

## Lecture 24

### 1. White dwarfs

A white dwarf is what stars like our Sun become after they have exhausted their nuclear fuel. Near the end of its nuclear burning stage, such a star expels most of its outer material, creating a planetary nebula. Only the hot core of the star remains. This core becomes a very hot ( $T > 100,000\text{K}$ ) young white dwarf, which cools down over the course of the next billion years or so. (That is, unless it is accreting matter from a nearby star (see Cataclysmic Variables).) Many nearby, young white dwarfs have been detected as sources of soft (*i.e. lower-energy*) X-rays ; recently, soft X-ray and extreme ultraviolet observations have become a powerful tool in the study the composition and structure of the thin atmosphere of these stars. A typical white dwarf is half as massive as the Sun, yet only slightly bigger than the Earth. This makes white dwarfs one of the densest forms of matter, surpassed only by neutron stars.

To say that white dwarfs are strange is an understatement. An earth-sized white dwarf has a density of  $1 \times 10^9 \text{ kg/m}^3$ . In comparison, the earth itself has an average density of only  $5.4 \times 10^3 \text{ kg/m}^3$ . That means a white dwarf is 200,000 times as dense! Because a white dwarf is not able to create internal pressure (e.g. from the release of energy from fusion), gravity crushes it down until even the very electrons making up a white dwarf's atoms are smashed together. In normal circumstances, identical electrons (those with the same "spin") are not allowed to occupy the same energy level. Since there are only two ways an electron can spin, only two electrons can occupy a single energy level. This is what's known in physics as the Pauli Exclusion Principle. And in a normal gas, this isn't a problem; there aren't enough electrons floating around to completely fill up all the energy levels. But in a white dwarf, all of the electrons are forced close together; soon all the energy levels in its atoms are filled up with electrons. If all the energy levels are filled, and it is impossible to put more than two electrons in each level, then our white dwarf has become degenerate. For gravity to compress the white dwarf anymore, it must force electrons where they cannot go. Once a star is degenerate, gravity cannot compress it any more because quantum mechanics tells us there is no more available space to be taken up. So our white dwarf survives, not by internal fusion, but by quantum mechanical

principles that prevent its complete collapse.



Degenerate matter has other unusual properties; for example, the more massive a white dwarf is, the smaller it is! This is because the more mass a white dwarf has, the more its electrons must squeeze together to maintain enough outward pressure to support the extra mass. There is a limit on the amount of mass a white dwarf can have, however. Subrahmanyan Chandrasekhar

discovered this limit to be 1.4 times the mass of our Sun. (This is appropriately known as the "Chandrasekhar limit".)

With a surface gravity of 100,000 times that of the earth, the atmosphere of a white dwarf is very strange. The heavier atoms in its atmosphere sink and the lighter ones remain at the surface. Some white dwarfs have almost pure hydrogen or helium atmospheres, the lightest of elements. Also, the very strong gravity pulls the atmosphere close around it in a very thin layer. If it were on earth, this atmosphere would be lower than the tops of skyscrapers!

Underneath the atmosphere of many white dwarfs, scientists think there is a 50 km thick crust. At the bottom of this crust is a crystalline lattice of carbon and oxygen atoms. Since a diamond is just crystallized carbon, one might make the comparison between a cool carbon/oxygen white dwarf and a diamond!

Some binary star systems in which a carbon-oxygen white dwarf is accreting matter from a companion result in supernova type I. (What kind of companion star is best suited to produce type I supernovae is hotly debated.) In a popular scenario, so much mass piles up on the white dwarf that its core reaches a critical density of  $2 \times 10^9 \text{ g/cm}^3$ . This is enough to result in an uncontrolled fusion of carbon and oxygen, thus detonating the star.

## **2. Neutron Stars**

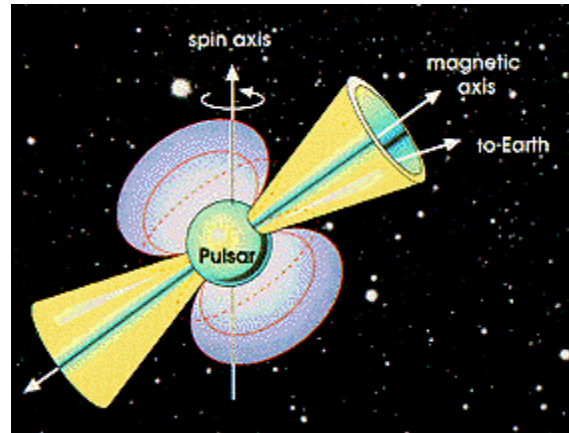
Stars which are 8 times or more massive than our Sun end their lives in a most spectacular way; they go supernova. A supernova explosion will occur when there is no longer enough fuel for the fusion process in the core of the star to create an outward pressure which combats the inward gravitational pull of the star's great mass. First, the star will swell into a red supergiant...at least on the outside. On the inside, the core yields to gravity and begins shrinking. As it shrinks, it grows hotter and denser. A new series of nuclear reactions begin to occur....temporarily halting the collapse of the core... but alas, it is only temporary. When the core contains essentially just iron, it has nothing left to fuse (because of iron's nuclear structure, it does not permit its atoms to fuse into heavier elements). Fusion in the core ceases. In less than a second, the star begins the final phase of gravitational collapse. The core temperature rises to over 100 billion degrees as the iron atoms are crushed together. The repulsive force between the nuclei overcomes the force of gravity. So the core compresses, but then recoils. The energy of the recoil is transferred to the envelope of the star, which then explodes and produces a shock wave. As the shock encounters material in the star's outer layers, the material is heated, fusing to form new elements and radioactive isotopes. The shock then propels the matter out into space. The material that is exploded away from the star is now known as a supernova remnant.

