Evolution of intermediate-mass stars

Intermediate-mass stars are defined as those which are nondegenerate when helium burning begins, but degenerate when CO burning begins. Specifically, the helium core mass is greater than $0.31\,M_\odot$ and the mass of the CO core is less than $1.06\,M_\odot$. These stars therefore burn helium quiescently, but might burn CO explosively. We're talking about stars with initial masses $\sim 3-9\,M_\odot$.

Key points:

(1) All these stars have central temperatures $T > 2\times 10^7$ K, so they burn hydrogen by CNO. Therefore, the energy generation rate is proportional to X (not X^2 like for pp), and there is thus less contraction required to counterbalance the drop in pressure resulting from transformation of H to He.

(2) For lower-mass stars in this range, opacity is well-represented by Kramers; for higher-mass stars, electron scattering dominates.

(3) There is a limit to the fractional mass of a helium core that can exist if ideal gas pressure dominates (this is the Schönberg-Chandrasekhar limit, and is about 0.1; they'll do an approximate derivation of this in the homework). Intermediate mass stars exceed this limit, with the result that core contraction is accelerated greatly in the red giant stage (where there is already an inert helium core and energy generation is from hydrogen shell burning).

(4) With one shell source and core contraction, the envelope expands greatly.

(5) Most of the energy released is used to expand the envelope, so the luminosity does not increase; the star therefore moves to the red part of the HR diagram. It does this very quickly ($\sim$1% of the star's lifetime, or $\sim 10^5$ yr for a $5\,M_\odot$ star), so there are few stars in this intermediate region between high-mass main sequence and high-mass red giant. This is called the Hertzprung gap.

(6) For stars of initial mass $M > 2.3\,M_\odot$, helium burning starts before the core is degenerate, so there is no helium flash.

(7) Temperature of core increases with increasing core mass, so burning rate goes up (and duration of quiescent He burning phase goes down) with increasing stellar mass. The ratio of He burning to H burning depends only weakly on stellar mass in this range: 0.25 for $M = 3\,M_\odot$ to 0.1 for $M = 9\,M_\odot$.

(8) Practically all stars in this range go through an instability phase, driven by the thermodynamic and opacity properties of the ionization zones. Low-mass become RR Lyrae variables, higher mass ($> 2.3\,M_\odot$) become Cepheids.

(9) **Ask class:** do they know of any Cepheids? One of them is among the most famous

stars in the sky. The North Star, Polaris, is a weak Cepheid (0.05 mag variations), which means that when Shakespeare had Julius Caesar say "But I am constant as the northern star, of whose true-fix'd and resting quality there is no fellow in the firmament" (just before Brutus et al. stabbed him to death), he was doubly wrong. Polaris was a good half degree from the North Pole at the time, and it isn't quite constant in brightness either!

(10) All stars with initial masses $M \sim 1 - 9\,M_\odot$ go through the asymptotic giant branch phase (see above as well). The cores of these stars are mainly CO, with degenerate electrons; this means that outward energy diffusion by electron conductivity is very efficient, so the temperature can't get high enough to ignite the CO.

(11) As before, thermal pulses occur. Convection occurs through the whole envelope when the helium layer burns (the helium shell burning can be explosive, and provides another example of thermonuclear propagation).

(12) After the maximum of a pulse, convection in the shell stops and the base of the convective layer moves inward, entering the carbon-rich layer which was produced by the previous episode of helium burning. Carbon and oxygen can be transferred to the surface in this way. This is called "dredge-up", and it means that by observing the surface spectra of such stars we get clues about their composition and by burning processes.

Evolution of massive stars

These have initial masses greater than about $9\,M_\odot$.

(1) The dominant new feature of these stars is there enormous losses of mass to stellar winds. The mass loss rate is correlated with luminosity and can be up to $3\times10^{-5}\,M_\odot\ \mathrm{yr}^{-1}$ for Wolf-Rayet stars.

(2) The velocity of the winds is comparable to the surface escape velocity, and is thought to be caused by radiation forces off of UV lines.

(3) The stellar mass therefore decreases, and the ISM is enriched with metals as a result. We also get to see what the star had for dinner, in the sense that its digestive (thermonuclear) products are brought to the surface.

