The 65^{th} Compton Lecture Series

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

Lecture 9: A Glimpse of the Future

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

1 Gamma Rays in Review

In these lectures, it has become apparent that gamma rays do not come from the normal, well-behaved, twinkling stars with which we are most familiar. They do come from a variety of interesting and violent places scattered throughout our Milky Way Galaxy and the Universe. Some places, like the blazar galaxies, are not uncommon, while others, like the modulated signal from the highly eccentric orbit of pulsar 1259-63 around a massive companion star, are incredibly unique. The gamma-ray bursts, the brightest events in the Universe, are only visible for a few seconds to hours before they fade away forever. Perhaps most fascinating of all, is the existence of many different objects that give off light not just at optical wavelengths, or radio, or X-ray, but across most of the electromagnetic spectrum. Maybe the most astonishing thing is the existence of objects, like the gamma-ray pulsars, that are brightest at these extremely short wavelengths.

There is a loose thread tying together the places that produce gamma rays. Most mark a dramatic and often catastrophic change in a celestial object. The gamma rays reveal extraordinary agents participating in a dynamic Universe. The processes that gamma-ray emission flags are intimately related to the ongoing distribution and redistribution of matter and energy within and between galaxies.

Sources of gamma rays

- **Blazar Galaxies** - Galaxies with central, supermassive black holes and extended energetic particle jets show incredibly rapid variations in a gamma-ray signal. What is the relationship between black holes, jets, and the galaxies around them?
- **Gamma Ray Bursts** - These are the brightest objects in the Universe for a few seconds. There are several types and are related to supernova explosions and sometimes the merger of other stars into a black hole. The details of how the process occurs are still being understood. How long after bursts can we see high energy gamma rays and how high in energy are the gamma rays from these bursts?
- **The Center of our Galaxy** - There is a massive black hole here, but the mechanism for producing gamma rays is still to be determined. How close to the black hole do the gamma rays originate?

- **Pulsars** - Periodic flashes of gamma rays come from rotating neutron stars. The big question is what part of the pulsar produces the signal.
- **Pulsar Wind Nebulae** - Some pulsars blow a bright nebula into their surroundings. How does the shape of this nebula reflect the effects of the supernova explosion that formed the pulsar?
- **Supernova Remnants** - Expanding shockwaves from the explosive death of a star create an expanding shell of accelerated particles. How many cosmic rays are accelerated here and to what energies?
- **Binaries** - Pulsars or black holes with a massive star companion produce periodic emission as they orbit each other. How does the modulation of the signal reflect the material around the star and its magnetic field?
- **Winds from Massive Stars** - Massive stars produce strong particle winds that can collide and accelerate particles. Are these also cosmic ray accelerators and what can we learn about how stars live and die from these ntense regions?
- **The Galaxy** - The disk and to some extent the halo of our galaxy glows in gamma rays from cosmic rays, probably from many supernova remnants, that have spread throughout the galaxy. What are cosmic rays like throughout the Galaxy and how do they compare with those found neary the Earth?

The quest for gamma rays has taken decades. They are tricky to detect in space and on the ground and become increasingly elusive at higher energies. Even once detected, interpreting the exact ways in which gamma rays are produced in celestial objects is never straightforward. Often what we learn from gamma rays is that our models of many violent places are not quite right. This makes gamma ray observations an important test of our understanding of how stars explode, how black holes accelerate particles, how very massive stars and the highly compact 'dead' stars interact with their surroundings, and other aspects of the violent parts of our Universe. What is now known about gamma-ray astronomy has moved far beyond the first detection of gamma-ray bursts in the 1960s and even the first detection of TeV gamma rays from the Crab Nebula in the 1980s. What do we need to do to further advance our study of the gamma-ray Universe?

Goals for Future Telescopes

- **More gamma rays!** - To understand gamma-ray sources better, we have to be able to collect more photons. The more sensitive telescopes become, the more objects that will be found. Making telescopes larger and more efficient for detecting gamma rays is critical for understanding all the phenomena discussed throughout the lectures.
  1. Seeing more gamma rays, means the ability to detect fainter objects that have not yet been seen. As more gamma-ray sources are detected, it becomes easier to distinguish characteristics they have in common or not. Are there additional types of gamma ray sources that we have not seen yet? Undoubtedly.

