Lec 22: 04/09/2012

Pulsing Sources:

We now begin to apply the theoretical tools we have developed to study individual classes of objects in high-energy astrophysics. The various classes are primarily based on observational criteria. We first discuss variable high-energy sources. As we stated at the very beginning of this course, rapid source variability is one of the features that distinguishes high-energy astrophysi from many other branches of astronomy. Therefore, highly variable sources (on timescales as short as milliseconds), in particular transient one, easily command our attention.

Radio Pulsars:

These are rotating magnetized neutron stars in isolation. The radio emission is due to synchrothron radiation by particles accelerated in the pulsar magnetosphere. The observed periods of pulsars ranges from approximately 1.5 ms to 5s, with the majority falling between 0.2 s and 2 s. Two of the best known pulsars are the Crab (33 ms pulsar in the Crab Nebula) and the Vela (89 ms pulsar in the Vela supernova remnant).

Most of the short-period pulsars are members of binary systems. The ms pulsars probably contain old neutron stars reactivated by the transfer of mass and angular momentum from a companion star, in a process called "spin-up". Pulsars also exhibit X-ray and γ-ray pulsations. In fact, Geminga is a radio quiet object that emits X-rays and γ-rays.

One can learn a great deal about pulsar emission from measurements of its period and period derivative. The moment of inertia of a typical neutron star ($R_{NS} \simeq 10$ km, $M_{NS} \simeq 1.4\, M_\odot$) is:

$$I_{NS} = \frac{2}{5} M_{NS} R_{NS}^2 \simeq 10^{45}\ \mathrm{g\ cm^2} \leftarrow \text{for Crab}$$

Taking the Crab pulsar ($T_{spin} \simeq 33$ ms) as an example, we fin

$$E_{rot} = \frac{1}{2} I_{NS} \left(\frac{2\pi}{T_{spin}}\right)^2 \simeq 2\times10^{49}\ \mathrm{erg} \leftarrow \text{for Crab}$$

The measured period derivative of the Crab pulsar is $\dot{T}_{spin} \simeq 4.2\times10^{-13}$ s s^{-1}, implying that:

$$\dot{E}_{rot} = -4\pi^2 I_{NS} \frac{\dot{T}_{spin}}{T_{spin}^3} \simeq 4.5\times10^{38}\ \mathrm{erg\ s^{-1}} \leftarrow \text{for Crab}$$

Rotating neutron star that have a magnetic field are essentially rotating magnetic dipoles. These radiate energy at a rate:

$$\dot{E}_{dip} = \frac{-2\ddot{m}^2}{3c^3}$$ (m: magnitude of the magnetic dipole moment)

Note that $m = \frac{1}{2} B_0 R_{NS}^3$, where B_0 is the magnitude of the magnetic field at the polar cap. Then, after using

$\ddot{m} \approx \left(\frac{2\pi}{T_{spin}}\right)^2 m$, we find:

$$\dot{E}_{dip} = \frac{-8\pi^4}{3c^3} \frac{B_0^2 R_{NS}^6}{T_{spin}^4}$$

Setting $\dot{E}_{rot} = \dot{E}_{dip}$, we conclude that:

$$B_0 = 1.3 \times 10^{19} \left(T_{spin} \dot{T}_{spin}\right)^{1/2} G$$

For example, for the Crab pulsar we find $B_0 = 7.6 \times 10^{12}$ G.

The observed spin-modulated power of pulsars is actually a puzzle. It accounts for only a tiny fraction of the expected emission: 10^{-7}–10^{-5} in the radio and optical bands, 10^{-4}–10^{-3} in X-rays, and 10^{-2}–10^{-1} in γ-rays. This discrepancy is usually taken as indirect evidence that a significant fraction of the pulsar's rotation energy is carried off by a pulsar wind, which is a mixture of relativistic particles and electromagnetic fields. This often produces a pulsar win nebula (PWN) radiating at radio, optical, and X-ray wavelengths.

Possible sources of high-energy emission from radio pulsars include both thermal and non-thermal processes. Emission from th hot surface of a cooling neutron star produces a modified blackbody spectrum, which extends from the optical through the soft X-ray spectrum. The charged particle emit synchrothron and curvature radiation as they get accelerated and move along the magnetic field lines. Due to electric fields in the magnetosphere, the charged particles attain a power-la distribution due to acceleration stretching from optical to γ-ray. Inverse Compton scattering of photons off the charged particles can produce γ-rays.

