Investigating the Nature of Flat-Spectrum Radio Quasars 3C 279 and PKS 1222+216

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ABSTRACT

Sources such as flat-spectrum radio quasars (FSRQs) are interesting because they give us insight into the radiation-producing mechanisms at work in an active galactic nucleus (AGN) with a powerful relativistic jet. In order to narrow down the processes that could be occurring in FSRQs, a key analytical tool to work with is the spectral energy distribution (SED). The SED shows the relative fluxes of the source across all energies of the electromagnetic spectrum. As there are many detected FSRQ sources, there are many FSRQs for which there is little spectral data. This investigation seeks to produce broadband SEDs for 3C 279, a well-studied FSRQ, and PKS 1222+216, a far less studied FSRQ, as a response to new very-high-energy (VHE; $E > 100$ GeV) gamma-ray upper limits from the VERITAS array in Tuscon, Arizona. Modeling of these two sources hopes to contribute to the process of ruling out potential models of FSRQ SEDs, helping to understand the processes at work and the qualities of the flat-spectrum radio quasar class.

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Figure 1. Graphic depiction of the structure of an active galactic nucleus. The type of source is composed of a central super-massive black hole surrounded by an accretion disk. The black hole powers two relativistic jets and broad/narrow line emission regions (Urry & Padovani 1995).

1. INTRODUCTION

1.1. Active Galactic Nuclei and FSRQs

Active galactic nuclei (AGN) are galaxies with a central super-massive black hole (SMBH) surrounded in one plane by an accretion disk of matter. The accretion disk powers two relativistic jets perpendicular to the accretion disk plane (Figure 1).

AGN are highly variable sources on the order with variability time scales of the order of minutes to years. Catching an AGN flare is one of the goals of gamma-ray detectors, although flare periods are unpredictable flare periods. Flare observations in the very-high energy (VHE; E \( \gtrsim \) 100 GeV) range are particularly useful because the large photon statistics allow studies of the variability time scale and could provide information on the size of the emitting region in the AGN jet. In addition to variability time scales, astronomical sources are often characterized by their spectral energy distributions (SEDs), which plots the flux from the sources emitted across the electromagnetic spectrum and plotted per logarithmic energy decade. However, a consequence of studying a variable source is that in order to build an accurate SED, the source must be observed simultaneously at all wavelengths.

AGN are sub-classified according to their relative orientation to the observer, and the notable effects that orientation has on their SEDs. Blazars are one of the sub-classifications of AGN, distinguished by the small angle of observation between the observer and the relativistic jet.

The focus of this investigation is flat-spectrum radio quasars (FSRQs), a type of blazar that is particularly powerful and has strong optical emission lines originating in the broad line region. Since FSRQs are powerful emitters at all wavelengths, the broad line region also has an imprint on the gamma-ray region of the SED, an effect that has the potential to further describe the environment of this type of source.

1.2. Modeling FSRQs

The SEDs of all blazars and, more specifically, FSRQs, have a distinct two-peak shape, one low-energy and one high-energy. The processes that drive those peaks are understood in theory, but the exact details of the environment of FSRQs continue to be widely studied and largely unknown. However, there are two popular ways of modeling FSRQ SEDs, distinguished from each other by the types of particles that cause the low- and high-energy peaks; they are the leptonic and lepto-hadronic models. The two sources I studied were FSRQs 3C 279 and PKS 1222+216.

1.2.1. The Leptonic Model

Figure 2 depicts an example of an SED of the FSRQ 3C 279 showing the two characteristics humps in the SED. The first peak is believed to be due to synchrotron emission, while the na-
nature of the second peak could be either leptonic or hadronic in origin. Figure 2 is also overlaid with a leptonic modeling method from a previous investigation (Bottacini et al. 2016). The leptonic model is a result of three mechanisms at work in the FSRQ: synchrotron radiation and two types of inverse Compton scattering.

Synchrotron radiation occurs when a charged particle moves through a magnetic field and therefore is moved in a helical path. The constantly changing direction causes acceleration, so the electron emits electromagnetic radiation. Those emitted photons account for the low-energy peak of the leptonic model.

