Abstract

Constructing a unification scenario for active galactic nuclei (AGN) is a forefront field of study in contemporary astrophysics. These highly variable and energetic objects produce radiation in wavelengths from radio through γ-ray. As more detectors of the most energetic electromagnetic regimes are developing, so is our knowledge of the emission models responsible for this cosmic radiation. Blazars, a category of AGN, are objects in which both thermal and non–thermal radiation take place, setting the stage for emission across the entire EM spectrum. The spectral energy distribution (SED) of these astrophysical sources are typically characterized by two peaks. While the peak at lower frequency is thought to be due to synchrotron radiation and the higher peak from inverse Compton scattering, current research suggests that the emission processes that rule the SED behavior is more complex than previously thought. I will analyze five low– and intermediate–frequency peaked BL Lac objects detected by the Fermi–LAT telescope, focusing particularly on a γ–ray flare detected in June 2011 in BL Lacertae. I will hypothesize the emission model responsible for the observed TeV flare and its relation to flaring detected in lower–energy wavelengths.

1 Introduction

Before the first γ–ray detectors were built, physicists predicted the existence of certain cosmic phenomena as responsible for high energy radiation in the Universe. By the 1960’s and 1970’s, military satellites provided the observational evidence to support this theory. Supernova explosions are one example of a violent and very energetic environment where electrons can be accelerated to the highest electromagnetic energies, about 100 keV and greater. Thermal processes play a dominant role in emission from stars and galaxies and can produce photons with energies up to the X–ray regime, but non–thermal processes are responsible for the most energetic radiation. Extreme astrophysical conditions set the stage for γ–ray production.
A blazar is a galaxy with an AGN. The immense radiation from the AGN is believed to be due to the accretion of mass by the black hole in the center of the galaxy. Due to the deep gravitational well of the black hole, particles lose a lot of potential energy that turns into kinetic energy as they fall in. This energy is released in many forms of radiation. Jets of energetic plasma can form near this hole–disk core and emit ultrarelativistic particles radially outward.

Launched in June 2008, the Large Array Telescope on the Fermi Gamma-ray Space Telescope satellite observatory began detections in August of the same year. It observes γ–ray emission by converting the incoming photons to electron–positron pairs via metal sheets that make pair production possible. These microstrip detector sheets ionize the charged particles as they pass through and note the electric charges. The layering of sheets makes it so multiple locations of each particle is taken, and the corresponding path can be known. The total particle intensities are measured by a calorimeter through the tracker. At a given moment, the telescope covers 20% of the sky. The field of view continually scans the sky and covers it all every 3 hours.

The atmosphere protects the Earth from γ–ray radiation, i.e. such emission is opaque to the atmosphere. When such radiation strikes the atmosphere, particle showers are produced and these can be detected from Earth. One such instrument is VERITAS, the Very Energetic Radiation Imaging Telescope Array System, which is an array of four ground–based 12 m telescopes. When γ–ray light hits the atmosphere, secondary radiation is produced in the form of particle showers. This is called Cherenkov radiation, which takes place when a particle moves through a particular medium faster than light would in the same medium. While the space telescopes can detect γ–ray radiation directly by pair production, ground detectors do so using the extended air shower (EAS) that results from the cascade of relativistic particles from the energetic photon collisions in the atmosphere.

Since the start of these two projects, organized efforts have been made to aid simultaneous observing with Fermi and VERITAS. By doing so, we can hope to examine the same radiation by two different methods. Additional appeal of studying very energetic emission from these enigmatic objects is that understanding the precise cause of the high–energy SED hump equips us with tools to learn more of how photons interact with matter, for example, with dark matter. Moreover, we can gain insight to the origins of the Universe, when all of space was a compact and very hot environment.

2 Fermi Analysis

Extensive tools and documentation are available to the public in order to perform analysis of Fermi–LAT data (available at http://fermi.gsfc.nasa.gov/). The five sources whose data I analyzed were 3C 66A, BL Lacertae, PKS 1424+240, S 0716+714, and W Comae. Energy ranges of 300–100,000 MeV were used in selection of approximately the last year of detections (June 2011 through June 2012). A region of interest sized 12° by 12° was centered on each respective source location, selected the photon events with rocking angles
Figure 1: The Fermi photon counts image for BL Lac (center).

