Summary of Lecture 21

Key points include:

1. Stars can end their lives in one of three ways: as white dwarfs, as neutron stars, or as black holes.
2. The overwhelming majority of stars, such as the Sun, will become white dwarfs. Only massive stars (beginning their lives with $M > 8\ M_\odot$) become neutron stars or black holes. Neutron stars and black holes are formed by the collapse of the core of a massive star at the end of its life, and are born in supernovae.
3. None of the three types of stellar remnants hold themselves up against gravity by producing energy. White dwarfs are held up by electron degeneracy pressure, neutron stars are held up by neutron degeneracy pressure, and black holes aren't held up at all; gravity wins for black holes!
4. Because they aren't producing significant energy, white dwarfs and neutron stars just cool off with time.
5. Focusing on white dwarfs, their electron degeneracy can be understood using the Heisenberg Uncertainty Principle. That principle states (among other things) that the uncertainty in position, Δx, times the uncertainty in momentum, Δp, can never be less than $\hbar/2$, where $\hbar = h/(2\pi)$ and h is Planck's constant. If the number of electrons per volume is very large, then the space per electron is small and Δx is correspondingly small. Since the product can't be smaller than $\hbar/2$, this means that Δp is large, and thus the momentum has to be large. This means that the electrons acquire a kind of energy, called the Fermi energy, which helps support the star against gravity.
6. Similarly, neutron stars are held up by neutron degeneracy: cramming the neutrons together gives them an energy which can oppose gravity.
7. One weird thing about objects supported by degeneracy pressure is that the more massive they are, the *smaller* they are! That's very different from normal things; if you build a pile of rocks, the more rocks you have the bigger the pile is.
8. A white dwarf with the mass of the Sun is about the size of the Earth. That means that its average density is a million times that of water; a cubic centimeter of white dwarf matter would weigh a ton.
9. But degeneracy pressure can't hold up an arbitrary amount of mass. Above $1.4\ M_\odot$, the electrons move close enough to the speed of light that, as it turns out, the white dwarf is unstable and collapses. This, you recall, is related to why the iron core of a massive star collapses.

10. White dwarfs, like other stars, can be in binaries. If the binary companion has a wind, or even more so if the companion is close enough, matter can flow from the companion to the white dwarf (this flow is called *accretion*). Under some circumstances, this matter can build up enough that there can be explosive fusion on the surface of the white dwarf. This is called a *nova*.

11. But if the mass of the white dwarf gets large enough (either through accretion onto a heavy white dwarf or, as most people now think, through the inspiral of two white dwarfs toward each other), most of the white dwarf can undergo explosive thermonuclear fusion and then the whole white dwarf blows up. This is a type of supernova, but it is different from the type that ends a massive star's life. We can call this a *white dwarf supernova*, although unfortunately in the literature this is called a *Type Ia supernova*. These are extremely important in cosmology because we can figure out their actual luminosity, and thus by measuring their flux we can determine their distance.

12. Neutron stars, which are held up against gravity by neutron degeneracy pressure, are much smaller and much denser than white dwarfs. Their masses are between 1.2 $M_\odot$ and at least 2.1 $M_\odot$, and their radii are between 12 km and 13 km. A good fraction of my own research involves ways to determine the sizes of neutron stars, because such measurements give us important hints about the nature of the matter in their cores (a key question in nuclear physics).

13. At those densities, all 8 billion people on Earth would fit into a teaspoon!

14. Such small objects might seem nearly impossible to detect, but in 1967, graduate student Jocelyn Bell discovered *pulsars*. Unlike what you might expect, these are rotating (not pulsating) neutron stars, with strong magnetic fields (from $\sim 10^8$ to $\sim 10^{16}$ times the Earth's magnetic field strength!!!), whose rotation sends out various electromagnetic signals. Now-Dr. Bell discovered the signals in radio waves.