BVRI COMPARISON STARS NEAR SELECTED VERY-HIGH ENERGY BLAZARS

by

Cameron Pace

A senior thesis submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirements for the degree of

Bachelor of Science

Department of Physics and Astronomy

Brigham Young University

April 2010

BRIGHAM YOUNG UNIVERSITY

DEPARTMENT APPROVAL

of a senior thesis submitted by

Cameron Pace

This thesis has been reviewed by the research advisor, research coordinator, and department chair and has been found to be satisfactory.

Date	J. Ward Moody, Advisor
Date	Eric Hintz, Research Coordinator
Date	Ross Spencer, Chair

ABSTRACT

BVRI COMPARISON STARS NEAR SELECTED

VERY-HIGH ENERGY BLAZARS

Cameron Pace

Department of Physics and Astronomy

Bachelor of Science

We have prepared magnitudes for 42 comparison stars near five very-high energy blazars. Some of these stars have been previously calibrated by others, and in general our magnitudes agree with these previously reported magnitudes. We have used transformation equations to tie our magnitudes into the standard stars established by Landolt. Our *I* band magnitudes are systematically fainter than those previously presented, but we must conclude that our measurements are correct as they are tied into the Landolt standards.

ACKNOWLEDGMENTS

First I would like to thank my wife for her loving support. Without her patience and gentle prodding, I doubt this would have been finished on time. I am also grateful for her understanding when I needed to run the ROVOR telescope at all hours.

I would also like to thank Michael D. Joner for his help with this project. His expertise and careful eye have helped my be as accurate as possible. I must also recognize Richard Pearson's help. He acquired much of the data, and he has been a great collaborator.

Finally, I must thank Dr. J. Ward Moody for trusting me with this project, and for helping me through the difficult moments.

Contents

List of Figures

Chapter 1

Introduction

1.1 Brief History of Photometry

Photometry, which is the measurement of the intensity of star light, is one of the most useful and commonly employed tools in astronomy. A wealth of information can be gathered from measuring the intensity of an object's emitted radiation. For example, photometry can tell us the magnitude of an object, which can be used with the inverse square law to determine the luminosity as well as the distance to stars.

I will give a brief history of the history of photometry as well as an account of the history and study of blazars. This introduction is not meant to be comprehensive, but rather to give enough information that the reader may understand the 'big picture' and how this current work fits into the larger body of work on standard stars & blazars.

Until about the 18th century, astronomers were much more concerned with accurately determining the positions of the stars rather than their brightness. They reported brightness mostly as an aid in identifying and locating stars. Since ancient astronomers had no instruments with which to measure starlight, they simply made visual estimates of stellar magnitudes [1]. The earliest known example of a publication reporting stellar brightness is the Almagest which was written by the Roman astronomer Ptolemy (c. 90-168 AD). Ptolemy relied on the observations of an earlier astronomer, Hipparchus, in the creation of this catalog. In the Almagest, Ptolemy recorded the position and estimated visual magnitude of over one thousand stars. The stars were assigned a number from one to six, one being the brightest. A modified version of this scale is still used by astronomers today.

Astronomy is interesting among the sciences in that modern astronomers can argue about observations made 2000 years ago with some confidence of accuracy. The magnitudes given in the Almagest are close enough to our current magnitude scale that the data in the Almagest is useful to the naked eye astronomer. We no longer use the cubit, rod, or shekel, but the magnitude system is one of the few ancient systems of measure still in use today. Even so, the magnitude scale has its problems. The practice of giving the dimmest stars the highest numbers is confusing.

While ancient astronomers used the naked eye to measure the magnitudes of stars, modern astronomers use CCDs to obtain magnitudes. CCDs are much more sensitive than the human eye, and they allow images to be stored digitally.

1.2 Blazars

One use of photometry is in the study of blazars. Blazars are an interesting class of variable objects in that they are variable across the spectrum. In some wavelengths, blazars can vary in brightness by a factor of two in a few short months. Blazars are characterized by non-thermal emission spectra: in other words the light from these objects comes from synchrotron radiation and inverse Compton scattering [2]. Some blazars are unique in that they emit very energetic gamma rays in the TeV range.

Blazars are powered by black holes. As matter falls onto a black hole, the tidal forces from the black hole rip the matter apart, and the matter forms an accretion disk around the black hole. This accretion disk is composed of a rotating charged plasma, and this plasma creates a magnetic field. This field is directed along the axis of rotation and is twisted due to the rotation of the plasma. Lumps of material can be ejected from the black hole from time to time, and this material travels along the magnetic field. This ejection of matter along the axial magnetic field is what makes blazars vary in brightness.

1.3 Standard Stars

The variable nature of blazars make them objects of intense study by many astronomers the world over. Astronomers must be able to compare their observations, but since there are slight differences in every telescope/filter set/CCD system, it is not possible for observers to make direct comparison of their observations. They must first transform their observations onto the standard system. This is accomplished by using standard stars, which are stars whose magnitudes have been transformed onto the standard system.

The process of transforming observations onto the standard system is quite simple. One observes the standard stars, and gets a magnitude as well as an airmass for the observation. Then, one can look up the star's magnitude on the standard system, and use this information together with the measured or instrumental magnitude as well as the airmass to derive an equation for transforming the instrumental magnitude onto the standard system.

Chapter 2

Observations

2.1 Targets

We have created new standard stars near five very-high energy blazars: a table with the locations of these blazars is presented below. The blazars we have chosen are some of the most energetic known, as they emit photons in the TeV range [3]. Observations of these blazars could help us understand the energy source of such high-energy photons. All of the blazars already had nearby comparison stars, but many of the

Name	R.A.(2000)	Dec(2000)	z
$MRK421$	11 04 27	+38 12 32	0.031
$H1426 + 428$	14 28 33	+42 40 20	0.129
$MRK501$	16 53 52	+39 45 36	0.034
$1ES1959 + 650$	19 59 59	+65 08 55	0.048
$BLLac$	22 02 43	+42 16 40	0.069

Table 2.1 List of blazars for which we have provided standards.

comparison stars lacked magnitudes in one or more filters. We intended to observe these existing comparison stars to get magnitudes in the missing filters. We also sought to create new comparison stars that encompassed a range of magnitudes. The brighter comparison stars could be used when the blazar is flaring and the fainter comparison stars could be used when the blazar is in a quiescent state. We ultimately determined that it was more important to provide magnitudes in the missing filters than to provide comparison stars over a range of magnitudes.

As discussed earlier, it is important for observers to transform their observations onto the standard system: this makes it possible for them to compare their work. Observers must use transformation relations to convert their instrumental magnitudes, which are the raw magnitudes collected at the telescope, to magnitudes on the standard system. These transformation relations are unique to each telescope/CCD/filter system, and must be determined by observing comparison stars whose magnitudes have already been placed on the standard system.