The high-energy peak of the leptonic model is attributed to the combination of two processes that both belong under the umbrella of inverse Compton scattering: external Compton and synchrotron self Compton.

External Compton scattering occurs when an electron gives some of its energy to a photon that originated outside of the jet, upscattering it.

Synchrotron self Compton occurs when low-energy photons produced via synchrotron radiation are given energy via Compton scattering from the same electron population that created them initially.

1.2.2. The Lepto-Hadronic Model

Figure 3 depicts the same SED from Figure 2, except overlaid with lepto-hadronic methods. This modeling method operates under the assumption that the sources of electromagnetic emission in an FSRQ include both electrons and protons.

The low-energy peak in the lepto-hadronic model has the same source as that of the previous model, electron synchrotron radiation.

However, where the two differ is the consideration of the source of high-energy emission. The high-energy peak of the lepto-hadronic model is based on emission from hadronic processes including proton synchrotron radiation, photomeson production, and nuclear collisions.

This particular model focuses on proton synchrotron radiation, which is the same mechanism as electron synchrotron except with an opposite charge, causing it to follow a helical path of the opposite direction in the magnetic field. However, since protons have a rest mass that is about 1800 times greater than that of an electron, they must have much higher energies in order to emit synchrotron radiation. If an AGN is well-fit by a lepto-hadronic model using proton synchrotron radiation, it could be a source of some of the highest energy cosmic rays in the universe.

1.3. Extragalactic Background Light

One of the main scientific motivations for studying FSRQs is their potential to constrain the model of Extragalactic Background Light (EBL). The idea of the EBL is similar to the Cosmic Microwave Background (CMB) in that it is a baseline level of ambient light in the uni-
verse. The difference between the two is that EBL is composed of fewer photons of higher energies. The EBL is made up of light from galaxies and star forming systems. Figure 4 shows the spectrum of background light, where EBL is the combination of the Cosmic Optical Background and Cosmic Infrared Background. Also plotted for comparison is the Cosmic Microwave Background.

The EBL is important to astronomy, particularly VHE astronomy, because it interacts with gamma-ray radiation from sources via pair production, absorbing the gamma-rays and preventing detection from Earth (Alonso & M. for the VERITAS Collaboration 2017).

Very high-energy photons coming from very distance sources (high redshifts) are particularly vulnerable to EBL absorption. However, this means that SEDs from VHE sources can be used to constrain the EBL model using the high-energy drop off in flux. Directly measuring the EBL with optical or UV telescopes is extremely challenging due to foreground contamination from galactic light. As a result, we can make indirect inferences about the EBL by studying high-energy gamma-ray spectra of distant AGN.

2. TECHNIQUES

2.1. Mid-High-Energy Astronomy

High-energy radiation is generally includes X-ray to gamma-ray energies, including a subclassification of VHE astronomy where E > 100 GeV. While ultraviolet (UV) radiation is not included under the “high-energy” umbrella, it is often useful to study UV emission in tandem with high-energy emission.

The observational study of sources of mid-to-high-energy radiation presents numerous opportunities for discovery and furthering astrophysical understanding including studies of the early universe, star formation, and black hole characteristics. For the purposes of this investigation, the primary focus will be on UV and X-ray radiation (specifically 1 eV to 10 keV) with auxiliary attention paid to VHE gamma-rays.

High-energy radiation presents a problem when it comes to detection because the particles in Earth’s atmosphere scatter 100% of photons at energies above that of visible light. As a
result, there are two ways of getting around the opacity of the atmosphere: telescopes on Earth that, instead of directly detecting the light, detect the effects that fall to the surface, and telescopes that orbit Earth, removing the atmospheric barrier.

2.1.1. The VERITAS Array

The first solution to the problem of the opacity of the atmosphere is to aim to detect, instead of the photons themselves, the signature effects they have on the atmosphere. This technique is used for VHE gamma-rays due to their special interactions with molecules.

When a gamma-ray reaches Earth from a source, it interacts with a photon in the atmosphere, engaging in pair production of an electron and a positron. This happens far more frequently once it reaches Earth because the photon must be near a nucleus in order for pair production to be triggered, which is very unlikely in space but extremely likely upon entry into the atmosphere. Due to the very high-energy of the gamma-ray, the electron and positron move towards the surface of Earth at relativistic speeds.

