8. The Life and Death of Stars

Reading: Thorne, chapters 4 and 5

Chapter 4: Focus on what white dwarfs are, what degenerate electron pressure is, and why Chandrasekhar concluded that there is a maximum possible mass of white dwarfs.

Chapter 5: Focus on what supernovae are, what neutron stars are, what the connection is between supernovae and neutron stars, and how Oppenheimer, Volkoff, and Wheeler showed that there is a maximum possible mass of neutron stars.

Recognize the connection between these maximum masses and the inevitable formation of black holes.

What is the sun?

A ball of hot gas.

Held together by gravity.

Supported against gravity by pressure.

Radiating energy into space because it is hotter than its surroundings.

Replenishing that lost energy by fusing hydrogen into helium in its core.

This description applies to all "main sequence" stars, the most common sort.

The first four apply to all stars.

Pressure balance in a star

Why doesn't the sun collapse?

Gravity is pulling the sun inward.

It doesn't collapse because high pressure gas in the core of the sun is pushing back out.

Without pressure, the sun would collapse in about an hour.

For a star to be stable, there must be a balance at every point within the star between the inward force of gravity and the outward force of pressure. Otherwise the star contracts or expands until the balance is restored.

Roughly speaking, we can think of a star as having a core that pulls on the surrounding envelope with its gravity; the pressure of the core must be enough to support the weight of the envelope.

Pressure comes from fast-moving particles: atomic nuclei, or electrons, or individual protons and neutrons, or a combination.

These fast-moving particles also have kinetic energy (energy of motion).

By considering pressure balance, one can show that the total energy of the moving particles in the core of a star must be approximately

$$E \sim \frac{GM^2}{R},$$

where M is the mass of the star and R is the radius.

If the star is more compact (smaller R), then the force of gravity on the envelope is stronger, and there must be higher pressure to balance it, hence more energy.

If the star is more massive (larger M), then the force of gravity on the envelope is stronger (by M^2 because both the core and the envelope are more massive), and there must be higher pressure to balance it, hence more energy.

Pressure, Gravity, Energy

To avoid collapse, a star must have high pressure at center.

In the sun, that pressure comes from hot atoms.

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

In the sun, the leaking energy is replenished by nuclear fusion in the core of the sun, which converts hydrogen into helium and releases energy.

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

The core of the sun will contract (slowly). Compression heats the gas, raises the pressure.

Eventually, as the temperature and density rise, helium ignites, fuses to carbon and oxygen.

But helium is a less efficient fuel. It can't sustain the star for long.

The outer envelope drifts off, and the hot core is left behind.

Degeneracy pressure and white dwarfs

Everyday life: can't put two things in the same place.

Quantum mechanical version of this "exclusion" principle: You can't put two particles in the same place unless one of them has higher momentum. (Analogy of cars in a garage, with higher momentum corresponding to other floors. Momentum in quantum mechanics is similarly discrete.)

As the carbon/oxygen core contracts, atoms are squeezed together.

Electrons must move faster (gain momentum) to take up less volume.

Eventually, the speed of the electrons is enough to provide the pressure to support the star.

Pressure from squeezed electrons is called *degenerate electron pressure.*

Star can remain stable even as it radiates energy and cools. (The atomic nuclei, which are much more massive than the electrons, are slowing down.)

A white dwarf is a star supported by degenerate electron pressure, with no ongoing nuclear fusion.

Typical white dwarf properties: $M \sim 0.6 M_\odot$, $R \sim R_{\rm earth}$, $\rho \sim 1$ ton/teaspoon, mostly carbon/oxygen composition.

More massive white dwarfs have *smaller* radii.

The Chandrasekhar Mass Limit

Squeeze a white dwarf:

- Force on envelope goes up
- Density goes up $\longrightarrow$ electrons move faster.
- Pressure goes up, more than enough to counter extra gravity.
- Star springs back.

In a white dwarf of $1 M_\odot$, the electron speed at the center (where the pressure is greatest) is $\sim 0.5c$.

Need to worry about relativity.

Add more mass: Star must get smaller, electrons move faster, to counter stronger gravitational pull.

Chandrasekhar 1930: When electrons are moving close to speed of light, get less extra pressure from squeezing. (Momentum goes up, but speed can't go up because it is already near c, so gain less than when $v \ll c$.)

Squeezed star will no longer "spring back," it will collapse.

A white dwarf of mass $M > 1.4M_\odot$ would not have enough pressure to resist gravitational collapse.

Chandrasekhar presents this result at Royal Society meeting in 1935.

First clear argument that nature should be able to make black holes (which do not yet have that name).

