Photometric Observations of Eight Very High Energy (VHE) BL Lacertae (BL Lac) Objects

Abstract

Very High Energy (VHE) gamma rays greater than 100 GeV probe the non-thermal universe, identifying the areas of particle acceleration around black holes, neutron stars, astrophysical jets, massive star formation regions, and other objects where strong shocks are present. While earth-based particle accelerators currently can accelerate particles to a few tens of TeV (trillion electron volts), nature can accelerate particles to at least 10exp8 TeV. Gamma rays have been observed at energies above 100 TeV. High energy gamma ray observatories such as the High Altitude Water Cherenkov (HAWC) gamma ray observatory can continuously monitor large sections of the sky for activity. This study will present the photometric observations of eight very high energy BL Lacertae (BL Lac) objects that have been observed by HAWC. The observed BL Lac objects are: MRK 180, MRK 501, MRK 421, PKS 2155-304, PKS 2005-489, S2 0109+244, S4 0954+658, and S5 0716+714.

1.0 Introduction

Very High Energy (VHE) gamma rays greater than 100 GeV probe the non-thermal universe, identifying the areas of particle acceleration around black holes, neutron stars, astrophysical jets, massive star formation regions, and other objects where strong shocks are present. While earth-based particle accelerators currently can accelerate particles to a few tens of TeV, nature can accelerate particles to at least 10exp8 TeV. Gamma rays have been observed at energies above 100 TeV. High energy gamma ray observatories such as the High Altitude Water Cherenkov (HAWC) gamma ray observatory can continuously monitor large sections of the sky for activity. There are three overlapping gamma ray energy regimes typically utilized. At low energies, space-based instruments such as Fermi-LAT are used to detect primary gamma rays from approximately 50 MeV to 100 GeV. Atmospheric Cherenkov detectors work from approximately 50 GeV to 10 TeV. These two detection schemes operate in the near earth environment and at high altitudes in the atmosphere, respectively. The third regime utilizes water Cherenkov detectors to detect particles that survive to ground level at high terrestrial altitudes. HAWC is such a detector that can detect from approximately 100 GeV to above 100 TeV. HAWC is located in Mexico at an altitude of 4100 meters above sea level.

The HAWC gamma ray observatory uses water Cherenkov detectors to observe particles in air showers. The detector incorporates 300 water-filled tanks with four photomultiplier tubes per tank. The photomultiplier tubes detect the Cherenkov optical signals that result from the interaction of particles with water molecules in the tanks.

Cherenkov radiation occurs when electrically charged particles travel faster than light in a clear medium such as water. The water molecules and particles interact to give off light which is then detected by the photomultiplier tubes.

The large majority of TeV extragalactic emitters are classified as high synchrotron peaked BL Lac objects. Extragalactic BL Lac objects are compact quasi-stellar objects showing almost continuous spectra with weak emission and absorption lines and relatively rapid irregular light changes of greater than 3 magnitudes in the optical V band. Due to ultra-relativistic velocities of particles in the jet, the jet emission is strongly boosted and dominates the overall luminosity. The particles appear ultra-relativistic since the jet is pointed nearly directly along the line of sight to the observer. BL Lac objects are sources of strong X-ray radiation and radio waves and their emission displays strong and variable linear polarization in the visible and infrared spectral regions.

2.0 Methods

The eight BL Lac objects were selected from the HAWC catalog of TeV sources, TeVCat. These objects are: MRK 180, MRK 501, MRK 421, PKS 2155-304, PKS 2005-489, S2 0109+244, S4 0954+658, and S5 0716+714. These are classified as high synchrotron peaked BL Lac objects or HBL in the TevCat database.