When a charged particle travels through the atmosphere, it passes by molecules and either attracts or repels the outermost electrons in the electron cloud of each molecule depending on its charge. An electron, for example, pushes the outermost electrons away from its path. After it passes, the pushed electrons rebound back to their initial states. That process of pushing and rebounding involves the acceleration of electrons, therefore the emission of radiation. This effect is amplified as the original electron/positron pair emit photons and begin a chain reaction of pair production and polarization of particles.

The radiating molecules in the path of the electron each create a spherical expanding wavefront, all of which combine to form a cone-shaped wavefront of light visible in the optical range.

![Figure 5. The VERTIAS array in Tuscon, Arizona (Columbia University Nevis Labs 2016).](image)

That light is called Cherenkov light, which is the type of radiation that instruments like the Very Energetic Radiation Imaging Telescope Array System (VERITAS), seen in Figure 5 are built to observe. VERITAS is an array of four atmospheric Cherenkov telescopes in Arizona, USA that uses optical photomultiplier tubes optimized to detect Cherenkov light in the blue and near-UV range. The four telescopes are spaced by 100 m in order to provide multiple images of each air shower and use stereo reconstruction to more accurately trace Cherenkov showers back to their sources in the gamma-ray sky.

2.1.2. The Neil Gehrels Swift Observatory

The other, simpler solution to atmospheric opacity at high energies is to use tools installed on satellites. This method allows for direct detection of ultraviolet, X-ray, and gamma-ray photons from galactic and extragalactic sources.

One of those satellites is the Swift Observatory, a multi-wavelength tool that includes three instruments operating at three different energies to compose a broadband picture of astronomical sources. The observatory’s focus is on gamma-ray burst (GRB) science, so its instruments are focused on the detection high-energy sources. The three instruments can be seen in Figure 6 and are as follows:

- Burst Alert Telescope (BAT) operating in the low gamma-ray range,
Figure 6. A rendering of the *Swift* Observatory, showing the locations of the BAT, XRT, and UVOT instruments (NASA 2012).

- X-Ray Telescope (XRT) operating in the X-ray range,
- UV/Optical Telescope (UVOT) operating in the ultraviolet to optical range.

Though all three instruments operate in mid-to-high-energy ranges, the *Swift*-BAT’s primary function is to alert the observatory’s other instruments and ground level observatories of possible GRBs so that they can point and detect the afterglow. The XRT and UVOT instruments on board help improve the accuracy of the location of the GRB, information which is also communicated to ground-level observatories. The XRT and UVOT will be the prioritized tools of the *Swift* Observatory.

The XRT is a grazing-incidence focusing X-ray telescope, and is sensitive to photons with the energy between 0.2 and 10 keV (Gehrels et al. 2004; Burrows et al. 2005).

The UVOT is a photon-counting ultraviolet and optical telescope sensitive to photons with energies ranging from 170 - 550 nm (Roming et al. 2005).

2.1.3. *The Fermi* Large Area Telescope

Another satellite, used specifically for high-energy detection, is the *Fermi* Large Area Telescope (*Fermi*-LAT). *Fermi*-LAT, as seen in Figure 7 detects higher energies than *Swift*-BAT (MeV-GeV range as opposed to keV range), making it a better tool to bridge the gap between *Swift*-XRT detected X-rays and VERITAS detected gamma-rays.

*Fermi*-LAT has a very large field of view covering about 20% of the sky, making it impractical to slew and point at specific sources in order to make observations. Instead, the telescope runs continuously, scanning the full sky approximately every three hours.

Even outside of the atmosphere, gamma-rays present an additional obstacle to detection. They cannot be focused with mirrors and lenses, so gamma-ray telescopes have to use other methods in order to detect. *Fermi*-LAT’s detector contains layers of materials, the outermost of which are scintillators used in order to identify and filter out cosmic rays, the main source of background signal. This device is called the anti-coincidence detector (ACD).

Inside the ACD, there is a tracker that consists of alternating layers of tungsten, a material that induces the process of pair production using the incoming gamma-ray radiation, and silicon, which tracks the progress of the resultant charged particles. The electron and positron travel to the center of the detector where their energies are measured by the ce-
sium iodide calorimeter, indicating the original energy of the incident gamma-ray.