2. Seeing more gamma rays also means improved measurements of how the brightness of an object changes over time. How often do blazar galaxies flare? Are the gamma rays coming from very close the supermassive black hole? Do the gamma rays always get brighter in the same way that X-rays do? What do the time lines for gamma rays from pulsars look like in detail and how does this compare to other wavelengths? To answer questions like these, a telescope needs to be able to monitor how behavior changes on short timescales or briefly and often.

- **Better gamma-ray locations** - When a gamma-ray source does not have a very accurate location, it is difficult to associate it with the highly detailed maps of numerous objects seen at longer wavelengths. Knowing the gamma rays are coming from an object is one thing. Figuring out how they are produced and specifically which part of a complex environment is accelerating the particles is another thing. If we see gamma rays from a supernova remnant, for example, it is important to then be able to separate light coming from the expanding shell from light that may be produced in a central nebula or nearby molecular clouds. Without getting accurate positions in the sky, we know gamma rays are there, but cannot understand them well.

2 Something Completely Different

Future telescopes are designed to make measurements of known objects that need more detailed study. Telescope properties are chosen to address specific questions about celestial objects and the Universe. However, astronomy is an observational pursuit and generally benefits from exploring “what is out there”. The science that we set out to do is almost always matched and often surpassed by the surprises we discover along the way. When observing we have to keep our eyes open and grab opportunities when they arise.

One surprise is that ground-based gamma-ray telescopes can also measure something that is not a gamma ray. Imaging atmospheric Cerenkov telescopes record the tracks of particel air showers passing through the atmosphere, but many of these are not caused by gamma rays. For every good gamma ray image, hundreds of other Čerenkov light flashes are recorded and later discarded. The background air showers are caused by cosmic rays, nuclei like protons, neon, oxygen, and iron that have been created in distant stars and probably accelerated by supernova remnants.

Measuring cosmic rays with gamma-ray telescopes

Cosmic rays are made up of nucleons, protons and neutrons, and undergo different particle interactions from gamma rays. Often this difference shows up in the appearance of air shower image. One special difference is that nuclei generate Čerenkov light in the upper atmosphere before starting an air shower cascade and gamma rays do not. Although the direct signal from the cosmic ray is faint compared to the light from the air shower, current telescopes are able to find some images where this light is visible.

There are two important things about seeing this signal. One is that it means the original particle was definitely not a gamma ray. The second is that the amount of early Čerenkov light produced by a nuclei depends on its type. Nuclei containing more protons, like iron, generate much more light than a single proton. By picking out the direct signal from the nuclei, a Čerenkov telescope can determine the type of cosmic ray. There are other methods of measuring cosmic rays, but this one is intriguing because it allows measurements at an energy [1] that is difficult for other techniques. This method promises a more accurate way to identify the type of cosmic ray.

A prototype cosmic-ray telescope

The Track Imaging Čerenkov Experiment, known as TrICE, uses a new type of Čerenkov camera. This allows a test of using air showers to measure the cosmic-ray type. It could also be very useful to future gamma-ray telescopes. Recognizing cosmic-ray showers is important for finding the gamma rays. In TrICE, a photon detector with small pixels has been adapted for use in a Čerenkov telescope. This means the images of air showers will have more detail than those recorded by previous telescopes. A camera with small pixels is a key requirement for looking for the direct Čerenkov light from a cosmic-ray nucleus.

Another key requirement is being able to take a series of very fast images of an air shower as the light hits the camera. The direct light does not arrive on the ground at quite the same time as the air shower light. It actually shows up a lfew nanoseconds late because of how far the light has to travel through the atmosphere. The direct signal comes from about 30 km above the ground. The speed of light in air is a little bit slower than the speed of light in a vacuum. ANother way to say this is that the index of refraction of air is a little bit bigger than 1. This means that the air shower particles traveling at the speed of light through the atmosphere can get ahead of the light created at higher altitudes. TrICE is not probing the timing properties of air shower images, but VERITAS, an array of 4 imaging Čerenkov telescopes, uses a system that is suitable for looking for the arrival times of light in the air shower at the camera. Because of having multiple telescopes VERITAS is also used to search for the direct Čerenkov emission from cosmic rays.

References

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[1] There is a strong interest in determining if the relative populations of cosmic rays at PeV energies is undergoing a change. Scientists would like figure out, for example, how frequently iron is seen in comparison to single protons, and if that changes with the particle energy.