The 65^{th} *Compton Lecture Series*

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

Lecture 6: A Blaze of Gamma Rays

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

1 Active Galactic Nuclei

Most galaxies emit a steady glow of visible starlight that traces their structure and allows us to determine their type, distance, age, and even some of their history. Less than 1% of the galaxies we observe differ substantially from this and show in the most extreme cases strongly variable and non-starlike radiation. These are known broadly as active galaxies and include objects like quasars[1].

An active galaxy is dominated by light from its core and so it is called an active galactic nucleus, or AGN. At the heart of the galaxy lies a supermassive black hole that serves as the power source for bright emission at most wavelengths visible for billions of light years. Similarly to our own Milky Way, an AGN is thought to contain a black hole with a mass that is millions or billions times that of our Sun. The radiation is caused by either the accretion disk that feeds material into the back hole or by a particle jet formed from the rotational energy of the disk. As bizarre and outlandish as the concept of a black hole may seem, it provides the most reasonable and workable explanation for the powerful and spectacularly variable emission from these distant galaxies.

One AGN, many views

Although these galaxies were originally classified as different types based on the waveband in which they were the brightest, and therefore, first discovered, they are now

[1]Originally AGN were observed to be variable and thought to be stars. Some of the naming conventions reflect this misperception, and the American Association of Variable Star Observers (AAVSO) has even featured several AGN as the "Variable Star of the Season" (*http://www.aavso.org/vstar/vsots/*). Then there is this delightful and oft-repeated poetic parody from George Gamow in 1964

Twinkle, twinkle quasi-star
Biggest puzzle from afar
How unlike the other ones
Brighter than a billion suns
Twinkle, twinkle, quasi-star
How I wonder what you are.

thought to be similarly structured galaxies being viewed at different orientations.[2] In some views the jets will be prominant; in others, the jets will appear shorter, but be directed towards us. Some views will include the effects of the surrounding dust and molecular clouds to a greater or lesser degree.

Components of an Active Galactic Nucleus (AGN)

- **Supermassive Black Hole** - The central objects of AGN are extremely dense and though to be black holes. The mass of the black hole may be similar to the black hole in the center of our own galaxy (equal to about 3 million Suns) or much larger (billions of Suns).
- **Accretion Disk** - As material gets closer to the black hole, it rotates around it in a hot disk that can radiate and support the kind of magnetic field structures required to produce jets. Most of the material in the accretion disk eventually falls into the black hole, but a small fraction may be accelerated away in a jet along the rotational axis.
- **Relativistic Particle Jet** - When our observational angle is favorable, we can see radio and X-ray jets extending thousands or even millions of light years away from the core of an AGN. High resolution radio images show blobs of emission moving along the jet at close to the speed of light. Structures or collisions happening in the jet are thought to cause the shortest time scale flares.
- **Dusty Torus** - Like our own Milky Way, the core of an AGN is surrounded by a dusty donut that obscures optical light.
- **Regions of Gas** - Clouds of atoms and molecules rotate around the central black hole at larger distances. Radio and optical radiation observed from or passing through these clouds will have spectral lines that indicate the content and velocity of the material.

Some AGN undergo particularly extreme behavior and are observed to have extended and highly relativistic particle jets. A fraction of these unique galaxies are oriented by chance with jets pointing close to our direction. These AGN show strong flares of light over periods as short as days and even minutes at some wavelengths, prompting the name blazars. Of the several types of observed galaxies considered to be active, we will focus only on those that show the strongest flaring and are thought to have jets, a type of quasar known as a blazar. Blazars are the AGN with jets pointing more directly at us. Because of this orientation, blazars give us the best view of particle acceleration that may be happening near the black hole or within the jet.

Characteristics of Blazars

1. Suprisingly bright. The core of a blazar may outshine the host galaxy by 1000 times.

[2] The unification of active galactic nuclei took a good deal of observational evidence and discussion before becoming accepted (Urry & Padovani, 1995).