An observed fact is that the γ-ray and radio pulses are generally out of phase. This can be interpretted as the pulses originating from different locations. Models of high energy emission in pulsars generally fall into two main categories: polar-cap models and outer-gap models. In the former case the emission zone is close to the polar cap, while in the latter case it is close to the pulsar's light cylinder ($R_L \equiv \frac{2\pi c}{T_{spin}}$).

An important motivation for hypothesizing a source of γ-rays distant from the surface is that within an intense magnetic field γ-rays may produce an electron-positron pair via $\gamma + B \rightarrow e^+ + e^-$. This results in a large optical depth, which reduces the efficiency of γ-rays to get out of the polar cap. Since $B \propto R^{-3}$, higher γ-ray emissiviti are possible well away from the polar cap.

It is clear that age plays a key role in determining a pulsar's high-energy profile. Young pulsars ($\lesssim 5000$ yr), like the Crab, produce a spectrum dominated by charged particles accelerated along the magnetic field lines. They are bright sources in X-rays and γ-rays, as well as in radio and optical-UV. They are strong non-thermal X-ray emitters with luminosities $\sim 10^{34} - 10^{36}$ erg s^{-1}.

When pulsars reach a spin-down age $\sim 10^{4} - 10^{5}$ yr, they develop charachteristic like those of Vela. They have a soft, primarily thermal, X-ray spectrum with a temperature $\sim 10^{6}$ K. At this temperature, even the surface emission has subsided below easily detectable levels. The old pulsars are thus visible as X-ray sources only at small distances from Earth. Note also that there are essentially no

γ-ray emissions from the old pulsars. The reason being that the seed photons produced via thermal emission at the surface are much fewer in number.

X-ray Pulsars:

What distinguishes X-ray pulsars from radio-pulsars is the fact that the former are in binary systems and powered by accretion while the latter are isolated and rotation powered.

The observed spin period of X-ray pulsars is between 2.5 ms and 3h, with most of them in the ~1 s to ~1000 s range.

The X-ray pulsars fall into two subclasses based on the Companion's spectral type. Most of them have massive binary partners, either OB supergiants or Be stars. The second class is associated with Cooler low mass main sequence stars, which have masses, luminosities and temperatures similar to those of Sun.

In both cases, the neutron star is invisible optically, and hence the optical observations refer to the companion star.

In the case of high mass binaries, it is possible to measure the individual masses of the neutron star and its companion. For the low mass binary systems, however, it is much more difficult to estimate masses. The reason for this is understood to be a selection effect. What is observed at X-ray wavelengths is strongly dependent on the angle of inclination of the binary plane to the plane of the sky. The brightest and most luminos sources are those in which the orbital plane is viewed face-on. The compact X-ray source is then observed unobstructed by the disc or the companion. However, this geometry also means that it is difficult to determine the binary properties of the orbit (for example, by using the Doppler shift due to radial component of the velocity).

As discussed earlier, X-ray emission by X-ray pulsars is due to accretion from the companion funneled to the polar caps due to the pulsar magnetic field. In the case of high mass binary systems, accretion results from the gravitational capture of the stellar wind. The supergiant companions have a large mass-loss rate $\dot{m} \sim 10^{-6} M_\odot \, yr^{-1}$ in this way. In the case of low mass binaries, the accretion is due to Roche lobe overflow. The low mass binary membership of accretion-powered pulsars is greatly underrepresented One possible explanation can be that neutron stars in these systems are weakly magnetized, and hence accrete over the whole stellar surface, mitigating any possible pulsed emission associated with rotation.

The spectra of X-ray pulsars exhibit no sharp features. As discussed earlier, the plasma falling onto polar caps converts gravitational energy into heat, which is then radiated away by a combination of bremsstrahlung and synchrothron processes. The X-rays must transfer through the magnetized, optically thick medium in the accretion column, which simulations suggest to be unstable. There is a blending that takes place via a superposition of emission components at different heights within the funnel. Most of the power is emitted in the 2-20 keV range, with a rapid falloff above ~20 keV. This is reminiscent of the bremsstrahlung shoulder that we discussed before.