Perhaps the most commonly used set of standard stars are those prepared by Arlo Landolt, who prepared a number of standard-star sequences situated near the celestial equator [4]. It can be time consuming to use Landolt's standards when studying blazars, since the blazars are usually far from Landolt's fields. It is more convenient for the comparison stars to be located close to the blazars so the observer can observe them at the same time as they observe the blazar. However, the standards near the blazars must be tied into Landolt's standards to be of any use.

2.2 Transformation Relations

Each telescope/filter combination attempts to match the standard system as closely as possible, but there are always some differences. These differences include variations in the telescope/detector sensitivity, as well as small disparities in the filter set. These differences are inherent in the equipment, but variations in the sky must be accounted for as well. The amount of water vapor and suspended particles changes from night to night, and so the atmospheric extinction changes from night to night as well. Because of this, it is vital to calculate the extinction for *every* night [5].

The first step in transforming magnitudes onto the standard system is to account for atmospheric extinction. Equations of the form

$$v_o = v_{inst} + k_{v1}\chi,$$

$$(b - v)_o = (b - v)_{inst} - k_{bv1}\chi - k_{bv2}(b - v)_{inst}\chi,$$

$$r_o = r_{inst} + k_{r1}\chi,$$

$$i_o = i_{inst} + k_{i1}\chi,$$

can be used to account for atmospheric extinction. The k_{b1}, k_{v1}, k_{r1}, and k_{i1} coefficients are the first-order extinction coefficients, and χ is the airmass of the observation. The first-order extinction coefficients are a measure of the atmospheric extinction for a given night for each filter. The k_{bv2} coefficient is the second-order extinction coefficient for the B filter. This coefficient is necessary for the B filter since the filter is wide enough that the amount of extinction can vary across it. The value of k_{bv2} is fairly stable, and need not be calculated for each night [5].

In order to calculte the first-order extinction coefficients, one must observe a star, preferably a standard star or at least a star that is known not to be a variable, over a large range of airmasses. Ideally, one would obtain magnitudes from 1.00 to 2.00 airmasses. Then, the slope of a plot of the magnitude versus the airmass will yield the extinction. For best results, several stars would be observed and the values of their slopes averaged, as shown in the figure below.

I wrote a simple `Java` program to quickly correct the instrumental magnitudes for extinction. The user supplied the first and second order extinction coefficients, as well as a .txt file that contained the star id numbers, magnitudes, HJD, airmasses,

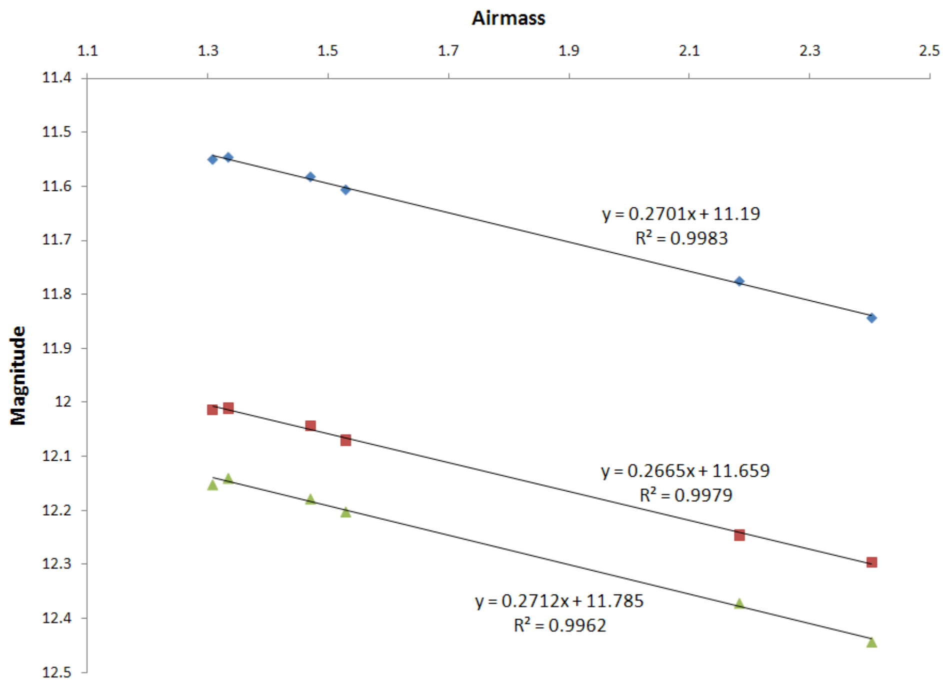

Figure 2.1 plots of magnitude versus airmass for several stars in the V filter on the night of August 1, 2009. Notice that the slope for each star is quite similar. A simple average of these slopes yields the V k_{v1} extinction coefficient for this night.

and filters, and the program would correct for atmospheric extinction. Once this was accomplished, it was possible to transform the magnitudes onto the standard system.

Transformation relations are equations that transform the instrumental magnitude onto the standard system. Each filter has its own transformation relation. The relation for the V filter is given by

$$V = v_o + a_0 + a_1(b_o - v_o).$$

The transformation relations for the other filters are

$$B = b_o + c_0 + c_1(b_o - v_o),$$

$$R = r_o + d_0 + d_1(v_o - r_o),$$

$$I = i_o + e_0 + e_1(v_o - i_o),$$

for B, R, and I respectively. The capital letters indicate standard magnitudes in the respective filters, while v_o, b_o, r_o and i_o are the instrumental magnitudes in the respective filters, corrected for extinction. The coefficients c_0, d_0, and e_0 are the zeropoints for the respective filters, and are a measure of the sensitivity of the telescope and CCD in that filter. The zeropoint exhibits nightly variability, although not as dramatically as the extinction.

Next, a_1, c_1, d_1, and e_1 are known as the 'color terms' and are a measure of how close the filters match those of the standard system. A value of less than 0.1 for these coefficients indicates that the filter set is a reasonable match of the standard system. We can expect the color term to be stable over long periods of time, since it depends solely on the filter set.

These two coefficients, a_0 and a_1, permit an instrumental magnitude corrected for extinction to be transformed onto the standard system. Determining these coefficients is perhaps the most difficult part of creating standard stars, since they must be calculated with careful precision. Observations for a given night may have an internal precision down to the millimag level, but applying the transformation equations can introduce errors that are ten times greater. If the transformation equations destroy the inherent accuracy of observations, the transformed magnitudes are of little value. The next section will describe how to carefully determine the transformation coefficients.

