The 65th Compton Lecture Series

The Quest for Gamma Rays: Exploring the Most Violent Places in the Universe

Lecture 3: The Puzzle of Gamma-Ray Pulsars

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Slides and additional information can be found at *http://kicp.uchicago.edu/∼ehays*

1 What are pulsars?

Pulsars are rotating neutron stars that emit a pulsed beam of radio waves. There are hundreds of radio pulsars in our Galaxy. They are the leftover remnants of supernova explosions. A massive star, more than eight time the mass of our Sun, collapses under its own weight after the nuclear fusion process ends. The collapse compacts the core of the star to the point that protons and electrons bind into neutrons. The energy released in this transformation process goes into the expanding shockwave of the supernova explosion. It can also go into the rotation of the remaining neutron star. The massive star leaves behind a strong magnetic field. As the neutron star rotates within this field, it generates currents of electrons, much like an electrical generator. Electrons are accelerated and generate emission that is beamed away from the pulsar. Most frequently we observe radio waves, but some pulsars emit optical light, x-rays, and gamma rays. The rotation of the neutron star causes us to see the beam as a periodic radio pulse.

Neutron Star Facts

- Diameter - 12 km (8 mi) - this is close to the size of Chicago!
- Mass - 2 times the mass of the Sun

Pulsar Facts

- Spin Period - Typically about a 1/2 second. Pulsars are observed with periods ranging from a millisecond to a few seconds. (Imagine something the size of Chicago rotating once a second...)
- Steadily decreasing spin period - The pulsar loses rotational energy and spins more slowly. It takes a typical pulsar more than 100,000 yrs to slow down a few milliseconds.
- Pulsars outlive the original supernova explosion by hundreds of thousands of years.

- Young pulsars, a few thousand to ten thousand years old, spin faster and lose rotational energy more quickly. They have the highest power output and are the best cadidates for producing gamma rays.

Pulsars are particle accelerators

Radio observations tell us that pulsars accelerate electrons. Electrons from the neutron star stream out along magnetic field lines at relativistic velocites. The energetic electrons are in a strong magnetic field and emit synchrotron radiation at radio and sometimes X-ray wavelengths. Although we observe radio emission from a large number of pulsars, we still don't know the details of how the pulsar generates pulses. Much of the uncertainty lies in determining where the pulse originates in the magnetic field structure surrounding the neutron star. This is the biggest puzzle about pulsars.

Detecting Gamma-Ray Pulsars

Gamma ray pulsars have been detected with space-based gamma-ray telescopes. The most recent high energy gamma-ray telescope was the EGRET instrument on the Compton Gamma Ray Observatory. The mission lasted from 1991 through 2000.

The goal of any gamma ray telescope is to make three basic measurements of the incoming gamma ray.

- **Direction** - where the gamma ray came from in the sky.
- **Energy** - the energy of the gamma ray.
- **Timing** - when the gamma ray entered the telescope.

EGRET was a type of gamma-ray telescope known as a pair production telescope. Pair production telescopes use layers of material to cause a gamma ray to convert to an electron and positron pair. The electron and positron are then used to infer the properties of the original gamma ray. This type of telescope consists of a series of sections designed to track and measure the energy of the electron-positron pair.

1. **Tracking** - This part of the instrument is made up of multiple layers of foil and gas chambers. The foil causes the gamma ray to pair produce. The gas becomes ionized by the passage of an electron or positron. The locations of ionization signals in each successive layer are used to track electrons and positrons as they pass through the detector.
2. **Calorimeter** - This system is used to make the energy measurement. It consists of a crystalline salt, sodium iodide NaI, which is doped with thallium. This makes it a scinitillating material, which will absorb the electron or positron and emit a pulse of light. The emitted light is measured to determine the energy of the electron and positron and ultimately, the energy of the incoming gamma ray. to measure energy, a trigger system to indicate when data should be recorded, and an anticoincidence shield to prevent unwanted events cause by cosmic rays.

3. **Trigger** - When a gamma generates a pair in the telescope, a trigger fires to record the tracking and calorimeter information and apply a timestamp. EGRET could record the arrival time of gamma rays with 50 microsecond accuracy. Timing accuracy is particularly important for finding periodic signals and matching them to those recorded by other telescopes.

EGRET detected seven gamma-ray pulsars. The best studied is the young Crab pulsar (953 years old), which shows strong pulsed emission from radio all the way to high energy gamma-ray wavelengths. It has a high spin rate with a rotation period of 33 millseconds.

