**Introduction**

- Recall that White Dwarfs are the second most common type of star.
- They are the remains of medium-sized stars
  - hydrogen fused to helium
  - failed to ignite carbon
  - drove away their envelopes to from planetary nebulae
  - collapsed and cooled to form White Dwarfs
- The more massive a White Dwarf, the smaller its radius
- Stars more massive than the Chandrasekhar limit of 1.4 solar masses cannot be White Dwarfs

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**Formation of Neutron Stars**

As the core of a massive star (residual mass greater than 1.4 solar masses) begins to collapse:
- density quickly reaches that of a white dwarf
- but weight is too great to be supported by degenerate electrons
- collapse of core continues; atomic nuclei are broken apart by gamma rays
- Almost instantaneously, the increasing density forces freed electrons to absorb electrons to form neutrons
- the star blasts away in a supernova explosion leaving behind a neutron star.

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**Properties of Neutron Stars**

- Neutrons stars predicted to have a radius of about 10 km and a density of $10^{14}$ g/cm$^3$.
- This density is about the same as the nucleus
- A sugar-cube-sized lump of this material would weigh 100 million tons
- The mass of a neutron star cannot be more than 2-3 solar masses
- Neutron stars are predicted to rotate very fast, to be very hot, and have a strong magnetic field.
- Such objects have been identified as pulsars, sources of pulsed radio energy.

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**Crab Nebula**

- In CE 1054, Chinese astronomers saw a supernova
- Pulsar is at center (arrow)
- It is very energetic; pulses are detectable at visual wavelengths
- Inset image taken by Hubble Space Telescope
Pulsars

- Pulsars are spinning neutron stars.
- They emit beams of radiation from their magnetic poles.
- As they spin, the beams sweep through the sky like a lighthouse.
- A few pulsars have been found in binary systems.
- Astronomers can estimate the masses of the pulsars.
- In some binary systems, such as Hercules X-1, mass flows into a hot, accretion disk around the neutron star.
- X rays are emitted.

Black Holes

- If the core of a star collapses and contains more than 3 solar masses, no force can stop it.
- As object shrinks, its density and gravitational strength increase.
- If it shrinks to zero radius, its density and gravity become infinite.
- Such a point is called a Singularity.
- A black hole is formed.

- Escape Velocity is the initial velocity an object needs to escape from a celestial body.
- For Earth, escape velocity is 11 km/s (25 000 mph).

- A black hole forms when an object collapses to a small size (perhaps to a singularity).
- The escape velocity in its neighborhood is so great light cannot escape.
- This boundary is the Event Horizon.
- Radius $R_s$ is Schwarzschild radius.
- Events inside event horizon cannot be seen.

Entering a Black Hole

- If we were to leap, feet first, into a black hole, outside observers would notice two relativistic effects.
- Time dilation—they would see our clock slow down.
- Our light would seem to be red-shifted to longer wavelengths.
- We would not notice these effects.
Entering a Black Hole

- Entering feet first toward event horizon, we would feel our feet being pulled more strongly than our heads.
- This is a tidal force
- It will at first be minor

Search for Black Holes

- Do black holes exist?
  - A black hole alone is totally invisible.
  - If a gas is flowing rapidly into it, the gas will heat up and emit X-rays before it enters event horizon.
  - Consider a black hole in a close binary system.
  - Black hole could drain mass from companion star, and form a hot accretion disk that would emit X-rays

Misconceptions of Black Holes

- Black holes exist only in theory.
  - Recent observations obtained by the Hubble Space Telescope have given considerable support to the presence of supermassive black holes at the centers of some galaxies, but there is not yet absolute proof. There has been very good evidence for the existence of stellar black holes for at least 20 years, based on the effects of an unseen companion in the double-star system, Cygnus X-1. The existence of black holes seems likely, given our understanding of physical processes, but it is not absolutely confirmed.

- Black holes are giant cosmic vacuum cleaners that swallow up everything around them.
  - In reality, at a given distance from its center a black hole creates the same gravity as would a normal object with the same mass. Therefore, black holes at a distance do not attract matter more strongly than ordinary stars do. However, another important factor that determines the magnitude of the force of gravity is the radius of the object. The mass of a black hole is so compressed that it is possible to get very close to its center where gravity will be enormously strong.
Black holes can be detected visually. We observe black holes indirectly by the effect they have on material around them, but by definition a black hole cannot be “seen.”

Our Sun will become a black hole. Only stars that are more massive than our Sun might become black holes when they run out of fuel at the end of their lives. The Sun is not massive enough to become a black hole.