2.3 Determining Coefficients

At first glance, the transformation equations appear to be nothing but a string of unknowns. However, the only unknowns are the coefficients a_0 and a_1: all other values can either be obtained observationally or by consulting previously published

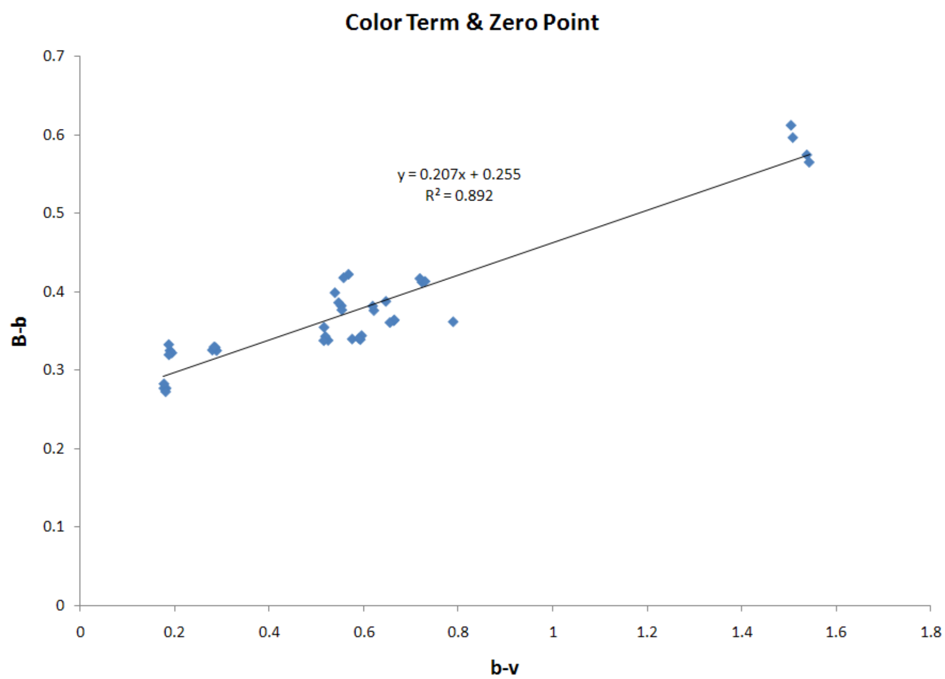

Figure 2.2 B-b vs. b-v plot for the night of August 10, 2009. The slope and zeropoint of the trend line provides values for c_1 and c_0, respectively.

values.

As an example, again consider the case of the B filter. We previously introduced the transformation relation:

$$B = b_o + c_0 + c_1(b_o - v_o),$$

which can be rewritten as

$$B - b_o = c_0 + c_1(b_o - v_o).$$

The standard magnitude B can be obtained from one of Landolt's papers. Observations corrected for extinction provide values for b_o and $(b_o - v_o)$. Then a list of ordered pairs of the form $((b_o - v_o),\ B - b_o)$ provide x and y values for a plot such as the one shown above. The slope and zeropoint of a trend line fitted to the points provide values for c_1 and c_0 respectively. The transformation coefficients for the other filters can be found in a similar manner. Once all of the transformation coefficients for a given night are known, then any instrumental magnitude corrected for extinction can be transformed onto the standard system.

When observing Landolt standards, it is important to gather data on many stars with a wide color range in order to determine the transformation coefficients with the greatest accuracy. We used Landolt standards in 3 selected areas to provide magnitudes for our transformation equations. The table below provides values for the coefficients for the night of August 10th. These values are comparable to the values acquired for other nights.

Transformation Coefficients for August 10th		
Filter	Coefficient	Value (σ)
B	c_0	0.255 (0.008)
	c_1	0.208 (0.012)
V	a_0	-0.033 (0.008)
	a_1	-0.108 (0.011)
R	d_0	0.12 (0.008)
	d_1	-0.059 (0.01)
I	e_0	-.348 (0.015)
	e_1	0.071 (0.012)

Table 2.2 Typical Values for Transformation Coefficients.

2.4 Data Collection

Our data were collected on only the best nights: no clouds of any sort, no more than a quarter moon, and good seeing. Nights that exhibit these ideal conditions are known as photometric nights. Photometric conditions are essential for creating standard stars since we make observations throughout the entire sky. We collected data on fifteen nights from June to August, but only eight nights were found to be perfectly photometric. Since we were striving for the greatest accuracy, we only used data from these perfectly photometric nights. Data from parts of the other nights may have been of acceptable quality, but upon the advice of [5] we felt that it was best not to risk polluting excellent data with data of questionable reliability.

We used the 16” Remote Observatory for Variable Object Research (ROVOR) to make our observations. This scope uses the Software Bisque suite of software for telescope and CCD control. Software Bisque also provides a program that allows ROVOR to be controlled robotically: the observer simple loads a list of commands that the telescope then executes. This robotic control greatly simplifies the observing process, since everything from slewing the telescope to acquiring calibration frames can be preprogrammed. Further motivation for using a robotic telescope will be provided in the next section.

2.5 Nightly Observing Routine

All of our nightly observing procedures are described in detail in [5]. We began and ended each night by observing a group of ten or so standard stars. We also observed another ten stars roughly every hour throughout the night. In other words, roughly one-third of our observing time was spent observing standard stars. In part, this is because we must observe the standard stars at a wide range of airmasses: it is best to observe over a range of one airmass or so. This large range of airmasses is necessary to accurately determine the extinction coefficients, while a large number of observations is necessary to “beat down the errors.” In an effort to further improve accuracy, we only made observations in the western half of the sky.

Observationally, we began observing the standard stars when they were near the meridian, and the airmass was near one. The standards were then observed at higher and higher airmasses, until they were at an airmass of two, then we began the process over with another standard field near the meridian. In between observations of standard star fields, we observed our program stars. We followed the standard practice of observing in a palindrome sequence: *VBRIIRBV*. We also adjusted our exposure times in each filter due to the inherent color differences of the stars as well as the quantum efficiency of our detector. All of our images in B were five minutes long, while our V images were three minutes long. Images acquired in R were 90-120 seconds, and our I images were 30-60 seconds long.

2.6 Data Reduction

We used two programs to reduce our data frames: `iraf` and `Mira`. We used `Mira` to apply the bias, dark, and flat frames, and `iraf` to perform the aperture photometry. We used `Mira` for calibrating the data rather than `iraf` because we used so many different exposure times, and calibrating frames of different exposure times in the same data set can be time consuming in `iraf`.

Although `Mira` can perform aperture photometry, we used `iraf` because we could request the results of the photometry to be output into simple .txt files. These .txt files include the star id number, the instrumental magnitude, the airmass, and the filter of each observation. This information was used to calculate the transformation coefficients described in section 2.3.

Once the coefficients were calculated, they needed to be applied to the instrumental magnitudes. I wrote a simple time-saving `java` program to perform this task. This program required the user to provide the coefficients for each filter, as well as the .txt files with the instrumental magnitudes, airmasses, and filters. With this information, the program then used the appropriate transformation equations to convert the instrumental magnitudes into standard magnitudes.