2.2. Previous Investigation

This investigation in particular is motivated by an ongoing VERITAS study of the FSRQs 3C 279 and PKS 1222+216. 3C 279 has a redshift of about 0.536 and is widely observed and investigated, as shown by the reference to the modeling of Bottacini et al. (2016). PKS 1222+216, however, is a far less studied source with a similarly large redshift of about 0.434.

VERITAS has measured new upper limits for the two sources, the results of which can be seen in Figures 8 (3C 279) and 9 (PKS 1222+216) with. All data was taken from periods of time during which the sources were seen flaring by the Fermi-LAT. The specific date ranges were based on the VERITAS observation period rounded to the nearest day.

In these plots, the high-energy portion of the FSRQ spectra is modeled, including the steep drop off between the Fermi-LAT and VERITAS data. The goal of this investigation is to further this analysis by adding lower energy data to create a full broadband SED of the two FSRQs during flares for modeling.

3. DATA COLLECTION

Fermi-LAT observed the flares of the objects, triggering follow-up observations from other instruments. The date ranges used for the flaring periods were restricted according to the observation period of VERITAS follow-ups rounded to the nearest day.

Swift-UVOT observed both sources approximately concurrently with the Swift-XRT telescope during the three flares of 3C 279 and the flare of PKS 1222+216. All Swift data is stored in the HEASARC Swift Data Archive.

Table 1 lists the energy ranges of each instrument along with the total observation time for the given instrument during the listed flare date range of 3C 279. Table 2 gives a similar descrip-

Figure 8. Gamma-ray spectra of 3C 279 during three flaring periods: January 2014, April 2014, and June 2015. They include upper limits from VERITAS and VHE data from Fermi-LAT.
Figure 9. Gamma-ray spectrum of PKS 1222+216 during its flaring period in March 2014. They include upper limits from VERITAS and VHE data from Fermi-LAT.

ation of the extracted data, but for the single PKS 1222+216 flare studied.

Both tables also include information on the VERITAS and Fermi-LAT data, as the final SED is composed of data from all four instruments.

4. ANALYSIS

4.1. XRT Data Analysis

Neutral hydrogen in interstellar gas absorbs low-energy (soft) X-rays before they get to Earth via the photoelectric effect. As a result, the data we get from the source needs to be corrected for in order to negate the effects of that absorption and plot what would be detected if there were no absorption. Mathematically, that correction is the multiplication of the measured fluxes by a factor:

\[
dN\,dE_{\text{deabs}} = dN\,dE_{\text{meas}} \, e^{N_H \sigma(E)},
\]

where \(N_H\) is the column density of neutral hydrogen and \(\sigma(E)\) is the cross section at the given energy.

Figure 10 shows the graphical effects of the correction of the data, where the top image shows how it originally drops off at low energies and the bottom shows the reconstruction of what the telescope would likely detect if there were no neutral hydrogen absorption. NASA HEASARC’s Xselect and Xspec tools were used for this data analysis.

4.1.1. 3C 279

The deabsorbed 3C 279 data appeared generally linear on a log-log plot (visible on the second plot of Figure 10), so the fitting model chosen was a power law:

\[
dN\,dE = K \left( \frac{E}{1\,\text{keV}} \right)^{-\alpha},
\]

where the normalization \(K\) alters the y-intercept of the log-log line and the photon index \(\alpha\) alters the slope.

