Lecture 27

Collapsed Stellar Remnants: Pulsars and Black Holes

Neutron Stars
Pulsars
Size-Variability Rule
Crab Pulsar
Black Holes
Schwarzschild Radius

Neutron Stars
What is left after a supernova? Collapsed remnants: neutron star, black hole

- **Neutron stars**: degenerate gas stars, but electrons and protons are combined into neutrons.
  - Recall for White dwarfs: electron degeneracy works up to $M < 1.4 \, M_{\text{sun}}$ (“Chandrasekhar Limit”)
  - Neutron Stars: neutron degeneracy works up to $M < (\text{roughly!}) \, 3 \, M_{\text{sun}}$
- The supernova scenario suggests neutron-degenerate objects may be formed in the evolution of the most massive stars.
Pulsars: Observable Neutron Stars

• Neutron stars would be very exotic objects. For instance
  – Mass 1.3 $M_{\text{sun}}$
  – Radius: 16 km. Surface area small: thermal radiation too tiny to observe (until recently).
  – Central Density: $4\times10^{14}$ gm/cm$^3$ (the density of an atomic nucleus)
  – Escape velocity: 1/2 speed of light

• How to observe neutron stars? Accidental discovery: radio pulsars
  – All of radio power concentrated in pulses 25 ms long with period $P=1.3373011$ sec, regular to 8 decimal places.

Guessing Size from Variability

• The first rule to apply to any rapidly variable phenomenon:

  Any variable object must be smaller than the distance light travels in its observed variability time:

  \[ R(\text{var}) < c \cdot t(\text{var}) \]

• This is because any actual variability that might be faster is smeared out when we observe it by the delay between the light reaching us from the front and back part.

• In this case $t(\text{var}) = 25$ ms, so $R(\text{var}) < 7500$ km. This is comparable with the size of a white dwarf, so some early ideas used them (but the regularity is very hard to attain!)
The Crab Pulsar

- Then (1968): NP 0531+21 clinches neutron star hypothesis:
  - Pulse length = 1.9 ms (R(var) < 600 km!)
  - Period = .0330976 s
  - Visible star found, seen entirely in 33 ms pulses!
  - Right in middle of Crab nebula, known SN remnant (1054 AD!)
- Explanation for rapid pulses: lighthouse beam effect
- Pulse periodicity due to very rapid spin (also explains repeatability): Collapse to neutron star preserves angular momentum (spin period proportional to 1/size^2): if spins like sun, P ~ 1 month/10^8 ~ 1 ms

Pulsar Pulses

- Pulse mechanism is particle acceleration: Collapse to neutron star preserves magnetic field (field also proportional to 1/size^2): get 10^{10} - 10^{12} gauss. Particles accelerated in beam from magnetic pole, emits flash of radiation (radio, visible, X-ray when pointed at us).
- This mechanism is verified by the observation that pulsar periods are very gradually growing longer. (The particle acceleration energy is extracted from the energy of rotation!). A pulsar will slow down and fade in 10^5 yr.
- Particle beams light up the gaseous remnant for 1000 yr
- Will SN 1987A make a pulsar after gaseous remnant has cleared?? Stay tuned!
Black Holes

- Neutron stars are already very close to \(v(\text{escape}) = c\). If mass > 3 \(M_{\odot}\), nothing can stop it collapsing beyond that point. Then get "black hole". Description requires physics beyond Newton: special and general relativity (later). Here is the bottom line:
- If object not rotating, the resulting object is described by a single number: "Schwarzschild Radius". The radius of a sphere around a black hole of mass \(M\) from which the escape velocity is the speed of light. The Schwarzschild radius of a black hole is proportional to its mass.
  \[
  R(\text{Sch}) = \frac{2GM}{c^2}
  \]
  Doing ratios with sun,
  \[
  R(\text{Sch}) = 3 \text{ km} \times \frac{M}{M_{\odot}}
  \]
Crab Pulsar - Visible

Pulsar in Crab Nebula
Pulsar Mechanism

Young Pulsar Lights Crab

X-Ray
Visible
Crab Animation