Chapter 3

Results

3.1 Summary of Results

Table 3.1 gives the $BVRI$ magnitudes of the program stars, as well as the error and the number of nights (n) each star was observed. In general, our magnitudes agree well with those presented by others, with the exception of our I band data. The results for individual stars will be discussed in their respective sections.

The errors we have quoted are a simple standard deviation of the transformed magnitudes for a given star. The standard deviation is given by:

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2}$$

.

In my work, I have tried to follow the numbering schemes of Villata et al. [6] and Fiorucci et al. [7] in designating the comparison stars. However, there are a few discrepancies, and table 3.2 provides a list of designations that have been used in other papers that are different from my designations.

Blazar	Star	B(σ)	V(σ)	R(σ)	I(σ)	n
MRK 501	1	13.62 (0.02)	12.64 (0.01)	12.16 (0.02)	11.73 (0.01)	8
	2	14.10 (0.02)	13.20 (0.01)	12.77 (0.02)	12.38 (0.01)	8
	3	15.94 (0.05)	15.17(0.02)	14.76 (0.03)	14.39 (0.03)	8
	4	16.00 (0.04)	15.34 (0.03)	15.00 (0.04)	14.67 (0.04)	8
	5	16.22 (0.07)	15.44 (0.04)	15.05 (0.03)	14.64 (0.03)	8
	6	16.83 (0.09)	15.67 (0.04)	14.98 (0.03)	14.45 (0.03)	8
	7	16.78 (0.07)	15.48 (0.04)	14.68 (0.03)	14.03 (0.01)	8
	8	13.54 (0.02)	12.94 (0.01)	12.61 (0.01)	12.28 (0.01)	8
	9	15.00 (0.03)	14.38 (0.02)	14.05 (0.01)	13.71 (0.02)	8
	10	14.44 (0.02)	13.58 (0.01)	13.10(0.02)	12.65 (0.01)	8
	11	12.87 (0.02)	11.86 (0.02)	11.38(0.01)	10.92 (0.01)	8
BL Lac	1	14.69 (0.05)	12.94(0.03)	12.05(0.02)	11.24 (0.02)	5
	2	15.18 (0.04)	14.27 (0.03)	13.81(0.03)	13.39 (0.03)	5
	3	15.77 (0.05)	14.45 (0.03)	13.78(0.03)	13.15 (0.02)	5
	4	16.34 (0.06)	15.55 (0.05)	15.08(0.05)	14.64 (0.03)	4
	5	16.61 (0.10)	15.74 (0.05)	15.31(0.07)	14.87 (0.06)	4
	6	15.52 (0.04)	14.47 (0.03)	13.88(0.02)	13.38 (0.02)	4
	7	14.34 (0.05)	13.31 (0.04)	12.75(0.03)	12.24 (0.03)	4
	8	14.04 (0.03)	13.29 (0.04)	12.89(0.02)	12.49 (0.02)	4
	9	15.09 (0.04)	14.26 (0.04)	13.81(0.02)	13.33 (0.03)	4
	10	15.12 (0.05)	14.17 (0.04)	13.66(0.03)	13.15 (0.03)	4
1ES1959+650	1	13.39 (0.03)	12.69 (0.02)	12.33 (0.02)	11.96 (0.02)	5
	2	13.48 (0.02)	12.91 (0.02)	12.60 (0.02)	12.28 (0.02)	5
	3	15.04 (0.03)	13.28 (0.03)	12.40 (0.01)	11.54 (0.02)	5
	4	15.32 (0.03)	14.51 (0.02)	14.09 (0.03)	13.69 (0.02)	5
	5	15.64 (0.12)	14.62 (0.14)	14.04 (0.10)	13.48 (0.09)	5
	6	15.99 (0.05)	15.22 (0.03)	14.83 (0.03)	14.45 (0.03)	5
	7	16.02 (0.04)	15.24 (0.03)	14.81 (0.03)	14.37 (0.02)	5
	8	12.75 (0.02)	12.22 (0.02)	11.93 (0.02)	11.64 (0.01)	5
	9	14.12 (0.02)	13.50 (0.02)	13.15 (0.02)	12.81 (0.01)	5
	10	16.22 (0.07)	15.29 (0.03)	14.78(0.03)	14.35 (0.03)	5
	11	15.18 (0.02)	14.39 (0.02)	13.99 (0.02)	13.60 (0.02)	5
H 1426+428	1	15.62 (0.03)	14.19 (0.01)	13.33 (0.02)	12.59 (0.01)	5
	2	15.41 (0.03)	14.60 (0.02)	14.20 (0.02)	13.84 (0.01)	5
	3	14.21 (0.02)	13.44 (0.02)	13.05 (0.02)	12.70 (0.01)	5
	4	16.02 (0.05)	15.45 (0.04)	15.12 (0.03)	14.81 (0.03)	5
	5	16.00 (0.04)	15.23 (0.02)	14.82 (0.02)	14.46 (0.03)	5
MRK 421	1	14.95 (0.01)	14.29 (0.07)	14.00 (0.02)	13.66 (0.01)	2
	2	16.09 (0.02)	15.54 (0.06)	15.22 (0.06)	14.86 (0.06)	2
	3	16.39 (0.03)	15.70 (0.07)	15.10 (0.08)	14.62 (0.04)	2
	4	15.14 (0.01)	14.10 (0.01)	13.55 (0.01)	13.08 (0.01)	2
	5	14.41 (0.01)	13.55 (0.01)	13.09 (0.02)	12.69 (0.01)	2

Table 3.1 BVRI magnitudes of comparison stars.

Field	Star	Other Designations
MRK 501	1	1 [6],1 [8]
	3	3 [6],5 [8]
	8	3 [8]
BL Lac	1	B [6,9], 12 [8]
	2	C [6,9], 21 [8]
	3	H [6,9], 16 [8]
	4	K [6,9], 17 [8]
	6	3 [8]
	7	25 [8]
H1426+428	1	A [10]
	2	B [10]
	3	C [10]
	4	D [10]
MRK 421	2	3 [11]
	4	8 [11]
	5	2 [11]

Table 3.2 Comparison of designations used in other papers. Stars which have the same designation in my work as in others' are not included in this table.

3.2 1ES1959+650

In general, we agree with Villata et al. [6] and Doroshenko [11]. We agree particularly well on stars 1, 6, and 7. Doroshenko et al. [11] point out that star 5 is a variable. We found a high error associated with this star, which would seem to indicate variability, however the finder chart in Appendix A shows that there is a nearby companion, which I believe could cause the variability, as its light is included in the aperture from variable seeing and centering.

Doroshenko et al. [11] also suggest that star 3 is a low-amplitude variable. While we found no evidence of variability, our observations of star 3 were made in a relatively short three month span, so the star could be a long-term variable. Because of this, we recommend that star 3 not be used.