Figure 11 shows the fitted X-ray spectra of 3C 279 during the three flaring periods in question
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Energy Range</th>
<th>Date Range</th>
<th>Exposure (ks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swift-UVOT</td>
<td>170 - 650 nm</td>
<td>30 Dec 2013 - 10 Jan 2014</td>
<td>23.019</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 Mar 2014 - 07 Apr 2014</td>
<td>12.325</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16 Jun 2015 - 19 Jun 2015</td>
<td>4.574</td>
</tr>
<tr>
<td>Swift-XRT</td>
<td>0.3 - 10.0 keV</td>
<td>30 Dec 2013 - 10 Jan 2014</td>
<td>23.415</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 Mar 2014 - 07 Apr 2014</td>
<td>12.361</td>
</tr>
<tr>
<td>Fermi-LAT</td>
<td>20 MeV - 300 GeV</td>
<td>30 Dec 2013 - 10 Jan 2014</td>
<td>30.820</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 Mar 2014 - 07 Apr 2014</td>
<td>58.446</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16 Jun 2015 - 19 Jun 2015</td>
<td>5.784</td>
</tr>
<tr>
<td>VERITAS</td>
<td>100 GeV - 10 TeV</td>
<td>30 Dec 2013 - 10 Jan 2014</td>
<td>19.512</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 Mar 2014 - 07 Apr 2014</td>
<td>58.446</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16 Jun 2015 - 19 Jun 2015</td>
<td>5.784</td>
</tr>
</tbody>
</table>

Table 1. Observations of 3C 279

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Energy Range</th>
<th>Exposure (ks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swift-UVOT</td>
<td>170 - 650 nm</td>
<td>17.822</td>
</tr>
<tr>
<td>Swift-XRT</td>
<td>0.3 - 10.0 keV</td>
<td>18.296</td>
</tr>
<tr>
<td>Fermi-LAT</td>
<td>20 MeV - 300 GeV</td>
<td>18.296</td>
</tr>
<tr>
<td>VERITAS</td>
<td>100 GeV - 10 TeV</td>
<td>21.726</td>
</tr>
</tbody>
</table>

Table 2. Observations of PKS 1222+216, all in the date range 26 Feb 2014 - 10 Mar 2014

with the residuals of the model versus the data plotted below. The parameters of the power law fit and the values of the column density of neutral hydrogen used for deabsorbing the data can be found in Table 3, as \( N_H \) was also a free parameter of the fit.

4.1.2. PKS 1222+216

For PKS 1222+216, the power law model fit the data very poorly, so a different approach was necessary. It was instead fitted with a broken power law model (bknpowerlaw):

\[
\frac{dN}{dE} = \begin{cases} 
  KE^{-\alpha_1} & E \leq E_{\text{break}} \\
  K(E_{\text{break}})^{\alpha_2-\alpha_1}(E/E_{1\text{keV}})^{-\alpha_1} & E > E_{\text{break}} 
\end{cases}
\]

which functions similarly to the regular power law, except that a breaking energy, \( E_{\text{break}} \), and a second photon index for the part of the model after the breaking energy, \( \alpha_2 \) (1.476 ± 6.82e-2), are incorporated. \( K \) is the normalization for the entire model, and \( \alpha_1 \) is the photon index where the energy is less than or equal to the breaking energy.

Figure 12 shows the data from the flaring period of this source fitted with a broken power law model. The values of the fit parameters used are as follows: \( K = 1.390e-3 \pm 6.18e-5; \alpha_1 = 2.798 \pm 1.75e-1; \alpha_2 = 1.476 \pm 6.82e-2; N_H = 4.831e20 \pm 1.46e20; E_{\text{break}} = 1.344 \pm 8.12e-2. \)

4.2. UVOT Data Analysis

Each observation from the UV/optical telescope includes multiple images of the source, each using a different filter. Analytical code from a VERITAS collaborator (Karlen Shahinyan, University of Minnesota) was used in order to combine data for each filter and measure the fluxes of the source.
### Table 3.

Parameters used for the power law fit of the three X-ray spectra of 3C 279. Also included is the column density of neutral hydrogen used in deabsorption of the spectra.

<table>
<thead>
<tr>
<th>Date Range</th>
<th>$K$</th>
<th>$\alpha$</th>
<th>$N_H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 Dec 2013 - 10 Jan 2014</td>
<td>7.175e-4 ± 4.27e-5</td>
<td>1.451 ± 5.45e-2</td>
<td>3.5e20 ± 1.22e20</td>
</tr>
<tr>
<td>30 Mar 2014 - 07 Apr 2014</td>
<td>9.547e-4 ± 5.51e-5</td>
<td>1.377 ± 6.06e-2</td>
<td>2.090e20 ± 1.36e20</td>
</tr>
</tbody>
</table>

The analysis also accounted for the effects of dust absorption on the detected fluxes, as dust in the interstellar medium and atmosphere absorbs ultraviolet and optical light (Meurer et al. 1999).