The photometry data for these eight BL Lac objects was obtained primarily from the AAVSO VSX (American Association of Variable Star Observers; International Variable Star Index) (Kloppenborg 2022) database. Specifically, the data was in the Johnson-Cousins BVRI photometric magnitude ranges (Johnson B at 400-500 nm, Johnson V at 500-700 nm, Cousins R at 550-800 nm, and Cousins I at 700-900 nm). Additional data was obtained from the database of the ASAS-SN (All-Sky Automated Survey for SuperNova) (Shappee, et al. 2014) global network of robotic telescopes. The ASAS-SN photometric magnitude range is Sloan g (402.5-551.5 nm). An ASAS-SN light curve was computed for 200 days for each of the objects, combined with the Johnson-Cousins BVRI data, and analyzed with the AAVSO VStar (Benn, D. 2012, “Algorithms + Observations = VStar”, JAAVSO, v40, n2, pp.852-866) software. VStar is a multi-platform variable star data visualization and analysis tool. Specifically, Fourier analysis of the combined photometric data was performed to yield a detailed periodogram for each of the BL Lac objects from which periodicities and other variations can potentially be identified.

VStar utilizes the Date Compensated Discrete Fourier Transform (DCDFT) algorithm (Ferraz-Mello 1981) to produce a power spectrum, a period range, and a resolution. The Date Compensated DFT compensates for gaps in the data, which is common for variable star observations. The resulting analysis can include one or more periods and one or more harmonics. These can be selected to create a model that can also include a polynomial function that is used as a smoothing mechanism to capture key aspects of the data set without all the noise and fine fluctuations. When a model is created, it is subtracted from observations in the series to yield a second series called residuals. The residuals can also be analyzed to look for other signals (periods) in a process called pre-whitening. Periodicities and other potential variations were analyzed utilizing BVRI and Sloan g photometry, models created from the photometry, computed mean series, and residuals to obtain all possible variations.

3.0 Analysis and Results

Below are the composite light curves for BL Lacs MRK 180, MRK 501, MRK 421, S2 0109+244, PKS 2155-304, PKS 2005-489, S4 0954+658, and S5 0716+714. Each has a clickable link to the AAVSO VSX which contains all of the information about that star. Additionally, the HAWC TeVCat catalog has detailed information about the eight studied BL Lac objects (as well as numerous other high energy objects), including distance, red shift, spectral index, and links to numerous technical papers and other sources of information.

MRK 501 is located in the constellation Hercules at coordinates 16:53:52.22, +39:45:36.6. It has an energy threshold of 300 GeV.

MRK 421 is located in the constellation Ursa Major at coordinates 11:04:27.32, +38:12:31.8. It has an energy threshold of 500 GeV.

S2 0109+224 is located in the constellation Pisces at coordinates 01:12:05.82, +22:44:38.8. It has an energy threshold of 100 GeV.

S5 0716+714 is located in the constellation Camelopardalis at coordinates 07:21:53.44, +71:20:36.4. It has an energy threshold of 0.4 GeV.

MRK 180 is located in the constellation Draco at coordinates 11:36:26.41, +70:09:27.2. It has an energy threshold of 280 GeV.

PKS 2155-304 is located in the constellation Piscis Austrinus at coordinates 21:58:52.06, -30:13:32.1. It has an energy threshold of 300 GeV.

PKS 2005-489 is located in the constellation Telescopium at coordinates 20:09:25.39, -48:49:53.7. It has an energy threshold of 400 GeV.

[S4 0954+658](#) is located in the constellation Ursa Major at coordinates 09:58:47.25, +65:33:54.8. It has an energy threshold of 150 GeV.