Star	filter	V98[1]	D07[2]	this work
1	B		13.371 ± 0.016	13.39 ± 0.03
1	V	12.67 ± 0.04	12.686 ± 0.017	12.69 ± 0.02
1	R	12.29 ± 0.02	12.280 ± 0.004	12.33 ± 0.02
1	I		11.917 ± 0.004	11.96 ± 0.02
2	B		13.45 ± 0.016	13.48 ± 0.02
2	V	12.86 ± 0.02	12.875 ± 0.017	12.91 ± 0.02
2	R	12.53 ± 0.02	12.531 ± 0.004	12.60 ± 0.02
2	I		12.217 ± 0.004	12.28 ± 0.02
3	B		14.934± 0.016	15.04± 0.03
3	V	13.18 ± 0.02	13.228 ± 0.017	13.28 ± 0.03
3	R	12.27 ± 0.02	12.261 ± 0.004	12.40 ± 0.01
3	I		11.373 ± 0.004	11.54 ± 0.02
4	B		15.282 ± 0.021	15.32 ± 0.03
4	V	14.53 ± 0.03	14.493 ± 0.017	14.51 ± 0.02
4	R	14.08 ± 0.03	14.037 ± 0.004	14.09 ± 0.03
4	I		13.619 ± 0.004	13.69 ± 0.02
5	B			15.64 ± 0.12
5	V	14.54 ± 0.03		14.62 ± 0.14
5	R	14.00 ± 0.02		14.04 ± 0.10
5	I			13.48 ± 0.09
6	B			15.99 ± 0.05
6	V	15.20 ± 0.03		15.22 ± 0.03
6	R	14.78 ± 0.03		14.83 ± 0.03
6	I			14.45 ± 0.03
7	B			16.02± 0.04
7	V	15.24 ± 0.03		15.24 ± 0.03
7	R	14.79 ± 0.03		14.81 ± 0.03
7	I			14.37 ± 0.02

Table 3.3 Comparison with previous standards in the field of 1ES1959+650. NOTES: (1) Villata et al. [6], (2) Doroshenko et al. [11].

3.3 MRK 421

The star field around MRK 421 is sparse, and so we were limited in which stars we could use as comparisons. In general, we agree with the magnitudes presented by Villata et al. [6] and Doroshenko et al. [11]. However, our magnitudes for star 3 are brighter than those presented by Villata et al. [6]. This is probably due to the orientation of our telescope, which, as can be seen in the finder chart for MRK 421, caused diffraction spikes from the nearby bright stars to overlap the comparison star. Thus, I recommend that star three not be used as a comparison star.

Star	filter	V98[1]	D07[2]	this work
1	B	15.02 ± 0.03	14.98 ± 0.011	14.95 ± 0.01
1	V	14.36 ± 0.02	14.392 ± 0.007	14.29 ± 0.07
1	R	14.04 ± 0.02	14.022 ± 0.004	14.00 ± 0.02
1	I		13.694 ± 0.001	13.66 ± 0.01
2	B	16.20 ± 0.04	16.174 ± 0.011	16.09 ± 0.02
2	V	15.57 ± 0.05	15.571 ± 0.007	15.54 ± 0.06
2	R	15.20 ± 0.03	15.20 ± 0.004	15.22 ± 0.06
2	I		14.866 ± 0.005	14.86 ± 0.06
3	B	16.69 ± 0.03		16.39 ± 0.03
3	V	15.77 ± 0.03		15.70 ± 0.07
3	R	15.24 ± 0.03		15.10 ± 0.08
3	I			14.62 ± 0.04
4	B		15.124 ± 0.011	15.14 ± 0.01
4	V		14.121 ± 0.007	14.10 ± 0.01
4	R		13.534 ± 0.004	13.55 ± 0.01
4	I		13.017 ± 0.004	13.08 ± 0.01
5	B		14.381 ± 0.013	14.41 ± 0.01
5	V		13.565 ± 0.008	13.55 ± 0.01
5	R		13.062 ± 0.004	13.09 ± 0.02
5	I		12.624 ± 0.004	12.69 ± 0.01

Table 3.4 Comparison with previous standards in the field of MRK 421. NOTES: (1) Fiorucci et al. [7], (2) Villata et al. [6], (3) Doroshenko et al. [11].

3.4 H1426+428

The field near H1426+428 contains even fewer stars than the field around MRK 421. Because of this, we have added only one new comparison star to those presented by Smith et al. [10].

Star	filter	S91[1]	this work
1	B	15.61 ± 0.03	15.62 ± 0.03
1	V	14.16 ± 0.01	14.19 ± 0.01
1	R	13.23 ± 0.02	13.33 ± 0.02
1	I	12.43 ± 0.02	12.59 ± 0.01
2	B	15.47 ± 0.02	15.41 ± 0.03
2	V	14.61 ± 0.01	14.60 ± 0.02
2	R	14.17 ± 0.02	14.20 ± 0.02
2	I	13.79 ± 0.02	13.84 ± 0.01
3	B	14.22± 0.02	14.21± 0.02
3	V	13.46 ± 0.02	13.44 ± 0.02
3	R	13.00 ± 0.02	13.05 ± 0.02
3	I	12.62 ± 0.03	12.70 ± 0.01
4	B	16.14 ± 0.06	16.02 ± 0.05
4	V	15.53 ± 0.04	15.45 ± 0.04
4	R	15.20 ± 0.04	15.12 ± 0.03
4	I	14.82 ± 0.05	14.81 ± 0.03

Table 3.5 Comparison with previous standards in the field of H1426+428. NOTE: (1) Smith et al. [9].

3.5 MRK 501

This is the only object we observed on all eight nights. The internal consistency of our observations is evident in the small errors we report for MRK 501. MRK 501 is well studied, as is evidenced by the number of authors who have prepared comparison stars in the field. The best comparison stars to use in the field of MRK 501 would be stars 1, 3, 4, and 6, which show the best agreement between authors. However, the proximity of star 6 to the blazar itself could cause small fluctuations in the star's instrumental magnitude.