#### 4.3. Incorporation of Archival Data

The final addition to the SEDs was the incorporation of archival data. The archival data was extracted from the Space Science Data Center - ASI and plotted behind the data points from the four instruments in order to provide a general idea of the full shape of the SED as described by previous data. The archival data is not restricted to any period of time, and therefore includes high and low states of each source, indicating the range of variability observed.

5. **RESULTS AND CONCLUSIONS**

5.1. **Broadband SEDs**

The main products of this investigation are three broadband SEDs for 3C 279 and one for PKS 1222+216, which can be seen in Figures 13 and 14, respectively.

For most of the SEDs, the flare data plotted lies either above or at the high-flux region of the archival data, which makes sense because the archival data includes all time, whether the object is flaring or not. The most apparent difference between the flare data and archival data is seen in the Fermi-LAT energy range. For example, in the SED for the April 2014 flare of 3C 279, the Fermi-LAT data has a flux of about an order of magnitude higher than the archival data indicates.

However, for the January 2014 flare of 3C 279, the Fermi-LAT data approximately agrees with the archival data. This effect could be a result of the way that the date ranges were defined. As noted, the data in the SED for the non-VERITAS instruments were constrained according to the VERITAS observation dates. However, the VERITAS observations were a response to the Fermi-LAT observations, and as a result could have been taken after the Fermi-LAT flaring period when the source had returned to a low state.

The next step necessary in order to draw conclusions from the broadband SEDs is modeling. Modeling the FSRQs uses a large number of parameters that have the potential to describe parts of the environments of the sources, like magnetic field strength, particle energy density, and source size.

The most interesting feature of the final SEDs is the capturing of the X-ray turnover for the PKS source. While there are many parameters that control the location and shape of that turnover between the low- and high-energy peaks, it is very useful as a tool for ruling out potential models. The steepness of the slope between the UVOT data and the XRT amplified that usefulness, as some models can’t account for that extreme drop off. For example, if the low-energy part of the PKS 1222+216 XRT fit were extended to the energy range of the UVOT points, the fit would under-predict the observed data.

For example, Qi Feng (VERITAS, Columbia University) attempted to model the PKS 1222+216 SED using the simplest model available for FSRQs: the one-zone synchrotron self Compton model (Krawczynski et al. 2000). Two
Figure 11. X-Ray spectra of 3C 279 during its three flaring periods in January 2014, April 2014, and June 2015, respectively. Each spectrum is fit with a power law model. The shaded butterfly regions indicate a one-sigma uncertainty.

Figure 12. X-Ray spectrum of PKS 1222+216 during its flaring period in March 2014 fit with a broken power law model. Additional versions of the fit can be seen in Figure 15, each using different parameter values in an attempt to best fit the data. There is not a way to use this model that adequately accounts for the steep slope between the XRT and UVOT points. As a result, this PKS 1222+216 broadband SED disfavors this sort of model and suggests that additional components are necessary.

However, future investigations plan to apply an external Compton model to the FSRQ data, as that model is more likely to accurately describe the nature of FSRQs (Böttcher et al. 2013).

Special thanks go to Brian Humensky, Reshmi Mukherjee, Qi Feng, and Ari Brill for their day to day support throughout this research experience. Thanks also to John Parsons, Georgia Karagiorgi, and the rest of the faculty, postdocs, and graduate students of Nevis Laboratories for investing their time and energy into the REU program, and the National Science Foundation for funding it.
Figure 13. Broadband SEDs of 3C 279 including Swift UVOT and XRT, Fermi-LAT, VERITAS, and archival data for the January 2014, April 2014, and June 2015 flares.

Part of this work is based on archival data, software or online services provided by the Space Science Data Center - ASI.

Figure 14. Broadband SED of PKS 1222+216 including Swift UVOT and XRT, Fermi-LAT, VERITAS, and archival data for the March 2014 flare.

Figure 15. Two examples of one-zone synchrotron self Compton models of the broadband SED for PKS 1222+216. Each model attempts to use different parameter values to best fit the data.
REFERENCES