less than 52° and zenith angle less than 100°. A further quality cut was specified to exclude time periods when another spacecraft event affected the quality of the data. For all analyses, the P7SOURCE_V6 Instrument Response Function (IRF) was implemented, which in essence describes the telescope’s performance during detection time. My method of analysis followed very closely the tutorials available online. An important note is that I performed unbinned analyses for BL Lac during the month of June 2011 in addition to the year–long binned analysis. These unbinned ones were done in three specified energy ranges (100–100000 MeV or all, 100–1000 MeV or low, and 1000–100000 MeV or high). The table above summarizes the 5 LBL/IBL object characteristics. Below the table is an intermediate image during the Fermi analysis. It shows our BL Lac source in the center, and the color scheme illustrates the number of photon detections on the Fermi sky. Figure 2 shows a composite plot of the five binned analysis light curves.
Figure 2: Light curves for the five blazars of interest across many epochs of detection. The BL Lac flare around $t = 55700$ is very noticeable.
3 AGN Emission Models and BL Lacertae’s Energetic Flare

Historically, the recognizable double–bumped SED of blazars has been attributed to two emission components. The first typically peaks in the IR to X–ray regions while the second is in the $\gamma$–ray up to TeV energy bands. BL Lac objects are thought to be radio–loud AGN sources with one jet pointed along or near our line of sight. The difference between this group of objects and the Flat Spectrum Radio Quasars (FSRQs) is they exhibit featureless optical spectra while the latter do indeed show prominent spectral lines. BL Lacs are further categorized in two subgroups: low–frequency peaked BL Lacs (LBLs) have their first SED bump in the IR–optical range whereas high–frequency peaked BL Lacs (HBLs) have it in the UV–X–ray range. This is illustrated in Figure 3 above. More recently, a third group has been defined as intermediate–frequency BL Lacs (IBLs), bridging this transitional region of approximately IR–UV. It is generally held that synchrotron radiation causes the lower peak and inverse Compton scattering the higher, but the emergence of this intermediate group brings into question whether such classically defines groups exist. Perhaps such distinctions are blurred and the distribution of spectral shapes is a continuous one.
3.1 Emission Processes in AGN

Theoretical models have emerged to illustrate blazar radiation. Some are purely geometrical, making it possible to adjust spectral shape simply by altering parameters such as angle to the line of sight. As summarized by Massaro (2008), the discovery of γ-ray radiation in more than 60 blazars by the Energetic Gamma Ray Experiment Telescope (EGRET, active from 1991 to 2000) showed that non-thermal processes are critical in the dissipation of jet energy, which is caused by accretion of matter around a black hole. Furthermore, where the electron density, particle energy, and magnetic field decreases as the radial distance along the jet increases, it is expected that synchrotron emission of the highest energies originates in the innermost AGN region, progressively extending to longer wavelength with extended distance from core. Emission from the Compton component is due to the scattering of ambient UV–X–ray photons by the same electron population responsible for the radiated synchrotron photons. The schematic below illustrates what is known as synchrotron self–Compton.

There exists debate today whether the photon population behind the IC scattering is the synchrotron one, or if they come from UV or X–ray light of the accretion disk, or from broad–line region photons. Modeling efforts have been made to determine the dominant radiation processes in given regions and frequencies. It is held that in X–ray bright BL Lacs, synchrotron and SSC components rule the emission. Some extant models take into account secondary effects that may occur in compact sources when one electron population causes synchrotron radiation, inverse Compton emission, and radiates once again via IC scattering with the IC photons seeds of the first–order phenomena (see Figure 4). For the purpose of studying BL Lac’s high–frequency bump, we will deal with the leptonic model where very energetic radiation is generated via IC scattering by the same lepton population of the synchrotron process.

Figure 4: Illustration of the synchrotron self–Compton process in nebula. The seed photons are composed of the synchrotron photon population.
3.2 Setting the Framework for BL Lac

Every object with a temperature greater than absolute zero emits thermal radiation. As derived in Cheng & Romero (2004), the average energy of such photons is

$$\langle E_{ph} \rangle = 2.7kT \approx 2.3 \times 10^{-10} \left( \frac{T}{K} \right)$$

in MeV. As we are interested in the most energetic radiation regime, we can notice that in order to have average photon energies of 1 GeV, temperatures on the order of $10^{13}$ K are required. No such temperatures exist in astrophysical objects observable today. Further consideration reveals that the corresponding photon density is also physically impossible.

