Astronomy 114

Lecture 22: Neutron Stars

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UMass/Astronomy Department
Announcements

- PS#5 due Wednesday
- Questionnaires?
Announcements

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- Questionnaires?

Today:
- Supernovae: two types!
  - Standard candles
- Neutron stars
- Pulsars
- *Neutron Stars & Black Holes, Chaps. 23 & 24*
Mass transfer in binary stars \(\Rightarrow\) Supernova

What happens when binary star evolves?

- a Detached binary
- b Semi-detached binary
- c Contact binary
- d Overcontact binary
Mass transfer in binary stars $\Rightarrow$ Supernova

What happens when binary star evolves?

- Suppose one star is a white dwarf
- Material from evolving star is transferred to white dwarf
- Mass on surface of white dwarf builds up
- Exceeds Chandrasekhar limits
- Begins to collapse . . .
- Supernova
Supernova as standard candles

Standard candle: an object whose luminosity is known and reveals its distance by a brightness measurement

Two kinds of supernova:

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SN 1987N (Type Ia)
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![Graph showing light intensity over time with peaks for He I and SN 1984L (Type Ib).]
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![Graph showing relative intensity over time for SN 1987M (Type Ic) with an illustration of a supernova explosion.]
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Standard candle: an object whose luminosity is known and reveals its distance by a brightness measurement.

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SN 1992H (Type II)

Supergiant star with outer layers largely intact → Core collapse, explosion

H_\alpha
Supernova lightcurve

- Data suggests that Type Ia curves are always similar
- Good *standard candles*
The latest results

Even more violent events

- **Hypernovae**
  - 100 times more energy than supernovae
  - Remnants in distant galaxies, may be related to GRBs

- **Gamma ray bursts (GRBs)**
  - $\gamma$ rays (and light, and neutrinos)
  - Discovered by satellites designed to verify the conditions of the Nuclear Test Ban Treaty (1970s)
  - Compton Gamma Ray Observatory: observes one per day
  - Length: seconds or minutes, longer afterglows at lower energy
Type II Supernova \Rightarrow \text{Neutron star}

- During collapse: \( e^- + p \rightarrow n + \text{neutrino} \)
- Roughly \(10^{57}\) neutrinos created in the iron core as protons are converted to neutrons
- After the “bounce”, becomes a sphere of tightly packed neutrons, known as: \textit{neutron star}
- Neutron star: single humongous atomic nucleus
  - Mass between 1 and 3 solar masses
  - Radius: 5 to 20 kilometers
- Strong magnetic fields
Magnetic fields

- Magnetic fields are produced by electric currents
  - Examples:
    - Currents in wires
    - Currents caused by electrons in atomic orbits
- A permanent magnet is a collection of atoms whose internal currents are lined up in a single direction on average
- A magnet will tend to try to align itself with a magnetic field
- We call that direction a field line
How magnetic fields work

- Current in a straight wire
- The magnetic field lines are concentric circles
How magnetic fields work

- Electric current in a circular loop
- Magnetic field concentrated in the center of the loop
How magnetic fields work

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- Stacking multiple loops concentrates the field; *solenoid* or *electromagnet*
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How magnetic fields work

- Circulating electric currents in the Earth’s molten metallic core generate a magnetic field
- Current loop
- Similar in Sun
Magnetic fields in neutron stars

- *Rapidly rotating:*
  - Frequency: 1000 rotations/second
    (1 rotation/month for the Sun)
  - Due to conservation of ang mom (recall skater)
Magnetic fields in neutron stars

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  - $10^{12}$ Gauss (1 and 0.5 Gauss for the Sun & Earth)
  - Why? Magnetic field lines are conserved and compressed as star collapses.
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- **Very hot:**
  - $10^6$ K at surface after collapse (5800 K for Sun)
NS supported by degeneracy pressure

- Core is compressed to nuclear density
- Neutrons also must obey the Pauli exclusion principle
  - Density of $1 \text{ ton/cm}^3$, electrons are degenerate
  - Density of $4 \times 10^8 \text{ tons/cm}^3$ neutrons are degenerate
- Upper limit to mass: $M > 2 - 3M_\odot$
  - Above this mass, the degenerate-neutron pressure is insufficient to prevent collapse
  - Larger mass: black hole (?)
NS structure

Neutron star “quake”
Beamed radiation (1/2)

- The strong magnetic field and rapid rotation of a neutron star generate strong electromagnetic fields.
- Like electric power generators: rotating magnets inside a coil of wires.
- Field generated by rotating magnetized neutron star pull electrons from neutron star surface.
- Charged particles confined to magnetic field lines.
- Acceleration: causes *synchrotron* radiation.
- We see narrow beams of radiation along the magnetic poles.
- Only observe if beam is pointing toward observer.
Beamed radiation (1/2)
Beamed radiation (2/2)

- Magnetic pole does not coincide with rotation axis
- Beams of radiation are at an angle to the rotation axis of the neutron star
- As the neutron star rotates, the beams swing around in a cone
- If a beam happens to sweep across our location in space, we see a brief flash of light ("Lighthouse effect")
- Neutron stars whose beams of electromagnetic radiation happen to sweep across us are called *pulsars*
Pulsars

- Discovered in 1967: origin of pulses was initially unknown
- Strong radio sources
- Emit their bursts of radio emission at very regular intervals: first pulsar had period of 1.34 seconds
- Periods are typically less than a second. Some as short as millisecond
- Time between pulses corresponds to one stellar rotation
Crab pulsar

\[ P = 0.033 \text{ seconds} \]
Crab pulsar

Observable in X-ray

- \( R = 10 \text{ km} = 0.000014 \ R_\odot \)
- \( T = 10^6 K = 170 T_\odot \)
- \( L_n/L_\odot = \left( \frac{R_n}{R_\odot} \right)^2 \left( \frac{T_n}{T_\odot} \right)^4 = 0.2 \)
- Wien’s law: x-ray
Pulsars slow with time

- Crab Nebula: \( P = 0.033 \) seconds
- \( P \) increasing by 0.001 seconds per century
- Rotational energy is converted to kinetic energy of electrons and other charged particles
  - Accelerated charges radiate (photons)
  - Energy of motion converted to photons
Binary systems with Pulsars

- Pulsar in a close binary system with an ordinary star can increase its rotation speed
- The force exerted by the falling gas can make the pulsar spin faster (angular momentum)
- Pulsars with millisecond periods have all been spun up by mass transfer
- Powerful energy sources