Star	filter	F96[3]	V98[4]	D05[5]	this work
1	B		13.55 ± 0.03	13.54 ± 0.003	13.62 ± 0.02
1	V	12.61 ± 0.03	12.61 ± 0.02	12.598 ± 0.003	12.64 ± 0.01
1	R	12.15 ± 0.03	12.11 ± 0.02	12.082 ± 0.003	12.16 ± 0.02
1	I	11.65± 0.04		11.613 ± 0.001	11.73 ± 0.01
2	B		14.10 ± 0.03	14.055 ± 0.006	14.10 ± 0.02
2	V		13.23 ± 0.02	13.186 ± 0.005	13.20 ± 0.01
2	R		12.79 ± 0.02	12.719 ± 0.006	12.77 ± 0.02
2	I			12.297 ± 0.005	12.38 ± 0.01
3	B		15.98 ± 0.04	15.932± 0.022	15.94± 0.05
3	V		15.24 ± 0.02	15.158 ± 0.01	15.17 ± 0.02
3	R		14.80 ± 0.02	14.729 ± 0.009	14.76 ± 0.03
3	I			14.327 ± 0.009	14.39 ± 0.03
4	B		16.05 ± 0.05	15.977 ± 0.021	16.00 ± 0.04
4	V	15.30± 0.07	15.30 ± 0.02	15.313 ± 0.012	15.34 ± 0.03
4	R	14.91 ± 0.07	14.96 ± 0.02	14.926 ± 0.01	15.00 ± 0.04
4	I	14.56 ± 0.07		14.572 ± 0.011	14.67 ± 0.04
5	B		16.27 ± 0.04	15.977 ± 0.021	16.22 ± 0.07
5	V		15.51 ± 0.02	15.313 ± 0.012	15.44 ± 0.04
5	R		15.08 ± 0.02	14.926 ± 0.01	15.05 ± 0.03
5	I				14.64 ± 0.03
6	B		16.82 ± 0.05		16.84 ± 0.08
6	V	15.68 ± 0.08	15.67 ± 0.04		15.68 ± 0.04
6	R	14.97 ± 0.08	14.99 ± 0.04		14.99 ± 0.03
6	I	14.34 ± 0.08			14.44 ± 0.05
8	B			13.541 ± 0.009	13.54± 0.02
8	V			12.952 ± 0.009	12.94 ± 0.01
8	R			12.592 ± 0.007	12.61 ± 0.01
8	I			12.256 ± 0.009	12.28 ± 0.01

Table 3.6 Comparison with previous standards in the field of MRK 501. NOTES: (1) Fiorucci et al. [7], (2) Villata et al. [6], (3) Doroshenko et al. [8].

3.6 BL Lac

The field of BL Lac is dense, with a variety of stars close to the blazar. Several comparison stars have been created near BL Lac, the first of which were created by Bertaud et al. [12]. Later, Smith et al. [9] created more standards in the field, but their magnitudes are systematically brighter than those reported by any other observer. Stars 2 and 3 show the best agreement among authors, and should always be used as comparison stars.

Star	filter	B69[1]	S85[2]	F95[3]	D05[4]	this work
1	B		14.52 ± 0.04		14.636 ± 0.019	14.69 ± 0.05
1	V	12.90	12.78 ± 0.04	12.90 ± 0.04	12.928 ± 0.011	12.94 ± 0.03
1	R		11.93 ± 0.05	11.99 ± 0.04	11.957 ± 0.015	12.05 ± 0.02
1	I		11.09 ± 0.06	11.12 ± 0.05	11.107 ± 0.017	11.24 ± 0.02
2	B		15.09 ± 0.03		15.185 ± 0.013	15.18 ± 0.04
2	V	14.28	14.19 ± 0.03	14.26 ± 0.06	14.28 ± 0.008	14.27 ± 0.03
2	R		13.69 ± 0.03	13.79 ± 0.05	13.753 ± 0.014	13.81 ± 0.03
2	I		13.23 ± 0.04	13.32 ± 0.05	13.313 ± 0.015	13.39 ± 0.03
3	B		15.68 ± 0.03		15.76± 0.021	15.77± 0.05
3	V	14.42(<0.10)	14.31 ± 0.05	14.40 ± 0.06	14.456 ± 0.01	14.45 ± 0.03
3	R		13.60 ± 0.03	13.73 ± 0.06	13.705 ± 0.015	13.78 ± 0.03
3	I		12.93 ± 0.04	13.07 ± 0.06	13.048 ± 0.016	13.15 ± 0.02
4	B		16.26 ± 0.05		16.404 ± 0.023	16.34 ± 0.06
4	V	15.48(<0.10)	15.44 ± 0.03	15.47 ± 0.07	15.583 ± 0.014	15.55 ± 0.05
4	R		14.88 ± 0.05	15.00 ± 0.06	15.07 ± 0.016	15.08 ± 0.05
4	I		14.34 ± 0.10	14.54 ± 0.07	14.605 ± 0.018	14.64 ± 0.03
6	B				15.523 ± 0.021	15.52 ± 0.04
6	V				14.457 ± 0.013	14.47 ± 0.03
6	R				13.812 ± 0.016	13.88 ± 0.02
6	I				13.272 ± 0.017	13.38 ± 0.02
7	B				14.326 ± 0.021	14.34 ± 0.05
7	V				13.288 ± 0.013	13.31 ± 0.04
7	R				12.666 ± 0.017	12.75 ± 0.03
7	I				12.146 ± 0.017	12.24 ± 0.03

Table 3.7 Comparison with previous standards in the field of BL Lac. NOTES: (1) Bertaud et al. [12], (2) Smith et al. [9], (3) Fiorucci et al. [7], (4) Doroshenko et al. [8].

3.7 Discrepancy in the I Band

We report I band magnitudes that are systematically dimmer than those presented by other observers. This is cause for some concern, and we have examined many possible causes of this discrepancy. Our transformation equations for the I band are accurate, as we agree with the Landolt standards to within 0.006 mag. We must conclude that our I magnitudes are accurate, and should be trusted.

Chapter 4

Conclusion

We have prepared magnitudes for 42 comparison stars near five very-high energy blazars. Magnitudes for many of these stars have been presented by others, and in general we agree with the magnitudes presented by other authors. We have extended the usefulness of these comparison stars by preparing magnitudes for all of these stars in all of the filters $BVRI$ system. Although our I band magnitudes are systematically fainter than those presented by others, we suggest that our magnitudes are accurate as our transformation equations agree very well with the Landolt standards.

Bibliography

[1] J. B. Hearnshaw, *The Measurement of Starlight*, 4th ed. (Cambridge University Press: Cambridge, Cambridge, 1996).

[2] G. A. Shields, "A Brief History of Active Galactic Nuclei," Publ. Astron. Soc. Pac. **111,** 661–678 (1999).

[3] D. Horan and T. C. Weekes, "Extragalactic sources of TeV gamma rays: a summary," New Astron. Rev. **48,** 527–535 (2004).

[4] A. U. Landolt, "UBVRI Photometric Standard Stars Around the Celestial Equator: Updates and Additions," Astron. J. **137,** 4186–4269 (2009).

[5] A. U. Landolt, "Standardization in the Classical UBVRI Photometric System," In *The Future of Photometric, Spectrophotometric and Polarimetric Standardization*, C. Sterken, ed., Astron. Soc. Pac. Conf. Ser. **364,** 27–61 (2007).

[6] M. Villata, C. M. Raiteri, L. Lanteri, G. Sobrito, and M. Cavallone, "BVR photometry of comparison stars in selected blazar fields. I. Photometric sequences for 10 BL Lacertae objects," Astron. Astrophys. Suppl. Ser. **130,** 305–310 (1998).