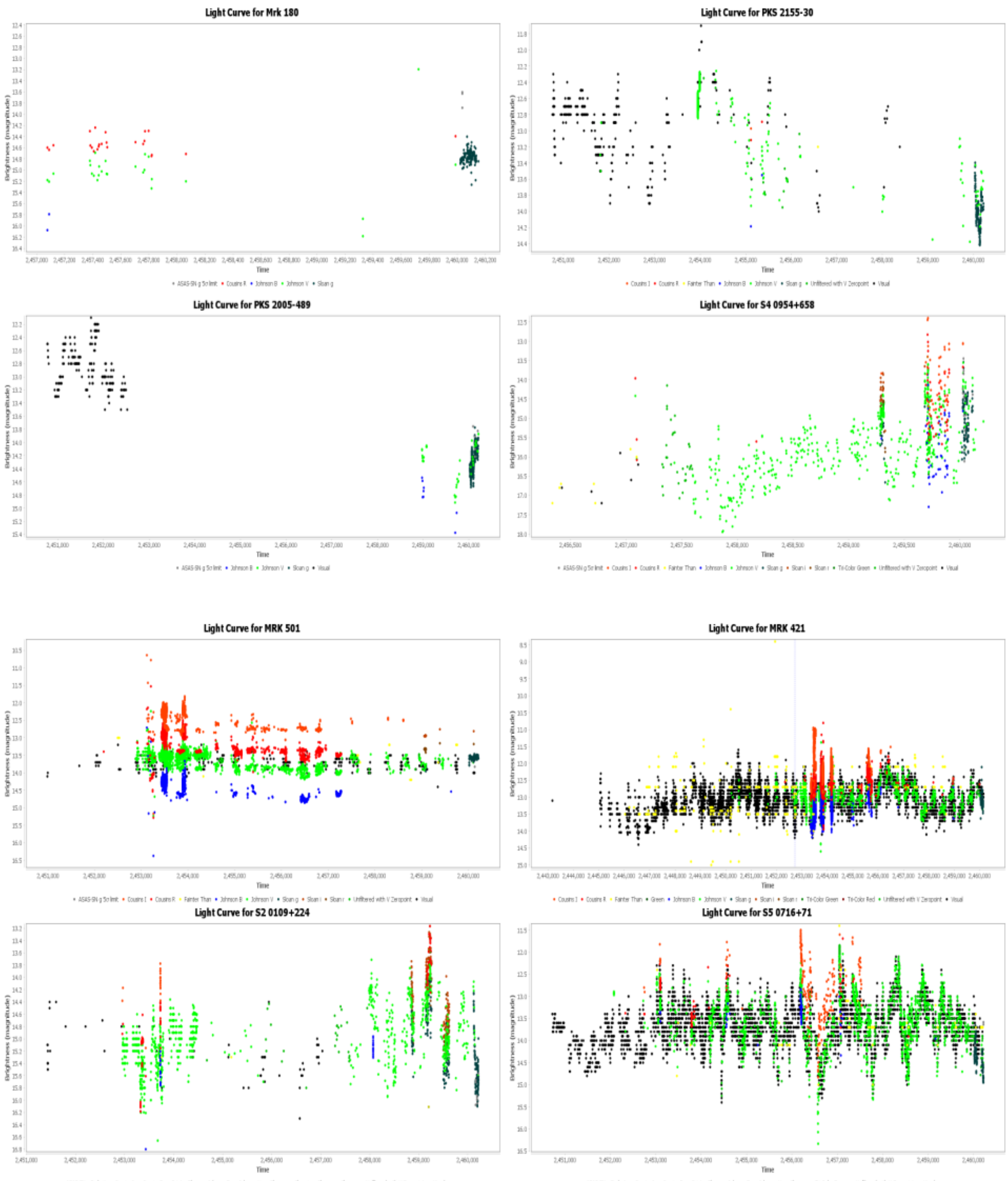

Figure 1: Composite Light Curves of Very High Energy BL Lac Objects

4.0 Conclusions

As can be seen in Figure 1, there is significant variation in the light curve amplitude, approximately 3-7.5 magnitudes, for all BL Lac objects. Additionally, there are several well pronounced peaks in light amplitude as well as an indication of possible periodicity. All of these objects would be good candidates for long term photometric observation and more detailed analysis. It is proposed that the long term observation be carried out with the AAVSOnet global telescope network and detailed analysis be performed by the AAVSO VStar data analysis software.

References

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The HAWC catalog of TeV sources, TeVCat. Hosted by the University of Chicago.