Neutron stars are compact objects that are created in the cores of massive stars during supernova explosions. The core of the star collapses, and crushes together every proton with a corresponding electron turning each electron-proton pair into a neutron. The neutrons, however, can often stop the collapse and remain as a neutron star.

Neutron stars are fascinating objects because they are the most dense objects known. They are only about 10 miles in diameter, yet they are more massive than the Sun. One sugar cube of neutron star material weighs about 100 million tons, which is about as much as a mountain. Like their less massive counterparts, white dwarfs, the heavier a neutron star gets the smaller it gets. Imagine if a 10 pound bag of flour was smaller than a 5 pound bag!

Neutron stars can be observed occasionally as an extremely small and hot star within a supernova remnant. However, they are more likely to be seen when they are a pulsar or part of an X-ray binary.

What are pulsars? Simply put, pulsars are rotating neutron stars. And pulsars pulse because they rotate! Pulsars were first discovered in late 1967 by graduate student Jocelyn Bell Burnell as radio sources that blink on and off at a constant frequency. Now we observe the brightest ones at almost every wavelength of light. Pulsars are spinning neutron stars that have jets of particles moving almost at the speed of light streaming out above their magnetic poles. These jets produce very



powerful beams of light. For a similar reason that "true north" and "magnetic north" are different on Earth, the magnetic and rotational axes of a pulsar are also misaligned. Therefore, the beams of light from the jets sweep around as the pulsar rotates, just as the spotlight in a lighthouse does. Like a ship in the ocean that sees only regular flashes of light, we see pulsars turn on and off as the beam sweeps over the Earth. Neutron stars for which we see such pulses are called "pulsars", or sometimes "spin-powered pulsars," indicating that the source of energy is the rotation of the neutron star.

### 3. Black holes

There are many popular myths concerning black holes, many of them perpetuated by Hollywood. Television and movies have portrayed them as time-traveling tunnels to another dimension, cosmic vacuum cleaners sucking up everything in sight, and so on. It can be said that black holes are really just the evolutionary end point of massive stars. But somehow, this simple explanation makes them no easier to understand or less mysterious.

Black holes are the evolutionary endpoints of stars at least 10 to 15 times as massive as the Sun. If a star that massive or larger undergoes a supernova explosion, it may leave behind a fairly massive burned out stellar remnant. With no outward forces to oppose gravitational forces, the remnant will collapse in on itself. The star eventually collapses to the point of zero volume and infinite density, creating what is known as a "singularity". As the density increases, the path of light rays emitted from the star are bent and

eventually wrapped irrevocably around the star. Any emitted photons are trapped into an orbit by the intense gravitational field; they will never leave it. Because no light escapes after the star reaches this infinite density, it is called a black hole.

But contrary to popular myth, a black hole is not a cosmic vacuum cleaner. If our Sun was suddenly replaced with a black hole of the same mass, the earth's orbit around the Sun would be unchanged. (Of course the Earth's temperature would change, and there would be no solar wind or solar magnetic storms affecting us.) To be "sucked" into a black hole, one has to cross inside the Schwarzschild radius. At this radius, the escape speed is equal to the speed of light, and once light passes through, even it cannot escape.

The Schwarzschild radius can be calculated using the equation for escape speed.

$$v_{\text{esc}} = (2GM/R)^{1/2}$$

For photons, or objects with no [mass](#), we can substitute  $c$  (the speed of light) for  $V_{\text{esc}}$  and find the Schwarzschild radius,  $R$ , to be

$$R = 2GM/c^2$$

If the Sun was replaced with a black hole that had the same mass as the Sun, the Schwarzschild radius would be 3 km (compared to the Sun's radius of nearly 700,000 km). Hence the Earth would have to get very close to get sucked into a black hole at the center of our solar system.

If we can't see them, how do we know they're there? Since black holes are small (only a few to a few tens of kilometers in size), and light that would allow us to see them cannot escape, a black hole floating alone in space would be hard, if not impossible, to see. For instance, the photograph above shows the optical companion star to the (invisible) black hole candidate Cyg X-1.



However, if a black hole passes through a cloud of interstellar matter, or is close to another "normal" star, the black hole can accrete matter into itself. As the matter falls or is pulled towards the black hole, it gains kinetic energy, heats up and is squeezed by tidal forces. The heating ionizes the atoms, and when the atoms reach a few million degrees Kelvin, they emit X-rays. The X-rays are sent off into space before the matter crosses the Schwarzschild radius and crashes into the singularity. Thus we can see this X-ray emission.