The 65^{th} Compton Lecture Series

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

Lecture 7: The Gamma-Ray Burst Hunters

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

1 Gamma Ray Bursts

Gamma-ray bursts (GRBs) are very bright and extremely fast flashes of gamma rays coming from the most powerful explosions in space. This phenomena was first observed by the U.S. military's Vela satellites in the 1960's. They were looking for nuclear weapons testing, but instead they found one of the most spectacular astrophysical events in the Universe. Since then, we have learned about GRBs through a series of satellite missions.

Selected Gamma-Ray Burst Missions

- **BATSE 1991-2000** - The Burst and Transient Source Experiment. Eight low energy gamma-ray detectors located on the corners of the Compton Gamma Ray Observatory. BATSE discovered thousands of GRBs and revealed that they come from all over the sky. This indicates that the explosions happen in other galaxies and therefore, must be incredibly powerful to be seen so far away. BATSE also helped determine there are two distinct types of GRBs with different durations.

- **BeppoSAX 1996-2003** - BeppoSax was an Italian-Dutch X-ray satellite. Although primarily an X-ray satellite, BeppoSAX also carried a gamma-ray burst monitor that sent out several GRB alerts to other telescopes. It successfully followed up a GRB alerts to discover that GRBs have X-ray afterglows that fade out in the hours and days after the initial burst. The X-ray images also aided ground-based telescopes by providing improved locations for bursts.

- **Swift 2004-present** - Swift detects GRBs and then rapidly points X-ray, optical and ultraviolet telescopes to the location of the burst. This allows Swift to provide its own follow up observations of GRB afterglows. Swift has now observed hundreds of GRBs. Swift discovered that both long and short GRBs have afterglows. The afterglow measurements indicate that long GRBs are associated with supernova explosions and short GRBs are not. The Swift telescopes also determine how far away the burst is and what the host galaxy is like. Suprisingly, GRBs are some of the most distant objects we observe. The furthest GRBs at 13 billion light years away are only surpassed by quasars.

The Gamma-Ray Coordinates Network

To better study GRBs, we need to respond quickly with telescopes in other wavelengths. While BATSE was observing GRBs, scientists developed an important tool for alerting telescopes around the world. The Gamma-Ray Coordinates Network uses the internet to rapidly distribute GRB alerts received from satellites to telescopes on the ground. This allows optical and ground-based gamma-ray telescopes among others to know about a GRB within seconds or minutes so they can repoint their telescopes to observe the GRB. This network enabled the first optical measurement of a GRB by a robotic optical telescope called ROTSE. The optical measurements are critical for determining how far away the GRB is and if it looks like a supernova.

What are GRBs?

The large number of GRB detections made by BATSE and Swift in combination with multiwavelength measurements of GRBs and their afterglows have helped us learn what causes GRBs.[1]

1. **Collapsars** - The gigantic explosions from a massive star collapsing to a black hole produce long GRBs that last for several seconds up to 100 seconds. Not only do the afterglows of long GRBs show the right fading behavior for a supernova, but they also indicate the presence of elements that we know are produced by supernova. In the seconds after the black hole forms we now observe multiple explosions happening, probably as a series of shockwaves blast through material leftover from the former star.

2. **Mergers** - Short GRBs last for milliseconds to a second and must come from smaller objects than massive stars. Short GRBs have afterglows, too, but careful measurements by Swift and others have shown that there are no supernovae to be found at the location of these bursts. We suspect these are instead caused by a merger of two neutron stars or a merger of a neutron star and a black hole.[2] This means that short GRBs should also produce ripples in space-time that can be detected by experiments designed to measure gravitational waves.

Why don't we see GRBs from all supernova?

The power output we measure for GRBs is enormous and their explanation requires the most powerful supernova explosions that can happen. In fact, GRBs are so powerful that if we assume the explosion sends the same amount of energy out in all directions, we cannot explain how it could happen. The power output from supernova explosions suggests that GRB explosions must dump energy into a directed blast wave. It is because the explosion is directed toward us that we are able see an event happening in a single star out to the edge of teh Universe. This also means that there must be many explosions that we don't see because they are not pointed at us.

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[1] Check out the websites listed at the end of this handout for the most recent information about GRB observations and what they mean.

[2] A recent review (Nakar, 2007) gives a detailed discussion of the Swift results for short GRBs and the theory that may explain them.