[7] M. Fiorrucci and G. Tosti, "VRI Photometry of stars in the fields of 12 BL Lacertae objects," Astron. Astrophys. Suppl. Ser. **116,** 403–407 (1996).

[8] V. T. Doroshenko, S. G. Sergeev, N. I. Merkulova, E. A. Sergeeva, Y. V. Golubinsky, V. I. Pronik, and N. N. Okhmat, "BVRI CCD-Photometry of Comparison Stars in the Neighborhoods of Galaxies with Active Nuclei. II," Astrophys. **48,** 304–320 (2005).

[9] P. S. Smith, T. J. Balonek, P. A. Heckert, R. Elston, and G. D. Schmidt, "UBVRI Field Comparison Stars for Selected Active Quasars and BL Lacertae Objects," Astron. J. **90,** 1184–1187 (1985).

[10] P. S. Smith, B. T. Jannuzi, and R. Elston, "UBVRI Photometry of Stars in the Fields of X-Ray Selected BL Lacertae Objects," Astrophys. J. Supp. Ser. **77,** 67–73 (1991).

[11] V. T. Doroshenko, S. G. Sergeev, Y. S. Efimov, S. Nazarov, V. I. Pronik, E. A. Sergeeva, and G. A. Sivtsov, "BVRI CCD-Photometry of Comparison Stars in the Neighborhoods of Galaxies with Active Nuclei. III," Astrophys. **50,** 40–53 (2007).

[12] C. Bertaud, B. Dumortier, P. Véron, G. Wlérick, G. Adam, J. Bigay, R. Garnier, and M. Duruy, "Optical and radio study of BL Lacertae.," Astron. Astrophys. **3,** 436–442 (1969).

Appendix A

Finder Charts

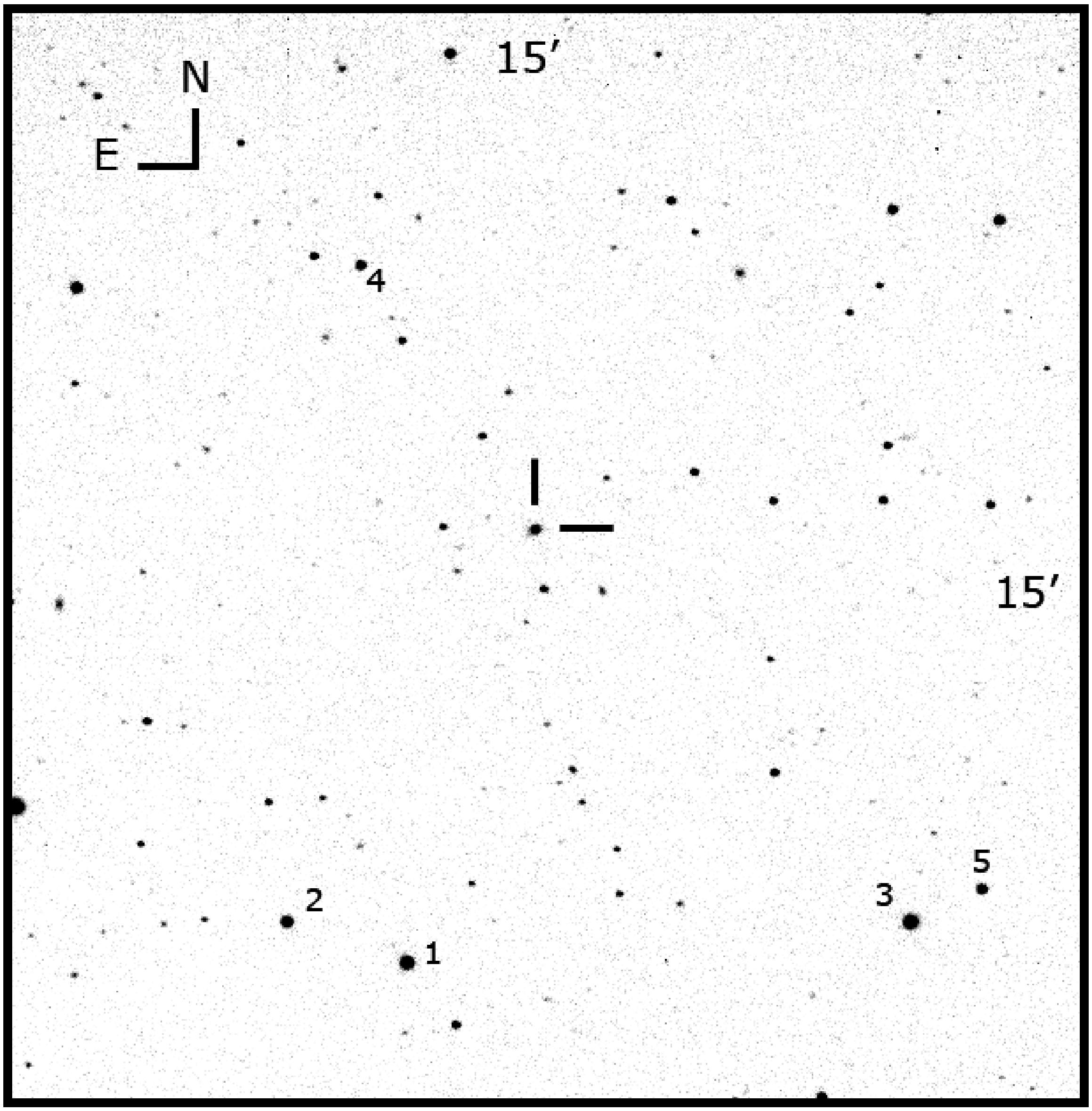

Figure A.1 H 1426+428 α = 14:26:35.9 δ = 42:53:46 (2000)

