Studying the gamma-ray emission of the blazar Mrk 421, an 11 years data set from the Fermi-LAT space telescope.

William J Ryan

October 2019

1 Abstract

The blazar Mrk 421 is the brightest HBL (High-frequency peaked BL Lac) in the sky and the only HBL with enough gamma-ray emission in its average state to build a daily (or bi-daily) light-curve from the Fermi-LAT telescope. With 11 years worth of data, 3 more years than the most recent Fermi catalog 4FGL, we can define with high accuracy the gamma-ray spectral shape of Mrk 421. I used the 'Binned Likelihood Analysis' technique to statistically compare four models, Log-parabola and Power-law, with and without an exponential cutoff over a spectrum spanning from 100 MeV to 513 GeV. I will be presenting the model comparisons and the one statistically favored. The final goal of this analysis is to create a day binned light-curve to study variability patterns of the source which may be linked to successive shocks accelerating particles.

2 An Introduction To Blazars

At the center of every galaxy lies a super massive black hole (SMBH) whose mass ranges from 10^6 to 10^{10} times the mass of our sun. These are the most massive objects in the known universe and produce a variety of effects.

Many of theses SMBH's have accretion disks[1] that heat up as matter falls into the object, often producing luminosities[2] greater than the host galaxy. Those SMBH's that actively accrete matter are called Active Galactic Nuclei (AGN).

[1] Like a merry-go-round, an accretion disk is a circular pancake of matter that spins around the SMBH due to gravity

[2] Luminosity refers to how bright something is. It has units of power, $\frac{E}{t}$, and transports energy using photons.

Among theses AGNs about twenty percent have jets. Jets are open magnetic field lines whose Lorentz forces accelerate particles to near light speed, and should the the jets of an AGN be pointed towards Earth then the AGN is called a Blazar. As particles spiral up the magnetic field lines they produce synchrotron radiation, of which some photons will escapes to space while others will combine with neighboring photons and then escape. This phenomenon produces a two hump model on a photon-energy-Flux versus photon-energy graph. The first hump is called the Synchrotron peak, which can peak anywhere from infrared to x-ray, and the second is called the Inverse-Compton Peak. Should the Blazar have a Synchrotron peak in x-ray then it is called a High-frequency-peaked BL Lac[3] (HBL). HBLs have the minimum amount of interference between the jets and the blazar's other features which make HBLs prime targets to study jets.

The two hump model mentioned previously works under the assumption that blobs of particles are moving through the jet at near luminal speeds. We can detect radiation emitted from the blobs and attribute any movement of the radiation blob to movement of the particle blob. For many blazars this model is consistent with the data, however some blazars exhibit stationary radiation blobs. If radiation is emitted but no particles are moving then we have a contradiction.

Reculmination shocks provide a possible answer to this conundrum. When material in a gas travels faster than a wave can propagate, shock waves are formed. With a Blazar jet, the pressure difference between the fast plasma of the jet and the stationary plasma surrounding the jet form a shock wave at their initial boundary. The shocks propagate inward and converge at a single point, a node. The node reflects the shocks back towards the plasma boundary where the shock waves rebound again and repeat the process. The node is comprised of a high pressure and a low pressure zone. Particles approach the node at high velocities and low pressure. The front of the node is a low pressure of slow moving gas. The approaching particles will ram the slow moving ones and rebound back. The rebounded particles will again rebound but off the fast moving particles and travel back to the low pressure zone. This process repeats till the particle has enough energy to escape and travel to the next node. While the particle is stuck in the node, it still produces radiation, and from far away these nodes appear to be non-moving radiation blobs. This model solves our initial problem by allowing stationary radiation blobs and retaining the need for moving particles.

We would expect to see a increases in flux over time at regular intervals when an excess of particles, a flare, travels through the nodes of a blazar with stationary knots. As Markarian 421 (Mrk 421) is the only HBL with enough

[3]BL lac: BL lac stands for BL Lacertae. This is a star categorizing scheme made by Cuno Hoffmeister in 1929. Laceratae refers to a constellation and BL is a labeling scheme for all the stars in that constellation. It was later discovered that BL Lac was a Blazar so the name was used to categorize Blazars similar to BL Lacertae.

gamma-ray emission in its average state to build a daily or bi-daily light-curve, it is the prime target for a gamma ray spectrum analysis. A previous analysis of Markarian 421 (Mrk 421) created a lightcurve in x-ray that vilified the existence of these knots to 3σ certainty. Hence a gamma ray analysis will strengthen the validity reculmination shock model.

