LECTURE 14: SUPERNOVAE

14.1 CORE FUSION IN MASSIVE STARS

In a low-mass (main sequence mass $M < 8M_{\odot}$) star, degenerate electron pressure halts the contraction of the carbon/oxygen core (produced by helium fusion) before it gets hot enough to ignite carbon fusion.

In a high-mass star, the core contracts and heats to a temperature where carbon can fuse.

After the core runs out of carbon, it contracts again, until it becomes hot enough for oxygen fusion.

The core of the star continues through fusion cycles, building up an "onion" structure of layered elements.

Heavier elements are less efficient nuclear fuel, so each cycle takes less time. For a $20M_{\odot}$ star, which has a main-sequence (hydrogen-fusion) lifetime of about 8 million years, silicon fuses to iron in about a week!

14.2 CORE COLLAPSE AND ENVELOPE EXPLOSION

Eventually, fusion in a massive star turns the core to iron. But fusing iron into heavier elements *releases no energy.* (In fact, it takes energy.)

Without a fusion energy source, the core cannot maintain its pressure, and it is too massive to be supported by degenerate electrons. It implodes to a size of about 50 km in a fraction of a second.

The core now has enormously high density and temperature. The iron nuclei disintegrate, and the electrons are "squeezed" into the protons, turning them into neutrons and producing neutrinos.

Iron disintegration robs the core of its remaining heat, and it collapses to the density of an atomic nucleus, and beyond. The collapse is finally halted by the nuclear interaction, which becomes repulsive at extremely high densities.

The core 'bounces' and runs into the still infalling envelope. The collision drives a blast wave which rips through the envelope, exploding the star.

The details of the explosion process are not very well understood; this is a major area of current theoretical research. From theory alone, we might not be convinced that massive stars explode, but observations clearly show such events.

14.3 HISTORICAL SUPERNOVAE

Chinese astronomers recorded the appearance of "guest stars" in 1006, 1054, and 1181. European astronomers (Tycho and Kepler) described similar events in 1572 and 1604.

These "stars" appeared, brightened rapidly, then faded from visibility over the course of a year or two.

They were almost certainly what we now call *supernovae*, produced by exploding stars.

[*Novae* are explosive brightening events that occur in special kinds of binary stars. They are much more common than supernovae, but they are much less luminous.]

14.4 THE CRAB NEBULA

A cloud of glowing gas called the Crab Nebula lies at the location where the "guest star" of 1054 was recorded.

Doppler shifts and proper motions of the nebula's gas filaments show that it is expanding.

Extrapolating backwards implies that the gas should all have been in one place around the year 1140, entirely consistent with 1054 given the observational and theoretical uncertainties.

Conclusion: the Crab Nebula is the glowing, exploded envelope of the supernova the Chinese recorded in 1054.

14.5 MODERN SUPERNOVA OBSERVATIONS

Supernovae are bright enough to be seen in distant galaxies. On average, in a typical galaxy, they occur at a rate of about 1 per century.

At its peak luminosity (which lasts for only a few days), a supernova can be more than a billion times more luminous than the sun.

A typical supernova rises to its maximum luminosity in a few days, then fades by a factor of 100 over the next six months and continues to fade thereafter.

Theoretical interpretation:
- The rise over days occurs as the blast wave goes out through the star's envelope.
- Fading occurs as the envelope expands and cools.

The star's exploded envelope becomes a *supernova remnant* like the Crab Nebula, detectable with optical and radio telescopes for thousands of years.

14.6 SUPERNOVA 1987A

There have been no supernovae in the Milky Way since the invention of the telescope.

In February 1987, the next best thing happened: a supernova went off in the Large Magellanic Cloud, a galaxy very close to the Milky Way.

Supernova 1987A occurred 50,000 parsecs away, but at its peak it was visible to the naked eye. Detailed observations provided a wealth of information about the supernova and the massive star that gave rise to it.

The theory that supernovae result from collapse of a star's iron core predicts that at least 10^{57} neutrinos should be released as the protons and electrons are squeezed into neutrons.

Just before supernova 1987A became visible, 20 neutrinos were detected in two different underground experiments within a space of 15 seconds, a dramatic confirmation of supernova theory.

Betelgeuse, a bright star 320 parsecs away, is expected to become a supernova sometime in the next few thousand years. At its peak, it will be as bright as the full moon.

14.7 TYPE I AND TYPE II SUPERNOVAE

Observationally, there are two major classes of supernovae.
Type I: no hydrogen lines in spectrum
Type II: hydrogen lines in spectrum

Many (perhaps all) massive stars eventually explode as Type II supernovae.

Type I supernovae have similar power, but they are thought to have a quite different physical origin. They probably arise in fairly old binary star systems, when a white dwarf star has its mass pushed over the Chandrasekhar limit.

14.8 SUPERNOVAE AND HEAVY ELEMENTS

The Big Bang theory predicts, and observations strongly suggest, that before the first stars formed there were no atoms of elements heavier than hydrogen and helium.

The centers of massive stars are the only places we know of that are hot enough to produce heavy elements like iron.

Supernovae expel these heavy elements from stellar cores, enabling them to be incorporated into other objects.

Most of the atoms that make up the earth, everyday objects, and living things were formed in massive stars and expelled in supernovae.

Virtually all elements heavier than iron were made in supernovae.

14.9 NEUTRON STARS

A supernova explodes a star's envelope, but the core of neutrons is left behind.

Most (perhaps all) Type II supernovae produce a *neutron star*, a ball of $\sim 10^{57}$ neutrons with mass similar to the sun but a radius of about 10 miles.

The density (mass divided by volume) of a neutron star is about the density of an atomic nucleus, 100 trillion times the density of water, 100 million times the density of a white dwarf.

A neutron star resembles a giant atomic nucleus, but it is held together by gravity, not by the nuclear force.

A neutron star is supported against collapse by degenerate neutron pressure.

Disintegration of iron in the core of a supernova undoes all of the effects of nuclear fusion over the star's lifetime. Ultimately, the energy that powers a supernova comes from gravitational potential energy, released by collapsing a stellar core with the mass of the sun down to an object the size of a large city.

14.10 SUMMARY

Stars with $M > 8M_{\odot}$ (on the main sequence) go through repeated cycles of core fusion, building up an onion structure of heavier and heavier elements.

The cores of massive stars eventually implode, because once they turn to iron they have no source of fusion energy with which to maintain their pressure and stave off gravitational collapse.

After collapsing to nuclear density, the "bounce" of the neutron core drives a blast wave into the star's envelope. The resulting explosion produces a Type II supernova, about a billion times more luminous than the sun.

Supernovae are the source of most atomic elements heavier than helium.

Many, perhaps all massive stars end their lives by exploding as supernovae, leaving behind a supernova remnant and
a neutron star — supported by degenerate neutrons, a partial but costly victory for pressure
– or –
a black hole — a completely collapsed object, a victory for gravity