2 Hunting for GRBs with ground-based gamma-ray telescopes

Gamma-ray bursts are hard to observe because they are so short. The Swift mission addressed this problem by being fast. There is a gamma-ray telescope in the Canary Islands, called MAGIC, that uses the same tactic. Similarly, the VERITAS array attempts to repoint and observe GRBs within minutes of receiving an alert. The bursts are over so quickly that these telescopes are only likely to observe afterglow emission. An alternative to repointing a telescope quickly is to be able to see a large area of the sky at one time.

Wide field-of-view telescopes, instruments that can see a large area of the sky at once, are valuable tools for surveying the sky, observing largely extended sources, and for monitoring the sky for transients like flaring active galactic nuclei and GRBs. There is not enough time to repoint a telescope to catch the prompt emission from most GRBs. Telescopes capable of watching a large portion of the sky all the time are incredibly useful for studying GRBs.

Gamma-ray space telescopes have typically had a wide field of view. However, ground-based gamma-ray telescopes using the imaging atmospheric Čerenkov technique can only view an area that is a few degrees in diameter. The imaging atmospheric Čerenkov telescopes watch for brief flashes of light from cascades of particles produced when gamma rays strike the Earth's atmosphere. Other techniques have been explored over the years to exploit the non-light component of these air showers, the particles. The most successful technique makes use of a material that may surprise you.

Milagro, A Water Čerenkov Telescope

Milagro uses a large covered reservoir of water to detect gamma rays. This works because some of the particles in air showers from TeV gamma rays survive to mountain altitudes. Once these particles pass through a few feet of water, they will be absorbed. Before interacting, they emit visible Čerenkov light as they pass through the water. Sensitive light detectors placed in the water record the a flash of light int he water from a pancake of particles as they pass through the reservoir.

The time that the flash arrives at each light sensor is used to reconstruct where the original gamma ray came from in the sky. The distribution of light across the reservoir helps to distinguish air showers produced by gamma rays from those produced by cosmic rays. It also helps in determining the energy of the original gamma ray. Since air showers can hit the reservoir from anywhere above the reservoir, the entire overhead sky can be viewed at one time.

Monitoring gamma rays around the clock

Because Milagro does astronomy under a light-tight cover, observations can be made 24 hours-a-day. Although Milagro cannot see objects as faint as those detected by the current imaging atmspheric Čerenkov telescopes, it can look for bright objects all the time from a large portion of the sky.

Milagro looks for GRBs in two ways. In real-time the data is automatically scanned by computers for fast clusters of events that would signify a bright TeV burst. If a convincing signal were to be found, the information owuld be sent out over the Gamma-ray Coordinates Network to alert other telescopes of a possible GRB.

Milagro data is archived and we can go back through it later to search for gamma ray events in coincidence with satellite GRB detections. This is how an early version of Milagro found evidence for TeV gamma rays from a GRB in 1997 called 970417a.[3] The signal in Milagro was not strong enough to claim it as a definite TeV GRB. There are many ways to see a false positive in this kind of search, and so we have to make careful use of statistics to tell us the probability that a signal is a real one. However, 970417a is a tantalizing hint and we continue to look for more evidence for the most energetic photons coming from the most powerful explosions in our Universe.

A Few Interesting Web References

- Real-time map of Gamma Ray Burst locations in the sky - http://grb.sonoma.edu
- Information about the Swift GRB mission - http://swift.gsfc.nasa.gov
- Information about the upcoming Gamma-ray Large Area Space Telescope (GLAST) mission, which includes an instrument devoted to detecting GRBs - http://glast.gsfc.nasa.gov
- Real-time tracking of NASA satellites - http://science.nasa.gov/realtime/jtrack/Spacecraft.html
- Animated simulations of air showers interacting with the Milagro gamma-ray detector - http://scipp.ucsc.edu/milagro/Animations/AnimationIntro.html

References

Aharonian, F. A. 2004, Very high energy cosmic gamma radiation : a crucial window on the extreme Universe, River Edge, NJ: World Scientific Publishing, 2004

Atkins, R., et al. 2000, The Astrophysical Journal, 533, L119

Nakar, E. 2007, ArXiv Astrophysics e-prints, arXiv:astro-ph/0701748

Weekes, T. C. 2003, Very high energy gamma-ray astronomy, IoP Series in astronomy and astrophysics, Bristol, UK: The Institute of Physics Publishing, 2003

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[3] This result is publisehed in Atkins et al. (2000)