(4) Effects of mass loss on the hydrogen burning phase: (a) the decrease of mass means that the central temperature increases less rapidly, so the mass of the convective core increases less rapidly. However, (b) the total mass drops even faster, so the fractional mass of the core is higher. (c) The luminosity is lower. However, the star is undermassive for a given luminosity, i.e., overluminous for a given mass. (d) The main sequence lifetime is increased: there is less nuclear fuel in the burning regions, but the lower luminosity more than makes up for it. (e) The increase in the fractional core mass widens the main sequence band. (f) At the end of H core burning the mass of the helium core is smaller than for

evolution at constant mass.

(5) Effects of mass loss on the He burning phase. The position of He burning stars in the HR diagram depends on initial mass and mass loss rates.

(6) Stars above $9\,M_\odot$ evolve towards a phase of core collapse. Mass loss determines where in the HR diagram they are prior to collapse and the supernova. For $M > 30 - 40\,M_\odot$, the progenitor is a blue supergiant, whereas below that range the supernova progenitor is a red supergiant.

Core-collapse supernovae

Nomenclature of supernovae is observationally driven, and unfortunately does not divide the phenomena as we now know it. Type I supernovae have no hydrogen in their spectra; Type II do. Type I SNe are further divided depending on whether their early-time spectra show strong Si II (Type Ia), prominent He I (Type Ib) or neither Si II or He I (Type Ic). Observationally, however, everything except Type Ia are thought to be produced by the collapse of a core of a high-mass star. These are the ones that concern us. Type Ia, thought to be due to a thermonuclear runaway on an accreting white dwarf, are remarkably homogeneous in their luminosities (especially when the so-called Phillips relation is used), and are therefore used as cosmic "standard bombs" to probe the curvature and acceleration of the universe. But that's off topic, at least for now. We will focus on what is thought to cause core-collapse in massive stars, a topic that is very far from being resolved!

(1) The iron core doesn't generate energy (it's at the peak of the binding energy curve), and is therefore supported by semidegenerate electrons.

(2) When the core exceeds the mass that can be supported by these electrons, which is approximately the Chandrasekhar mass (around $1.4\,M_\odot$), it begins to collapse.

(3) Two major instabilities are involved, often simultaneously: (a) electron capture onto iron group elements removes electrons from supporting the core, and produces neutrinos that leave immediately without helping support the core, and (b) photodisintegration happens, putting energy into dissociating nuclei instead of raising the pressure. These instabilities cause the core to contract rapidly.

(4) The gravitational energy of collapse to $\sim$NS densities is about 10^{53} erg, a hundred times the kinetic and photon luminosity in an explosion. But how should this energy be coupled to the outer layers?

(5) In 1966, Colgate & White suggested a neutrino transport model: most of the energy is converted to neutrinos, which interact with the mantle and heat+expand it. At the time, this appeared not to work, because the coupling was insufficient.

(6) In the mid-1970's, the discovery of neutral currents suggested a twist: neutrinos

interact more strongly with high-A nuclei (like A^2) than with individual nucleons, so might bypass the dissociated core and deposit their energy in the iron-group elements in the mantle. But again, detailed calculations make this less promising; too high a fraction of the neutrinos remain in the core and are advected in.

(7) Core bounce. When the core reaches nuclear density (around 2×10^{14} g cm^{-3}), there is a bounce and a shock driven outwards.

(8) The shock has plenty of energy to drive the explosion (around 5×10^{51} erg), but many losses occur as it propagates outward (neutrino emission and photodisintegration, for example; note that $\sim 1.5 \times 10^{51}$ erg is required for each disintegration of $0.1\,M_\odot$ of iron to free nucleons). Can only survive if it gets to a point where the postshock temperatures aren't high enough to emit neutrinos or disintegrate nuclei, if prompt explosion is to be possible.

(9) The shock may be refreshed by input of energy or momentum from neutrinos, which at the $\sim$5 MeV energies are at optical depths greater than unity for most of the core.

(10) One suggestion for this is that convection brings neutrino-emitting matter out farther, where it can release its energy and help power the explosion at later times ($\sim$ 100 ms). However, recent 2-D simulations of rotating cores show that rotation inhibits convection and decreases dramatically the efficiency with which neutrino energy can be converted into kinetic energy. Polarization of supernova remnants suggests axes in many of them, naturally suggesting rotation, so it may not be possible to get away from it.

(11) So, lots and lots of uncertainty left! They happen, and happen frequently, so nature finds a way. Neutrinos, one way or the other, seem to be the best bet, since neutronization of matter generates them at the 10^{53} erg level and only $\sim$1% needs to be tapped, but it may require full 3-D calculations to get satisfactory supernovae with regularity in numerical simulations.