7. Stellar Death and Black Hole Birth

What is the sun?

1. A ball of hot gas.
2. Held together by gravity.
3. Supported against gravity by pressure.
4. Radiating energy into space because it is hotter than its surroundings.
5. Replenishing that lost energy by fusing hydrogen into helium in its core.

Items 1-4 apply to all stars.

Item 5 applies to all "main-sequence" stars, the most common sort.

Pressure balance in a star

High pressure in the core of a star supports it against the pull of its own gravity; otherwise a star would collapse fairly quickly.

In the sun and other main-sequence stars, that pressure comes from hot atoms.

But stars are always leaking energy into space, which tends to reduce pressure.

In main-sequence stars, the leaking energy is replenished by nuclear fusion in the core, which converts hydrogen into helium and releases $E = mc^2$ energy.

But eventually the hydrogen in the core will run out, and energy will still leak from the surface.

A star can still live for a while as a "red giant" by fusing hydrogen outside the core and by fusing helium into heavier elements (carbon, oxygen, etc.)

But fusing iron into heavier elements does not release energy, so this can't go on indefinitely.

The end game

Bottom line: Nuclear fusion can power a star for a long time, but eventually it runs out, and the star must end up in some very different state.

Theoretical calculations and astronomical observations suggest that there are three possible outcomes, each leaving behind a different kind of "exotic star."

White Dwarfs

A star that is initially less massive than about $8M_\odot$ eventually leaves behind a *white dwarf.*

A typical white dwarf is made of carbon and oxygen, has a mass of $0.6M_\odot$, and a radius comparable to the radius of the earth. The corresponding density is about 50 tons per cubic inch!

The core of the star never gets hot enough to fuse carbon and oxygen into heavier elements.

The rest of the star's mass (the envelope that once surrounded the core) drifts off into space when the star is at its most luminous.

A white dwarf is supported against its strong self-gravity by the pressure of *degenerate electrons*, electrons that are vibrating erratically at high speed because they are squeezed into a very small volume.

A more massive white dwarf has stronger gravity, squeezing it further and requiring more rapidly moving electrons to support it.

In 1930, *Subrahmanyan Chandrasekhar* showed that electrons moving close to c could not provide enough pressure to support a white dwarf against collapse.

His conclusion: The maximum possible mass of a white dwarf is $1.4M_\odot$. A star that leaves behind a core more massive than $1.4M_\odot$ cannot end its life as a white dwarf.

Nuclear Digression

See Thorne Box 5.1.

An atom is made of protons, neutrons, and electrons.

A proton has positive electric charge and an electron has negative electric charge. The electrical attraction between them holds the atom together.

A proton has 2000 times the mass of an electron.

A neutron has the same mass as a proton but no electric charge.

Protons and neutrons are held together in the *nucleus* of the atom, by the *strong nuclear force.*

Electrons orbit at a much larger distance.

For example: A carbon atom has a nucleus of six protons and six neutrons, orbited by six electrons.

The diameter of an atomic nucleus is about 100,000 times smaller than the diameter of the atom itself, so the density of the nucleus is about 10^{15} times higher than the density of the atom.

Neutron Stars

Stars that start more massive than $8M_\odot$ go through multiple cycles of fusion until they make an iron core, which cannot produce further energy.

When this core grows massive enough, it collapses under its own gravity.

One possible result is a *neutron star*, a ball of neutrons with the density of an atomic nucleus, held together by gravity.

A typical neutron star has a mass of about $1.4M_\odot$ and a radius of about 10 km.

It is supported against collapse by the pressure of degenerate neutrons.

One teaspoon of neutron star matter would weigh about as much as all human beings put together!

The existence of neutron stars was first suggested by Fritz Zwicky in the 1930s, with key details worked out over the next twenty years by J. Robert Oppenheimer, Lev Landau, and others.

First direct discovery of a neutron star (specifically, a radio pulsar) in 1967. Many hundreds since.

In 1938, Oppenheimer and Volkoff showed that there is a maximum possible for a neutron star. Exact value is still uncertain, but definitely no more than $3M_\odot$.

To date, the highest well measured neutron star mass is $2M_\odot$.

The collapse of a stellar core to form a neutron star releases a huge amount of gravitational energy. In many (perhaps all) cases this energy leads to a *supernova explosion*, causing violent and spectacular disruption of the rest of the star.

Black Holes

If a star produces a core larger than $3M_\odot$, then it cannot leave behind a neutron star.

If GR is correct, then the only alternative left is complete collapse to form a black hole.

We know that at least *some* core collapses produce a neutron star *and* a supernova explosion.

Since we also find stellar mass black holes (next section), we know that at least *some* core collapses produce black holes.

Still unknown:

Do all core collapses produce supernovae? (Probably not.)

Which core collapses produce black holes? (Probably the most massive stars, initially 30 $M_\odot$ or more, but the answer may depend in a complicated way on the structure of the star.)