Death of Stars - Part II
Neutron Stars
REMEMBER THIS !?
Guiding Questions

1. What led scientists to the idea of a neutron star?
2. What are pulsars, and how were they discovered?
3. How did astronomers determine the connection between pulsars and neutron stars?
4. How can a neutron star supply energy to a surrounding nebula?
5. What are conditions like inside a neutron star?
6. How are some neutron stars able to spin several hundred times per second?
7. Why do some pulsars emit fantastic amounts of X rays?
8. Are X-ray bursters and novae similar to supernovae?
9. How massive can a neutron star be?
Scientists first proposed the existence of neutron stars in the 1930s

- A neutron star is a dense stellar corpse consisting primarily of closely packed degenerate neutrons
- A neutron star typically has a diameter of about 20 km, a mass less than 3 times the mass of the Sun, a magnetic field $10^{12}$ times stronger than that of the Sun, and a rotation period of roughly 1 second
- Zwicky and Baade proposed that a highly compact ball of neutrons would produce a degenerate neutron pressure in star remnants too large to become white dwarfs
  - Not verified until 1960’s
The discovery of pulsars in the 1960s stimulated interest in neutron stars.

Pulsar PSR 0329+54
Interval between pulses: 0.714 second
Pulsars are rapidly rotating neutron stars with intense magnetic fields

- A pulsar is a source of periodic pulses of radio radiation.
- These pulses are produced as beams of radio waves from a neutron star’s magnetic poles sweep past the Earth.
Intense beams of radiation emanate from regions near the north and south magnetic poles of a neutron star.

These beams are produced by streams of charged particles moving in the star’s intense magnetic field.
The Crab pulsar in visible light

The Crab pulsar in X rays
Fast-moving material from the pulsar creates shock waves, forming X-ray-emitting rings.

The Crab pulsar

The pulsar’s magnetic field funnels outgoing material into two oppositely directed jets.

1 light-year
Superfluidity and superconductivity are among the strange properties of neutron stars

- A neutron star consists of a superfluid, superconducting core surrounded by a superfluid mantle and a thin, brittle crust
- There is evidence for an "atmosphere"
X-ray image

Neutron star 1E 1207.4-5209
The dashed curve shows the expected X-ray spectrum of neutron star 1E 1207.4-5209.

The solid curve shows the observed spectrum: The dips are caused by absorption of X-ray photons by the neutron star’s atmosphere.
Pulsars gradually slow down as they radiate energy into space

- The pulse rate of many pulsars is slowing down steadily
- This reflects the gradual slowing of the neutron star’s rotation as it radiates energy into space
- Sudden speedups of the pulse rate, called glitches, may be caused by interactions between the neutron star’s crust and its superfluid interior or material falling onto the crust
The neutron star’s rotation is gradually slowing down, so the pulsar period increases.

Pulsar glitch: The neutron star’s rotation suddenly speeds up and the period decreases.

After the glitch, the neutron star’s rotation resumes its slowdown and the period again increases.
The fastest pulsars were probably created by mass transfer in close binary systems

- If a neutron star is in a close binary system with an ordinary star, tidal forces will draw gas from the ordinary star onto the neutron star.
- The transfer of material onto the neutron star can make it rotate extremely rapidly, giving rise to a millisecond pulsar.
The Black Widow pulsar

X rays are emitted when high-energy particles in the pulsar “wind” run into the interstellar medium.
1. The Black Widow pulsar emits intense X-radiation and a strong wind of matter and antimatter.

2. The radiation and wind from the pulsar cause the companion star to evaporate.

3. A wind of evaporated material streams from the companion star.

4. Interactions between the two stars’ winds form a shock wave that emits even more X rays.

An illustration of the pulsar and its companion
Pulsating X-ray sources are also neutron stars in close binary systems

- Magnetic forces can funnel the gas onto the neutron star’s magnetic poles, producing hot spots
- These hot spots then radiate intense beams of X rays
- As the neutron star rotates, the X-ray beams appear to flash on and off
- Such a system is called a pulsating X-ray variable
X-ray pulses from Cen X-3 occur at intervals of only 4.84 s.

The measured intensity of the pulses changed as the spacecraft’s detectors rotated toward and away from Cen X-3.
1. The ordinary star has expanded to become a giant or supergiant, filling its Roche lobe: Some of its gas escapes.

2. Some gas from the ordinary star crosses the inner Lagrangian point and forms an accretion disk around the neutron star.

3. The neutron star’s magnetic field funnels gas onto the magnetic poles, forming hot spots.

4. As the neutron star rotates, beams of X rays from the hot spots sweep around the sky.
Explosive thermonuclear processes on white dwarfs and neutron stars produce novae and bursters

- Material from an ordinary star in a close binary can fall onto the surface of the companion white dwarf or neutron star to produce a surface layer in which thermonuclear reactions can explosively ignite.
- Explosive hydrogen fusion may occur in the surface layer of a companion white dwarf, producing the sudden increase in luminosity that we call a nova.
- The peak luminosity of a nova is only $10^{-4}$ of that observed in a supernova.
- Explosive helium fusion may occur in the surface layer of a companion neutron star.
- This produces a sudden increase in X-ray radiation, which we call a burster.
(a) Nova Herculis 1934 shortly after peak brightness  
(b) Two months later
1. Material from a star accretes onto a companion white dwarf.

2. When enough accreted material builds up, thermonuclear reactions occur on the white dwarf’s surface, creating a burst of visible light.

3. The nova fades over several weeks.
1. Material from a star accretes onto a companion neutron star.

2. When enough accreted material builds up, thermonuclear reactions occur on the neutron star’s surface, creating a burst of X rays.

3. The X-ray burster fades within seconds.
Like a white dwarf, a neutron star has an upper limit on its mass

- The pressure within a neutron star comes from two sources
  - One is the degenerate nature of the neutrons, and the other is the strong nuclear force that acts between the neutrons themselves
- The discovery of neutron stars inspired astrophysicists to examine seriously one of the most bizarre objects ever predicted by modern science, the black hole
Jargon

- degenerate neutron pressure
- glitch
- millisecond pulsar
- neutron star
- nova (*plural* novae)
- pair production
- pulsar
- pulsating X-ray source
- superconductivity
- superfluidity
- synchrotron radiation
- X-ray burster