Some of the unidentified sources in the EGRET high-energy gamma-ray sky map are close to the galactic plane. This suggests that there may be more gamma-ray pulsars that will be detected and identified by more sensitive telescopes in the future.

2 Why are gamma-ray pulsars puzzling?

The discovery of gamma-ray pulsars has provoked some questions.

1. **How high in energy is the pulsed emission?**
   Although the space-based measurements indicate that gamma ray emission extends above 30 GeV for some pulsars, no ground-based telescopes have detected pulsed emission at energies above 300 GeV. An interesting question about gamma ray pulsars is how high in energy the gamma rays are produced. This is an important parameter in models that attempt to explain how the pulsar signals are generated. The new ground-based telescopes can detect gamma rays at energies as low as 100 GeV. These telescope are in the process of making observations that will either discover very high energy pulsed emission or give a much better measurement of the maximum gamma ray energy.

2. **Geminga: a radio quiet pulsar?**
   The most intriguing of the gamma-ray pulsars is Geminga, which does not have a detectable radio or optical pulse. It is a radio quiet pulsar. Geminga was one of the earliest gamma-ray sources and is quite bright at gamma-ray wavelengths. The lack of a corresponding radio source still defies explanation. Pulsars like Geminga provide an important test for detailed models of how the emission is generated by the pulsar.

3. **Are unidentified high energy gamma ray sources radio quiet pulsars?**
   A difficulty with space-based gamma-ray observations is that although there are many gamma-ray emitters detected, it is hard to give an accurate location for high energy sources. This makes it very difficult to identify them with objects observed at other wavelengths. Many of the gamma-ray sources discovered by EGRET have not yet been associated with known objects at other wavelengths. A number of these sources are near the galactic plane and this makes it likely that some of them are supernova remnants and pulsars.

Although it may seem surprising to use gamma rays to find radio emitters (they do differ in frequency by 20 orders of magnitude!), locating faint radio pulsars or radio quiet pulsars using gamma rays is possible and important. In astronomy we are limited to studying the objects we can observe. Because we cannot interact directly with these sources to do a more typical controlled and repeatable physics experiment, we have to look at them in as many different ways as we can by using observations at different wavelengths and observations of different examples of the same class of source.

Gamma rays from pulsar wind nebulae

Young pulsars can inject enough energy into their surroundings to produce a glowing nebula of radio, optical, x-ray, and sometimes gamma-ray emission. The nebula is built up by the pressure of the wind of relativistic particles streaming out from the pulsar and into material from the supernova explosion. The expanding wind bubble produces steady emission over a region surrounding the neutron star. The pulsar and nebula evolve over time as the rotational energy of the pulsar drops, the nebula expands, and as echoes from the supernova blast return to the birthplace of the pulsar. Gamma-ray observations play a key role in understanding the formation of middle-aged nebula.

- **Early nebula** - During the early phase, the pulsar is young and energetic and the nebula is small with a strong magnetic field. The Crab Nebula is a good example, but is also unique. Most pulsar nebulae are not energetic and bright enough to produce this level of gamma-ray emission.

- **Middle-aged nebula** - The nebula expands into the material left after the supernova explosion. The pulsar has had time to build up a population of energetic electrons that can produce gamma rays through inverse Compton scattering. After about a thousands years, the reverse shock from the supernova blast wave returns and runs into the wind nebula. If the density of material around the supernova remnant is very irregular, then the reverse shock will travel at different speeds in different parts of the remnant. It may run into one side of the nebula earlier than another. This causes the nebula to appear crushed and makes it look off center from the pulsar. The Vela X nebula is the prototypical example of this type of nebula.

- **Old pulsar** - The earlier nebula has been dispersed by the reverse shock wave. The pulsar power output has dropped, and it can no longer generate a large, bright nebula. The pulsar has some velocity from the supernova explosion, and it may produce a small nebula as it moves beyond the original location of the supernova remnant and through interstellar space. This often looks like a bow shock, similar to a boat moving through water. This type of nebula is primarily seen in x-rays.

Pulsar wind nebulae are rapidly becoming the most common source found in our Galaxy by very high energy gamma-ray telescopes. The gamma-ray observations tell us about what the pulsar powering the nebula was like in the past because the gamma rays are produced by older electrons than those emitting x-rays. Many of these pulsar wind nebulae are not as bright at other wavelengths and the gamma-ray discoveries are in some cases leading us to new X-ray nebulae and even new radio pulsars.

Although our pulsar puzzles are still largely unsolved, the next few years will bring a variety of observations by new gamma-ray telescopes that will answer some of these questions and hopefully pose some brand new puzzles.