In the leptonic emission model, a population of energetic electrons produces synchrotron radiation at the lower frequencies, and then IC scatter the resultant photons. In classical Compton scattering, a photon collides with a stationary/free/unbound electron, giving it part of its energy. The end energy of the photon is a function of the scattering angle,

$$\lambda_{s} - \lambda = \frac{h}{mc} (1 - \cos \theta).$$

This is known as the Compton effect, the Compton wavelength being $h/mc = \lambda_c = 2.42 \times 10^{-12}$ m or 0.511 MeV—the rest energy of an electron. The energy–wavelength relation is $E(eV) = h\nu/e$, where $\lambda \nu = c$. In IC scattering, the energy of the photon instead increases
following a collision with a high–energy electron. Let’s return to synchrotron radiation now. This phenomenon occurs when charged particles (e.g. electrons) are accelerated radially in the presence of a magnetic field. Relativistic electrons and synchrotron radiation is emitted. Such radiation is emitted across a large range of frequencies. The characteristic angular frequency of synchrotron radiation in Hz is as follows:

\[ \nu_{\text{sync}} \equiv \frac{1}{2\pi} \left( \frac{U}{mc^2} \right)^2 \frac{qB}{m} \sin \phi. \]  

(3)

The component of electron velocity along the magnetic field line is accounted for by the \( \sin \phi \) factor; however, in assuming the particle in a circle about the field line with \( v \) perpendicular to \( B \), \( \sin \phi = 1 \).

Following IC scatter, the final photon energy averaged over all angles is the following:

\[ h\nu_{\text{s,iso}} = \frac{4}{3} \gamma^2 h\nu, \]  

(4)

where \( h\nu \) is the initial photon energy and \( \gamma = \frac{U}{mc^2} \) the factor that describes the initial energy of the interacting electron.

External Compton scattering takes place when a blob of relativistic electron from outside the jet (for example, the broad–line region), an IC spectrum is generated with its high–energy cutoff moving toward lower energies as time passes. This is simply due to the fact that the first particles to cool are the ones of highest energy. More complicated theoretical models have been proposed and continue to develop that incorporate both SSC and EC processes simultaneously, as it is believed they occur. Figure 5 labels the various regions, each with unique energy densities, that surround an AGN. Hypothetically, this complicator, the population of seed particles NOT intrinsic to the blazar jet, suits exactly the reason for such a flare as BL Lac June 2011 to happen. The next step in this realm of the research will be to support this qualitatively.

4 Edge Sensors

During this 10–week internship, a good amount of time was also dedicated to an engineering–focused project. We were faced with the task of constructing mirror edge detectors using a basic setup of laser and web camera CCD. Systems like these are to be implemented in the next generation of ground–based Cherenkov telescopes (e.g. CTA, the Cherenkov Telescope Array). Each mirror will be fitted with up to eight such detector systems. The laser will be mounted at one location with the corresponding CCD connected by a photo tube within a few centimeters of the light source. The purpose of implementing systems like these is to make it possible to remotely move individual mirrors and fully automate calibrations.

The way in which this laser–webcam system will be able to make such small physical adjustments is by correlating a change in peak intensity of the camera’s outputted images as the distance to laser varies, i.e. relate pixel position to a physical size to be then used.
Figure 6: Closer look at June 2011 light curve for BL Lac over full energy range; created using unbinned (i.e. number of events in each time bin is expected to be small) Fermi analysis.

Figure 7: Plots of spectral index versus flux for BL Lac are shown in the low (left) and high (right) energy regimes. Both support the same behavior of anti-correlation between the two parameters. Spectral index behavior is worth studying more for this blazar flare.
Figure 8: Composite SEDs for BL Lac for observations during 2008 August 20–September 9. The expected double-peaked behavior can be seen, with the lower peak attributed to synchrotron radiation and the higher most likely due to synchrotron self-Compton scattering. Abdo, et al. (2011)
Figure 9: Light curves generated using Unbinned Likelihood Analysis for BL Lac June 2011 detections; low energy range above and high energy plot is below.
in mirror movements as necessary. I wrote a C++ code (snapshotv3.cpp) that can accept either a specific image (.png or .jpg, for example) and output the peak intensity in pixel coordinates (dimensions of 640x480 pixels). If no image is specified, the code engages a USB–connected webcam and processes one video frame in the same manner. Each image is copied and converted into greyscale (from three– to one–channel), transformed into matrices, and weighted averages are computed on these corresponding color and grey matrices. Currently, only the red channel is used for the computation of color image centroid, but this can be easily altered to instead consider the green or blue channels.

