The 65^{th} Compton Lecture Series

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

Lecture 1: The Search Begins

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1 What are gamma rays?

Definition: Gamma rays (γ rays) are photons with the shortest wavelengths of light in the electromagnetic spectrum. Equivalently they have the highest frequencies and energies.

A Few Gamma Ray Facts

- Gamma rays are highly energetic. The wavelength of gamma rays is less than a few trillionths of a meter. This is similar to the size of an atom and smaller. It's not surpising that gamma rays are associated with nuclear reactions.
- Gamma rays span a very large portion of the electromagnetic spectrum. Frequencies range from 10^{19} to more than 10^{30} Hz (more than 11 orders of magnitude!). In units of energy this becomes 30,000 electron volts (eV) to more than a quadrillion (10^{15}) eV.
- Gamma rays are absorbed by matter (luckily for us!) but are very penetrating. The distance a gamma ray can travel through matter depends on the density of the material. They can pass through a few cm of lead or a few miles of the Earth's astmosphere.
- A gamma ray can also interact with a lower energy photon to create an electron and a positron. This happens more frequently for the very highest energy gamma rays and means that they can only travel so far in interstellar space before being absorbed.

Subdividing the Gamma Ray Spectrum

Gamma rays cover a very broad range of energy. Because of this and differences in detection techniques at different energies, they are commonly split into different energy divisions.

Energy Regime	*Energy Range*	*Type of Telescope*
Low/Medium Energy	100 keV - 30 MeV	Space
High Energy	30 MeV - 50 GeV	Space
Very High Energy	50 GeV - 100 TeV	Ground
Ultra High Energy	$>$ 100 TeV	Ground

The Discovery of Gamma Rays

Gamma rays were discovered in the early 1900s as a result of studying the newly discovered radioactive element radium. A French scientist, Paul Villard[1], first recognized that gamma rays differed from x-rays. The rays emitted by radium were far more penetrating than x-rays. A greater quantity of material was required to absorb them. Villard's interpretation of this as a new type of radiation was not very popular at the time, but ultimately radium was recognized as emitting three distinct types of radiation: dubbed α rays, β rays, and γ rays by Ernst Rutherford. We now know that α rays are helium nuclei, β rays are electrons, and γ rays are high energy photons. Later work by Ernest Rutherford confirmed the electromagnetic wave nature of x-rays and γ rays using newly discovered crystal diffraction techniques.

Another Important Discovery

Arthur Holly Compton, for whom this series is named, revealed a crucial property of photons: they scatter electrons[2]. This experimental result provided proof of the particle and quantum nature of electromagnetic radiation and earned Compton the 1927 Nobel Prize in physics. The Compton effect and the inverse effect, the scattering of photons to higher energies by electrons, are both fundamental to the production of cosmic gamma rays and the methods which we use to detect them.

How to Make Gamma Rays

Gamma rays are primarily produced by radioactive decay and the interactions of highly relativistic particles, protons or electrons travelling at speeds near the speed of light. Here are brief descriptions of several of the key processes. We have a good understanding of these processes at high energies from particle accelerator experiments. However, these experiments don't reach the very high energies we see from cosmic gamma rays. The universe has provided us with more powerful accelerators in space than we have yet built on the Earth.

- **pion decay** - Highly energetic protons that interact with matter produce particles called pions. Pions then decay to gamma rays. Cosmic rays, which are dominated by protons, permeate our galaxy, but we don't know exactly where they originate. We expect the sources of cosmic rays to also produce gamma rays from pion decay.

- **protron synchrotron radiation** - A charged particle travelling through a magnetic field experiences a force that causes it to follow a spiral path along the direction of motion. This acceleration produces synchrotron photons. Highly energetic protons in strong magnetic fields will radiate gamma rays.

- **inverse Compton scattering of photons by electrons** - Electrons scatter photons and increase their energy. For the right combination of energetic electrons and lower energy photons, gamma rays are generated. Radio and X-ray observations

[1] The historical context of this discovery is given by Lief Gerward in "Paul Villard and his Discovery of Gamma Rays", Physics in Perspective, Volume 1, Number 4, December 1999

[2] You can find this seminal paper posted on the American institute of Physics Center for History of Physics website at http://aip.org/history/

tell us that there are celestial objects with highly energetic electrons. Optical, infrared, and ultraviolet observations indicate the presence of lower energy 'target' photons. When these populations are in the same place and if the relative energies and densities are right, then we expect to see gamma rays, too.

- **electron brehmsstrahlung (braking radiation)** - Electrons that come close to a nucleus feel the influence of the nuclear electrical field and decelerate. For highly energetic electrons, the photon energy is similar to the electron energy. This means 1 TeV electrons passing through atomic or molecular material in space will produce photons at about 1 TeV.

2 The Development of Gamma Ray Astronomy

Despite an early interest, some early successes, and high expectations for celestial sources of gamma rays, it has taken decades for gamma ray astronomy to mature. One early motivation for searching for gamma rays was their connection to cosmic rays, the energetic nuclei that come from all directions in space. Locating the places that cosmic rays are produced is still a fundamental problem of astrophysics and one of the most important questions that gamma-ray observations may answer.

Early Success

- Explorer XI (1961) - First detection of cosmic gamma rays. Detected 22 gamma rays during the month-long mission.
- Vela Satellites (1969-1979) - Detected 73 gamma-ray bursts over 10 years. Gamma-ray bursts are bright flashes of gamma rays that last for only fractions of a second or a few seconds. This military mission was intended to monitor for nuclear testing and the detection of gamma-ray bursts from deep space was a wonderful suprise.

The discovery of gamma ray bursts created a new interest in gamma rays, but efforts following these early missions struggled to produce strong results. The early predictions for the brightness of the sources were too optimistic. Additionally, there were difficulties for the various types of telescopes that had to be overcome. Happily, more recent efforts have been highly successful and we now have the ability to explore a varied and dynamic high energy universe.

Some Key Discoveries

- First Discovery of A Very High Energy Source (1989) - The first high significance detection was of the Crab Nebula using a ground-based telescope, the Whipple 10-m reflector at Mt. Hopkins, Arizona.
- The Compton Gamma Ray Observatory (1991-2000) - This space-based mission, which incldued four separate gamma-ray instruments, detected more than 250 high energy gamma sources and 2704 gamma-ray bursts. It allowed the first detailed mapping of the gamma-ray sky.

- New Ground-Based Telescopes (2004) - In the last few years new and more sensitive ground-based telescopes have been making many new discoveries of very high energy objects.

In the last few years, new ground-based gamma-ray observatories have started to produce similarly stunning results for very high energy gamma rays. The ground-based telescopes detect very high energy gamma rays with energies from 100 GeV-50 TeV from a variety of galactic and extragalactic sources.

We now have detected gamma rays from objects in our galaxy and other galaxies. Here are some of the violent places we can now study using gamma rays.

- Pulsars - Rotating neutron stars created when a star dies.
- Supernova Remnants - The blastwave from the explosion of a massive star.
- Pulsar WInd Nebulae - The particle wind from a pulsar generates an energized nebula.
- Microquasars - Stellar mass black holes in our galaxy produce relativistic jets.
- Blazar Galaxies - Supermassive black holes at the center of galaxies accrete matter and produce extended relativistic jets.
- Gamma Ray Bursts - Powerful explosions in distant galaxies.
- Diffuse Emission - Our galaxy glows in gamma rays.
- The Unknown - There are some sources that have yet to be identified with the types of celestial objects that we know. There are also some places that are expected to produce gamma rays that we have not seen yet.

In future lectures we will cover the fascinating science of these places and the methods used to explore them.