Eddington responds: it must be wrong.

Doesn't have a good counter-argument. He just can't believe the result.

Neutron Stars

Suppose we add mass to a white dwarf, pushing it over the Chandrasekhar mass limit. It collapses.

At high enough density and pressure, electrons and protons will combine to make neutrons. Like protons, but no electric charge.

Eventually get a neutron star: Ball of neutrons held together by gravity, supported against collapse by degenerate neutron pressure.

Neutron mass is 2000 times electron mass.

Higher density needed to make neutrons degenerate.

Degenerate neutrons can provide more pressure than degenerate electrons, because each neutron has more momentum.

Result: Neutron star of a given mass is much smaller than a white dwarf of the same mass.

For $M = 1M_\odot$, $R_{\rm WD} \approx R_{\rm earth}$, $R_{\rm NS} \approx 20\,{\rm km}$. More massive neutron stars are smaller.

Note that $R_{\rm NS}$ is only a small number of Schwarzschild radii.

History

Soon after neutron is discovered, Zwicky and Baade propose that neutron stars form in supernovae, which are powered by gravitational energy released when neutron star forms.

Many errors in details, but hypothesis basically correct.

Details are hard because need to account for nuclear force as well as gravity.

Key aspects worked out by Landau, Oppenheimer.

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

Maximum Mass of a Neutron Star

Oppenheimer and Volkoff: Maximum mass of a neutron star is $2 - 3M_\odot$.

Reason similar to that for white dwarfs, once the degenerate neutron speed approaches c, star is unstable against collapse.

Calculation is more complicated than for white dwarfs, and final outcome somewhat more uncertain, because the nuclear force between neutrons is also important. (Nuclear force is what holds together atomic nuclei.)

Neutron star structure, maximum mass, still a major research area.

Most neutron stars with measured masses (pulsars in binary systems) have $M \approx 1.4M_\odot$, a few may be up to $2M_\odot$.

No convincing cases of neutron stars more massive than $2M_\odot$.

The Life and Death of Stars

After many decades of observations and theory, we have the following picture of the life cycle of stars.

- Stars form from gravitationally contracting gas clouds. Compression heats gas until it is hot enough to start nuclear fusion.
- "Main sequence" stars replenish lost energy by fusing hydrogen to helium in their cores. This is the longest phase of a star's life, 10 billion years for the sun. More massive stars begin life with more fuel, but they are much more luminous, so they have shorter lifetimes. ("Live fast, die young.")
- After star exhausts hydrogen, core contracts, envelope expands, star becomes a giant. Eventually ignites helium fusion to carbon and oxygen.

After helium exhaustion, two branches:

Initial stellar mass $M < 8M_\odot$:

- Outer envelope drifts off, white dwarf with $M < 1.4M_\odot$ left behind (typically $0.6M_\odot$).

Initial stellar mass $M > 8M_\odot$:

- Core gets hot enough to fuse carbon and oxygen to heavier elements.
- More fusion cycles leading to iron, which does not release energy when fused to heavier elements.
- Core collapses, producing a neutron star or a black hole.

At least some core collapses produce a neutron star *and* a supernova explosion.

Still unknown: Do all core collapses produce supernovae? Which core collapses produce black holes? (Probably the most massive stars, initially 30 $M_\odot$ or more.)

Evidence for existence of black holes, 1935, 1960

By 1920, we have the following circumstantial evidence for the existence of black holes (collapsed objects with event horizons):

General Relativity (GR) is empirically successful (orbit of mercury, light bending by sun).

Schwarzschild solution show black holes could exist in GR, if they could form.

Interpretation of Schwarzschild's solution near or inside the event horizon is controversial, and many physicists believe such objects are impossible.

By 1935 we have the additional piece of theoretical evidence, thanks to Chandrasekhar:

There is a maximum mass of white dwarf stars. A star with mass $M > 1.4M_\odot$ that uses up its nuclear fuel cannot be supported by degenerate electron pressure; it must collapse further.

This opens a plausible route to formation of black holes as the end state of massive stars.

By 1960, we have further circumstantial evidence:

Supernova explosions appear to be associated with the formation of neutron stars.

There is a maximum mass of neutron stars, something like $2 - 3M_\odot$ (Oppenheimer & Volkoff, Wheeler).

An object that is more massive than $3M_\odot$ and has no continuing source of energy (i.e., no nuclear fuel left) cannot support itself against gravitational collapse.

This case strengthens in late 1960s with the direct detection of neutron stars (as radio pulsars) and their association with supernova remnants.

There is still no *direct* empirical evidence for black holes.