From preliminary measurements, it seems that the greyscale images provide more accurate centroid readings than the color ones. This is somewhat counterintuitive as the laser light is red; one would expect the laser against a dark background to be read better from the red channel of an RGB image than the converted greyscale one, which averages the three color channels into a single channel image. Somehow, considering all three color bands does not reduce the centroid accuracy. I think this is positive as it will make our edge sensor system more universal in future applications, e.g. relevant for other colored lasers or against backgrounds that may not be uniformly dark to black.

Thus far we have measured the accuracy of these centroids by translating where the laser is pointed on the CCD plane. While the laser is mounted in an unchanging location upon the optics table, the web cameras sit upon a movable stage. Pistons connect this stage to a Newport Motion Controller that can change its position in three dimensions. We examined translations in the x– and y–axes by continually processing images at small changes in camera location. The sample of web cameras at our disposal were split in two general groups: the cheaper ones, which all seem to possess similar if not the same CCD chips, and the HD cameras. A Logitech brand camera belongs to this latter category. We expect that it will perform better than the other group because it possesses intrinsic technology to equalize gains and adjust its feed. This is a next step for the sensor tests.

In addition to measuring centroids in various laser–webcam configurations, we have also tested the effect of various voltage levels and aperture sizes. The purpose of this is to determine the best combination for consistently precise centroid calculations. To avoid pixel saturation in the camera, an opal diffuser is mounted between the laser and the camera. Thus, the light from the source is diffracted by the grater before being read by the video chip. We have tested various combinations (voltage of 2.2V, near the threshold, 3V, 4V, 5V and aperture openings of 0.1 mm, 1 mm, 2 mm) of light intensity and diffusing effect by using the snapshot code to process 300 images captured for each configuration. We can then find the distribution and deviation of centroids for each given setup. While a larger sample of images is desired for greater averaged accuracy, it is pertinent to keep in mind that in the real–world setup, no more than two or three images will be captured in a given location to determine mirror position and subsequent movement.

Most importantly, this is just the beginning step in the engineering of these edge sensors. Not only are there many more physical configurations and combinations to test and analyze, with various brands of web cameras, there are many more ways in which the snapshot code might be improved. For example, the centroid in $i$ and $j$ pixels is calculated now in one loop
Figure 10: A couple of image samples made with the Linux picture-taking software, Cheese. The left image is from a configuration using 3 voltage laser power and an aperture size of 2 mm. The right image also was fed a 3 V laser, but the aperture opening was diminished to 0.1 mm. Clearly, the former setup causes saturation in the center of the image as well as fringe effects as seen by reflection around the perimeter of the circular diffuser. Both issues may contribute to inaccurate centroid measurements.

each for color and grey. Perhaps peak precision may be improved if this is implemented in two or three levels; the first run finds a rough center, then a pixel cut is made to narrow the image analysis radius to the supposed center of laser detection, and the centroid is calculated once again. Another thought is to make an intensity cut by ignoring pixels of a certain percent of the total intensity in the centroid calculations. Such a threshold cut could work to remove edge–of–image and –diffuser effects as well as inhomogeneous background noise.

5 Conclusion and Future

For the future, I think it would be so interesting to execute a multi-wavelength study of a flare like the June 2011 one—similar to the multi-frequency monitoring campaigns previously done for this source. This would make it possible to compare theoretical models of today with those applied to the high-state flare observed in July 1997, for example. As I understand, a low-frequency peaked BL Lac object like BL Lacertae has not been simultaneously detected during a high-flaring state by $\gamma$-ray detection as well as low-energy instruments. Investigating correlations between different wavelengths will further the effort to determine the mechanisms for—as of yet, not fully explained—$\gamma$-ray emission. Also, applying the jet and BLR emission model quantitatively to the BL Lac flare help determine the seed particle population responsible.

There are many more trials to be performed on the edge sensor setups. Not only are various combinations of camera, aperture width, and laser intensity being studied, the image processing ought to also be a work in progress. In such preliminary tests as have been thus far executed, we are able to determine what yields accurate measurements and what is necessary to heighten precision. Settling on a pragmatic configuration (meaning, hopefully
Figure 11: Distribution statistics taken from 300 images with 3V–powered laser and aperture size of 0.1 mm.

not the most expensive web camera) is a long–term goal.

References


N.B. The location of my data, analyses, and all other files reside in /a/scratch/tehanu/valeriemarch/, while my contributions to the edge sensor research are located on the anarres computer in /home/cta/Programs/OpenCV-2.4.0_anarres/samples/c and /home/cta/code/.