The first stars

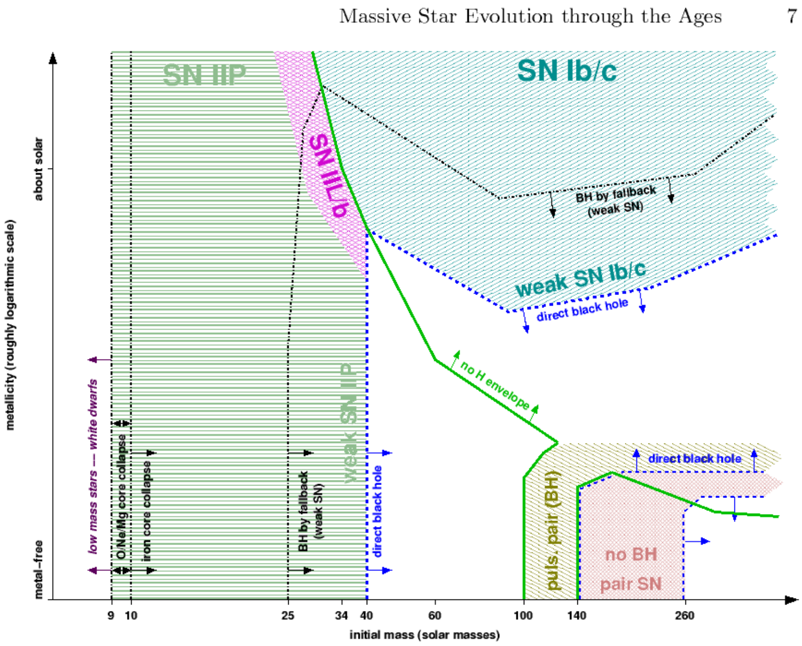
- star formation at zero Z: simpler?
  - ▷ no coolants (like CO) except for H_2 → models predict more massive stars
  - ▷ but role of angular momentum/magnetic field not clear plus unresolved numerical issues (e.g. too much viscosity?)
- different stellar evolution: only pp burning (no CNO elements!) → different final fates
- predicts numerous pair-instability supernova (not consistent with observations; see above)

8 Chemical enrichment

- dependence on wind mass loss (note: AGB winds important for CN enrichment, s-process enrichment)
- depends on final fate (i.e. neutron star or black hole) and final black-hole mass (plus supernova mixing)

→ details *extremely uncertain* → use published models at your own risk

9 The role of metallicity



- affects mass boundaries: WD/NS, NS/BH, BH/complete disruption
- affects wind mass loss in all phases ($\dot{M}_{\rm wind} \propto Z^{0.5-0.7}$) → minimum mass for WR-star formation

10 The role of binarity

- envelope loss → main cause of observed core-collapse diversity
  - ▷ II-P → II-L → IIb → Ib → Ic; sequence of increased loss of H and He envelope
- late core evolution depends on whether star has H-rich envelope (+ H-burning shell) during He core burning (i.e. whether star has lost the H-rich envelope by binary interaction)
  - ▷ no H-burning shell → lower Fe-core mass → stars with initial masses as massive as $50/60\,M_\odot$ may end as neutron stars rather than black holes (details depend on wind mass loss)
- electron-capture supernovae may only occur in close binaries
  - ▷ for single stars in $7-10\,M_\odot$ range → dredge-up of He core during AGB phase → ONeMg WD (envelope ejection before reaching condition for core collapse)
  - ▷ without H-rich envelope → no dredge-up → can reach core collapse conditions

11 Supernova kicks [3]

- well established for single pulsars: data consistent with Maxwellian distribution with $\sigma = 265\,{\rm km\,s^{-1}}$ (mean $400 \pm 40\,{\rm km\,s^{-1}}$) [4]
  - ▷ no significant number of single pulsars with low kicks
  - → problem with retaining neutron stars in globular clusters (escape velocity: $\sim 20{-}50\,{\rm km\,s^{-1}}$)
  - ▷ a *dichotomous kick scenario:* no kicks for stars in close binaries with low core masses (e-capture supernovae?)? [5]
- origin: accretion instability in core collapse phase (?)
- black-hole kicks? Two-step black-hole formation
  - ▷ yes in Nova Sco (BH binary): companion polluted with supernova ejecta + high space velocity of the system
  - → black hole formed in supernova (hypernova?) and experienced kick

12 Supernova remnants

- plerions (filled) and shell-like supernovae (existence of energetic pulsar)
- input of energy and heavy elements into ISM/IGM
- phases

- ▷ free expansion phase (constant T and v; $100 - 300\,\mathrm{yr}$)
- ▷ adiabatic or Sedov-Taylor phase ($10^2 - 10^4\,\mathrm{yr}$)
- ▷ snowplough or radiative phase (swept-up mass exceeds ejecta mass; rapid slowing down)
- ▷ dispersal phase (snowplough subsonic)

- Rankine-Hugoniot jump conditions
- cosmic rays: Fermi acceleration mechanism

References

[1] Han, Z. et al. 1994, "A possible criterion for envelope ejection in asymptotic giant branch stars or first giant branch stars", MNRAS, 270, 123

[2] Nomoto et al. 2003, *"Hypernovae and Other Black-Hole-Forming Supernovae"* (astro-ph/0308136)

[3] Brandt, N., & Podsiadlowski, Ph. 1995, *"The effects of high-velocity supernova kicks on the orbital properties and sky distribution of neutron-star kicks"*, MNRAS, 274, 461

[4] Hobbs, G. et al. 2005, *"A statistical study of 233 pulsar proper motions"*, MNRAS, 360, 974

[5] Podsiadlowski, Ph. et al. 2004, *"The Effects of Binary Evolution on the Dynamics of Core Collapse and Neutron Star Kicks"*, ApJ, 612, 1044