Plan of Lecture

Evolution of High-Mass Stars

First exam details and hints.

More about fusion.

Mass loss and pulsations.

Collapse and supernova.

Fate of high-mass stars.

First Exam

Here, Thursday, Feb 26, 11:00-12:15.

Closed book and closed notes.

Please bring pens (more than one!).

Not pencils (tough to read).

Bring a calculator, but don't program it.

Five questions.

30 points each.

Short essay or quantitative.

Can do in any order (label!).

If you finish all five, there is a bonus question for 15 extra credit points.

All or nothing!

Hints For First Exam

Exam covers entire class through today (high-mass stars).

All material in lectures, discussions, labs, and textbook is fair game.

Prime focus: lectures.

Read over exam first, do easiest questions.

Give concise answers! Don't waste time; I'll have to take off points for incorrect answers...

Cross out, don't erase (I can give partial credit...).

For numerical problems: show complete derivation, and give units!

If your answer is dead wrong and you say why, correctly, you'll get partial credit.

Massive Stars

Let's now think about more massive stars, say $M > 4\,M_{\odot}$.

Initial stages are similar to low-mass stars, but faster.

Sun: $\sim 10^{10}$ yr on MS.

$5\,M_{\odot}$ star: $\sim 10^{8}$ yr.

$20\,M_{\odot}$ star: $\sim 10^{7}$ yr!

Reason: $L \propto M^{3.5}$, so bigger stars run out of fuel faster.

Everything is hotter.

Low-mass: He degenerate.

Helium flash.

High-mass: *not* degenerate.

Steady burning, no flash.

Degeneracy

No, not moral reprehensibility!

Quantum mechanics says that no two electrons can occupy the same "state" at the same time.

State=position and momentum.

At high densities, this implies that electrons acquire extra energy.

This energy implies pressure, independent of temperature.

Degeneracy pressure.

Call this P_{deg}.

If $P_{\text{deg}} > nkT$, degenerate.

Expands little when heated!

Mass Loss and Pulsations

High luminosity during giant/supergiant phases can blow away a lot of matter.

For stars with initial $M < 8\,M_\odot$, enough mass is lost to leave behind a white dwarf.

In addition, high-mass stars have large pulsations.

Example: Cepheid variables.

Standard candles!

Idea: cycle of temperature and radius.

Small, hot star: puffs out.

Now cool star falls back.

Repeat!

At *very* high mass, pulsations eject matter.

Heavier and Heavier

Unlike for lower-mass stars, carbon mass is enough to burn after helium shell phase.

$^{12}\mathbf{C}+{}^{4}\mathbf{He}\rightarrow{}^{16}\mathbf{O}$.

At each stage, same pattern is repeated.

Burning in core provides energy.

Fuel is exhausted; inert core.

Burning in shell, expansion.

In this way, heavier and heavier elements can be produced: neon, magnesium, and for $M > 8\,M_\odot$, silicon and iron.

Can this continue indefinitely?

The Limits of Fusion

Each new step in fusion releases less and less energy.

Why? Concept of *binding energy.*

Energy required to destroy.

The strong nuclear force is binding, but very short range.

In nucleus, electrical force is weaker, but long range and repulsive.

Very small nuclei: strong force wins.

Very large nuclei: electrical force wins.

Most bound nucleus per mass: ^{56}Fe.

Lighter⇒fusion gives energy.

Heavier⇒fission gives energy.

Faster and Faster

Each fusion stage takes less and less time.

Higher pressure (more compact).

Higher energy rate needed.

Less energy release per nucleus.

For a 25 $M_\odot$ star:

H burning: 10^7 **yr.**

He burning: 10^6 **yr.**

C burning: 600 yr.

Ne burning: 1 yr.

O burning: 6 months.

Si burning to Fe: 1 day!

Loss of Support

Heavier nuclei need higher temperatures.

More neutrinos produced!

Escape immediately, no support.

Need even hotter temps.

Iron produces no energy at all.

Shrinks and cools.

Oh, well. At least we can rely on degeneracy pressure, right?

No! Limiting mass.

If gravity squeezes a star, the pressure increases, but so does the gravity.

Consider a cold star.

If $M > 1.4\,M_\odot$, gravity wins!

Chandrasekhar mass.

Taking the Plunge

Once the iron core exceeds the Chandrasekhar mass, it collapses.

$\sim 10^3$ km to $\sim$10 km in few ms!

Now density is $\sim 10^{14}$ times water.

At these densities, protons and electrons squeeze together to form neutrons.

Neutrons unstable in free space!

When enough neutrons have formed, neutron degeneracy pressure suddenly halts the collapse.

Proto-neutron star.

But what happens to all that energy?

Kaboom!

The amount of energy released in the collapse is $\sim 10^{46}$ Joules.

The Sun for 10^{12} yr!

Only about 1% is in photons and kinetic energy.

Rest in neutrinos.

Bounce at neutron star produces shocks, rebounding material.

Shocks strengthened by ν.

Explosion of envelope.

Supernova!

Simulations still difficult.

Heavy Element Production

How do various elements arise?

H, He: primordial nucleosynthesis.

Li to Fe: fusion in stars.

But elements heavier than iron require energy *input* to be produced.

There is a huge amount of energy in a supernova.

Rapid capture of protons, etc., can produce the rest of the periodic table.

All these elements are distributed through the universe by the supernova.

Carl Sagan: we are made of star stuff!

Crunch!

If only the iron core collapses, final state is neutron star.

But, some NS are seen that are more massive than just the core.

Fallback from higher layers.

Neutron stars have a maximum mass, too.

Probably $M_{\rm max} = 1.8 - 2.4\,M_\odot$.

If enough matter falls on, NS is pushed over its limit.

Collapses all the way.

Black hole!

Uncertain boundary: maybe $8\,M_\odot < M_{\rm init} < 20 - 25\,M_\odot$ becomes NS, lower becomes WD, higher becomes BH.

Summary

High-mass stars initially evolve as low-mass, but faster.

When core becomes iron, no further energy generation.

If core mass $> 1.4\, M_\odot$, collapse and supernova.

Star can end life as neutron star or black hole.

Challenge: how would all this change for a Population III star?