3 Fermi Analysis

3.1 Fermi Large Area Telescope

The Fermi Large Area telescope (Fermi-LAT) is a satellite telescope that detects gamma rays. Unlike visible light, gamma rays do not refract off mirrors, so Fermi-LAT uses sandwiches of tungsten and silicon detectors. A gamma ray will pass through these sandwiches till an interaction with a tungsten atom transforms the photon into an electron positron pair. The silicon below will detect the charged particle as they continue to pass through the device. The silicon strip detectors are layered in a cross-hatch pattern so that every two layers produces an x-y-z coordinate. With this information the trajectories of the particles can be discerned, and the location of the source can be calculated. At the bottom of the detector is a calorimeter that measures the remaining energy of the particles. The energy used in ionizing the silicon detectors and the energy detected in the calorimeter added together the gamma ray's original energy.

Fermi-LAT was calibrated using particle beams at the particle accelerators CERN, SLAC, and GSI paired with Monte Carlo simulations of all the instrument's parts. The satellite orbits the Earth once every 96 minutes and can survey the entire sky every 2 orbits. When a strong flare in activity is detected, the telescope will point towards the source to collect extra data for a few hours.

Fermi-LAT has a set of analysis tools, called Fermipy, built in python. Using Fermipy, I performed a binned likelihood analysis to determine the model that best fit the Spectral Energy Density (SED) of our source. The SED is an average-energy per average-photon-energy graph. Or put another way, it is a global average of the number of photons radiated by our source at a given photon energy. After finding the best fit model, we produced a light-curve for the source using said model. This is an energy-flux vs time graph that we binned in both one day bins and two day bins. If the bin size is too large then features within the data may be lost. If day one has a sudden spike in flux and day two has a low flux then their average flux, in a two day bin, will show no flare. But if the bin size is too small then their will be too small a flux per bin to have any statistical certainty of our results. Our assumption is that one day bins will be too small, but we want to check just in case.

After determining the best fit model, I created a light-curve, one day or bi-daily count bins summed up to form a day to day photon-flux per time graph. The model is used to transform the photon-flux per day into photon-energy-flux per day so the radiation blob behavior can be determined.

3.2 Binned Likelihood Analysis

Our analysis uses 11 years worth of data, starting on 1 July 2008 and ending on 1 July 2019.(need to check this). The analysis can be performed without bins and often is for analyzing data over short time periods. However, over larger data sets the binned analysis shortens the computational time tremendously and hence is the preferred method for Fermi-LAT analysis.

The Likelihood value L is the probability of attaining our data given an input model. As this is a binned analysis, the likelihood can be thought of as the product of the probabilities of observing the number of counts in each bin given an input model (source). The functional form of L can be seen below. This specific equation is a simplification in the limit of infinitesimal bin sizes, but the general shape will work fine for argument.

$$L = e^{N_{exp}} \prod m_i$$

Here N_{exp} is the number of expected counts and m_i is the number of counts detected. (definitely not right). After a fit has been calculated, instead of spitting back L, Fermipy spits out the log-likelihood. This value is often large and negative (Annex). This value provides an easier way to compare the models used in the fits. If two models have the same number of free parameters, then their log-likelihood values can be compared directly. The smaller the magnitude of the log-likelihood, the better the model. If the number of free variables differ between models then a different approach is required.

If a model has more free variables than another, then the model is called a complex hypothesis. The model with less free variables is called a simple hypothesis. If L_A is the likelihood of a simple hypotheses, L_B is the likelihood of a complex hypotheses, l_A is the log-likelihood of a simple hypotheses, l_B is the log-likelihood of a complex hypotheses then the ratio

$$\Lambda = -2(\frac{L_A}{L_B}) = -2(l_A - l_B)$$

is related to the chi-squared values of the two models. If Λ is greater than or equal to 3.85 then you have 95 percent certainty that the complex model fits better than the simple model.

4 Spectral Models

4.1 Power Law