Lec 24: 11/12/2018

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 criterion. 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 astrophysics from many other branches of astronomy. Therefore, highly variable sources (on timescales as short as millisecond), in particular transient ones, easily command our attention.

Radio Pulsars:

These are rotating magnetized neutron stars in isolation. The radio emission is due to synchrotron radiation by particles accelerated in the pulsar magnetosphere. The observed periods of radio pulsars ranges from approximately 1.5 ms to 5 s, 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 pulsar that emits X-rays and γ-rays. One can learn a great deal about pulsar emission from measurements of its period P_{spin} and period derivative $\dot{P}_{spin}$

The moment of inertia of a typical neutron star ($R_{NS} \simeq 10\,\mathrm{km}$, $M_{NS} \simeq 1.4\, M_{\odot}$) is:

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

Taking the Crab pulsar ($P_{spin} \simeq 33\,\mathrm{ms}$) as an example, we find:

$$E_{rot} = \frac{1}{2} I_{NS} \left(\frac{2\pi}{P_{spin}}\right)^{2} \simeq 2\times 10^{49}\ \mathrm{erg}$$

The measured period derivative of the Crab pulsar is $\dot{P}_{spin} = 4.2\times 10^{-13}\ \mathrm{s\ s^{-1}}$, which results in:

$$\dot{E}_{rot} = -4\pi^{2} I_{NS} \frac{\dot{P}_{spin}}{P_{spin}} \simeq 4.5\times 10^{38}\ \mathrm{erg\ s^{-1}}$$

Rotating neutron stars that have a magnetic field are essentially rotating magnetic dipoles. They radiate energy at a rate given by:

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

We note that for a neutron star $m = \frac{1}{2} B_{0} R_{NS}^{3}$, where

B_0 is the magnitude of the magnetic field at the polar cap. Then, after using $\ddot{m} = \left(\frac{2\pi}{P_{spin}}\right)^2 m$, we find:

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

Setting $\dot{E}_{rot} = \dot{E}_{dip}$, from conservation of energy, we have:

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

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

The above equation shows that $P_{spin} \dot{P}_{spin} = \text{const.}$ as long as B_0 is a constant. One can therefore find the "spin-down" age of the pulsar according to:

$$\tau_{spin} \equiv \int_{t_0}^{t} dP_{spin} \, \dot{P}_{spin}^{-1} = \frac{1}{2} P_{spin} \dot{P}_{spin}^{-1}$$

Here t_0 is the time of pulsar's birth, and t is the current time. This is a measure of how long it takes for the pulsar to lose its rotational energy via magnetic-dipole radiation. τ_{spin} is a reasonable estimate of the pulsar's age, and is often the only measure of time for these objects. For example, $\tau_{spin} \approx 1258$ yr for the Crab pulsar, with its actual age being 963 years.

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 the γ-rays. This discrepancy is usually taken as indirect evidence that a significant fraction of the pulsar's rotational energy is carried away by a pulsar wind, which is a mixture of relativistic particles and electromagnetic field. This often produces a pulsar wind 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 the 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 particles emit synchrotron and curvature radiation as they get accelerated and move along the magnetic field lines. Due to strong electric fields in the magnetosphere, the charged particles attain a power-law distribution as a result of acceleration that stretches from optical to γ-ray. Inverse Compton scattering of photons off the charged particles can therefore produce γ-rays. An observed fact is that the γ-ray and radio pulses are in general 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 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 ($R_L \equiv \frac{2\pi c}{P_{spin}}$).

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 emissivities 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 ($\tau_{spin} \lesssim 5000$ 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 characteristics 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 the Earth. We also note that there are essentially no γ-ray emission from the old pulsars. The reason being that the seed photons produced via thermal emission at the surface are much fewer in number.