2. Unusual appearance for a galaxy. Blazars appear pointlike or dominated by light from the center and not the surrounding stars and gas in the galaxy. Other unusual features include jets.

3. Visible over most of the electromagnetic spectrum. A blazar may be more or less luminous at various wavelengths, but can generally be detected from radio all the way up to X-ray and sometimes high energy and even very high energy gamma-ray bands.

4. No strong absorption line features in the spectrum like in stars or emission line features from clouds of hot gas.

5. Extremely variable - Optical brightness can vary in as short as days; X-ray and gamma ray, in as short as minutes.

6. Polarized - light in the radio and optical band is strongly polarized. This means there is a preferred orientation for the electromagnetic fields of the light, a hallmark of the synchrotron radiation of electrons travelling in a magnetic field.

What about our Galaxy?

The Milky Way, although it does have a central supermassive black hole, lacks some critical elements for being a blazar. It is not strongly dominated by radiation from the core and does not have extended relativistic particle jets. The black hole at the center of our Galaxy is not as massive as those found in active galaxies and it is not currently accreting material at a high enough rate to produce the strong emission seen from blazars.

2 Gamma-Ray Blazars

Some blazars are observed to emit gamma rays. In fact these extreme galaxies emit most of their energy in the gamma-ray waveband and not in radio, optical, or X-ray wavebands. This was an unexpected phenomenon and possibly the most important result produced by the Compton Gamma Ray Observatory in the 1990's. The EGRET instrument on this spacecraft detected more than 70 high energy gamma-ray AGN. Ground-based gamma-ray telescopes have detected ~ 18 AGN, all but one are blazars, and are still searching for more.[3] The next gamma-ray space mission, GLAST, is predicted to detect 1000's of gamma-ray quasars and blazars.

Almost all of the AGN detected with high energy and very high energy gamma rays are those with the jets pointed almost directly at us. This is because the relativistic jet provides some advantages for seeing gamma rays.

- **Relativistic beaming** - When light is radiated from an object travelling near the speed of light, it is angled along the direction of motion for an observer that is not moving with the object. This forward concentration amplifies the light from relativistic material in the jet.

[3]Weekes (2003) and Aharonian (2004) discuss the observations and theory of gamma ray blazars.

- **Relativistic Doppler Shift** - The light emitted by a relativistic object will have a shorter wavelength when viewed by a nonmoving observer. This means that the very high energy gamma rays are produced at lower energy in the reference frame of the jet and appear boosted up by a factor of 10 or so to an observer.

- **Transparency** - The brightness of the blazars in gamma rays suggests that the density of photons should be too high for us to ever see the gamma rays. This is because gamma rays interact with other photons to produce a pair, an electron and a positron. At lower densities, the interaction is infrequent, but at the high densities suggested by the observed brightness and short flares, gamma rays won't make it out of the production region without interacting. The region should be opaque to gamma rays. This apparent discrepency gave astrophysicists a real puzzle until they realized the gamma rays were probably being produced in a relativistic jet. Naively, we measure the region where the gamma rays are produced to be opaque without including relativistic effects. If we instead calculate properly what things are like in the relativistic regions in the jet, then the gamma rays can indeed be seen.

The Very High Energy Gamma-Ray Horizon

There are many fewer blazars detected with very high energy gamma-ray telescopes than with high energy gamma-ray space telescopes. Some blazars detected with GeV energy photons look like they should also produce TeV energy photons but do not. This may be largely due to details of the gamma production in the sources, but there is another effect to consider. TeV energy photons interact with infrared photons through pair production. Interstellar space is filled with infrared photons from stars. This means that a TeV photon can only travel a short distance before being absorbed by starlight. We don't expect to be able to see TeV photons from sources much beyond redshifts of 0.5, about 7 billion light years away.[4] As always in astrophysics, there is silver lining and the observation of this effect could give a unique measurement of the history of star formation in the Universe.

References

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

[4] This effect was predicted long before there was any observational evidence. (Gould & Schréder, 1966)