Class notes for 18 November

Reminders

- Exercise 6 due today
- Take-home exam due Nov. 30 (ready Friday?)
- Poster project coming up
- Kitt Peak trip

An excellent source of information about neutron stars can be found at M. Coleman Miller's neutron star web page: http://www.astro.indiana.edu/~miller/nstar.html.

15.6 Neutron Stars

Formation:

- Iron core collapse in massive stars (favored)
- White dwarfs that exceed the Chandrasekhar limit (speculative)

Properties

- Supported by neutron degeneracy - so again, radius depends on mass$^{-1/3}$. The more massive a neutron star is, the smaller the radius (and the higher the density).
- Radii about 10 km
- Typical density $6.6 \times 10^{14}$, three times denser than a typical nucleus
- Surface gravity = $2 \times 10^{14}$ cm s$^{-2}$ (log g=14.3)!
- Escape velocity is >0.6c
- Spin very rapidly (conservation of angular momentum, periods of a few milliseconds)
- Strong magnetic fields ($10^{14}$ gauss; magnetic flux conserved as the star collapses)
- Extremely hot ($10^{11}$ K when first formed)

Squeezing Nucleons

- When density reaches about $10^6$ g cm$^{-3}$, electrons become relativistic.
- When density exceeds about $10^9$ g cm$^{-3}$, protons in nuclei can capture electrons to become neutrons, producing a neutrino; electron kinetic energy is converted to mass.
- At still higher densities, nucleons are organized into a lattice of unstable, neutron rich nuclei (neutronization) and relativistic electrons.
- These unstable nuclei cannot beta-decay because there are no stable states for the electrons to occupy.
- At densities near $4 \times 10^{11}$ g cm$^{-3}$, neutrons begin to leak out of the nuclei (neutron drip); the "lattice" now includes relativistic electrons, neutron-rich nuclei, and neutrons.
- The fraction of neutrons continues to increase until the remaining nuclei effectively dissolve into the neutron fluid at a density of about $4 \times 10^{12}$ g cm$^{-3}$.
- The neutrons form a superfluid that is superconducting (no resistance) and has no viscosity.
• At still higher densities, the properties of the material are less well understood.

**Neutron Star Structure**
• Outer crust of heavy nuclei (either a fluid or a lattice) + degenerate, relativistic electrons
• Inner crust of lattice, superfluid of free neutrons, and relativistic electrons
• Interior of superfluid neutrons and protons + degenerate electrons
• Maybe a solid core of pions or other elementary particles (density $\sim 10^{15} \text{ g cm}^{-3}$)

**Maximum Mass of a Neutron Star**
The exact upper limit of the mass of a neutron star is not known, and depends on the detailed physics. But at around 3 solar masses, the neutron degeneracy pressure can no longer support the star.

**Cooling Processes**
• For the first day, neutron stars cool through neutrino emission (URCA process). In equilibrium, neutrons decay to protons + electrons, protons and electrons combine to form neutrons; both processes emit neutrinos that carry energy from the star.
• Once the nucleons become degenerate, this process is suppressed.
• Other neutrino-producing process continue to provide energy for about $10^3$ years.
• After about $10^3$ years, photon emission from the surface ($T=10^6 \text{ K}$) becomes the dominant energy loss.
• At a surface temperature of $10^6 \text{ K}$, the neutron has a luminosity comparable to the Sun, but the radiation is mostly in the form of X-rays.

### 15.7 – Pulsars

**The famous story…**

**Pulsar Characteristics**
• Periods between 0.25 and 2 seconds
  o Longest period is about 4 seconds
  o Shortest is about 0.0016 seconds
• Pulse periods are extremely well-defined (accurate to $10^{-18}$ seconds)
• Pulse periods increased very gradually, with slow-down times scales of tens to hundreds of millions of years.

**Pulsar Models**
• Why can't they be binary stars?
• Why can't they be pulsating stars?
• Rotation works…

**Famous Pulsars**
• The Crab Pulsar: 0.0333 second period (young ones rotate fastest)
• Geminga: the nearest at about 90 pc; first discovered as a gamma ray source; 0.237s period

**Pulsar Continuum Radiation**

• Crab nebula illuminated by a source of white light (NOT a black body spectrum)
• White light is from synchrotron emission (emission from relativistic electrons circling around magnetic field lines).
• Synchrotron radiation is linearly polarized, and the Crab light is.
• The presence of synchrotron radiation implies a magnetic field and relativistic electrons.
• Estimate the energy from the rate of spindown of the Crab Pulsar: it's just the energy needed to power the Nebula.
• Energy not transported by the pulse, but by the rotating magnetic field.

**The Pulses**

• Brief (1-5% of the pulse period)
• Seen at radio wave frequencies (between 20 MHz and 10 GHz) (the Crab is seen pulsing in optical light)
• The index of refraction of the ISM varies with frequency, so the pulses at different frequencies travel at different speeds. These pulse dispersions give the distances to pulsars.
• Pulse shapes vary even for individual pulsars, but the average pulse is stable.

**Lighthouse Model**

• Axis of the magnetic dipole is not aligned with the rotation axis.
• The model is well understood but the mechanism of the pulse emission is not understood.
• The rotating magnetic field induces a strong electric field that accelerates charged particles (protons and electrons), producing a pulsar wind.
• Accelerated charged particles near the poles emit gamma rays, initiating a cascade of pair production, which leads to synchrotron radiation.

**Glitches**

• As the pulsar slows, the crust must adapt to changing centrifugal forces.
• The crust "settles" a fraction of a millimeter, and the spin increases suddenly
• Or the crust gets a sudden jolt from superfluid vortices…

**Why don't we see longer period pulsars?**

• Does the magnetic field decay? It becomes too weak and the pulse turns off?
• Or the pulses become too weak to be detected as the spin rate decreases?
• We don't know…