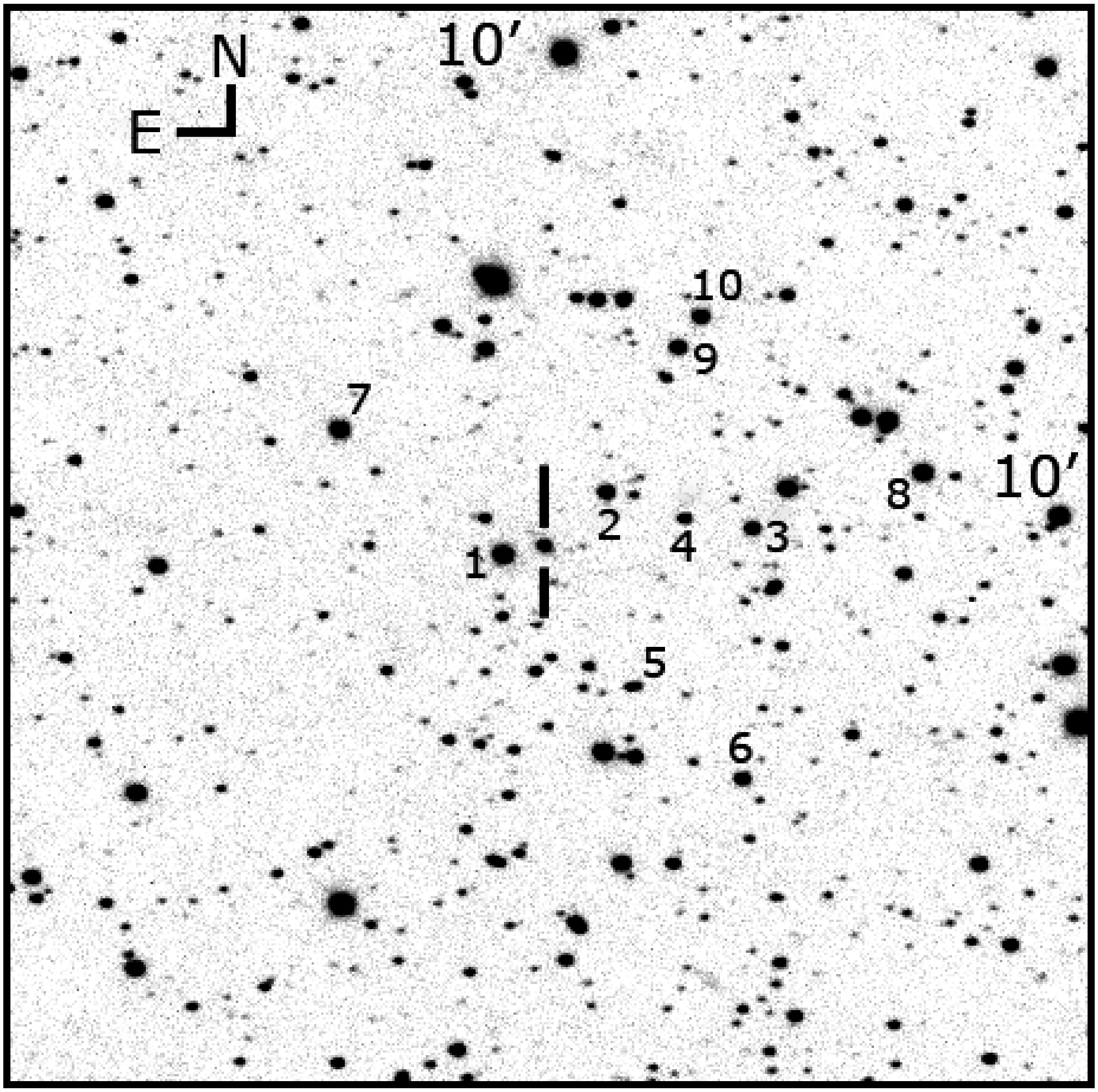

Figure A.2 BL Lac α = 22:02:43.29 δ = 42:16:39.98 (2000)

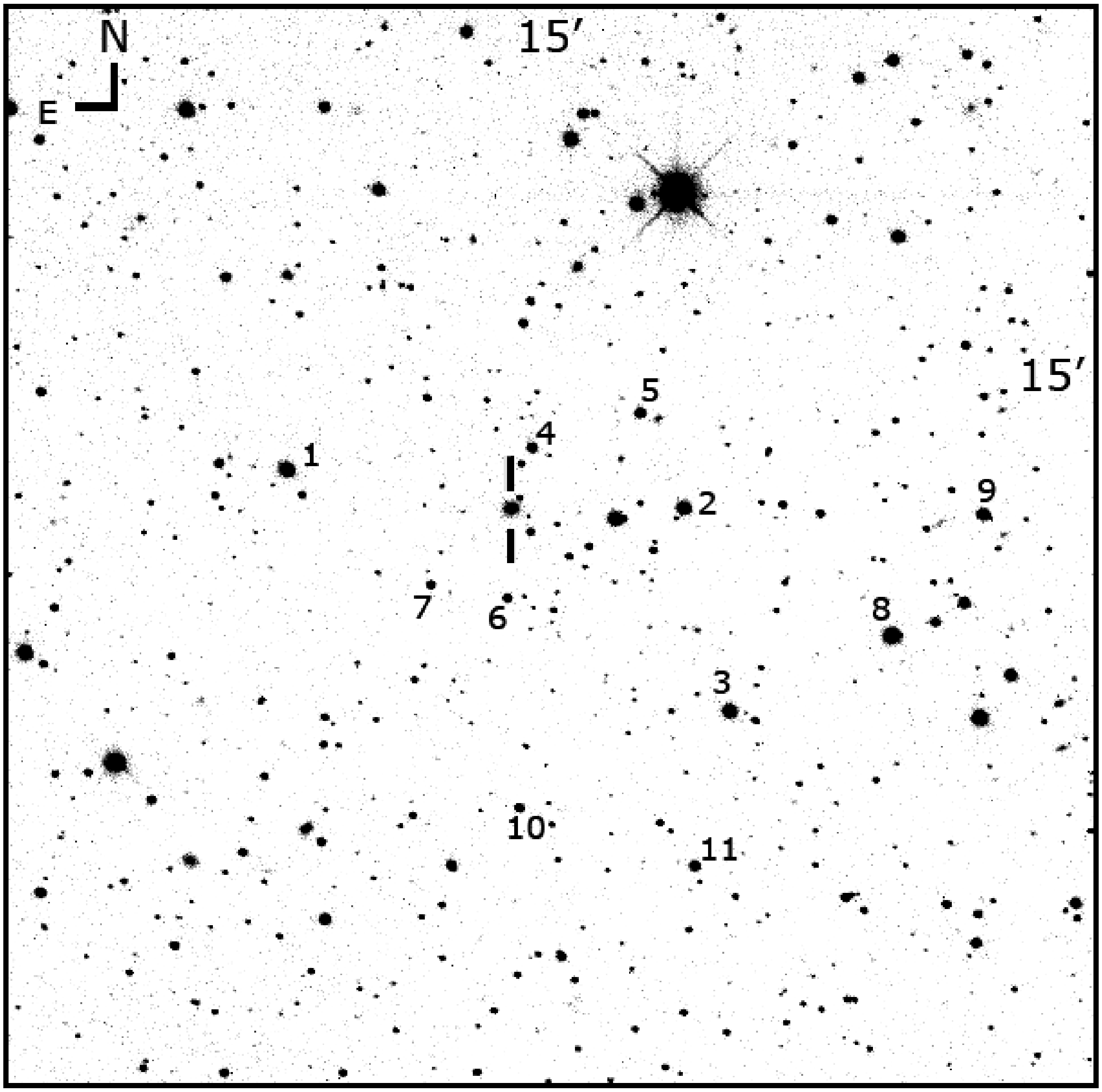

Figure A.3 1ES1959+650 α = 19:59:59.85 δ = 65:08:54.67 (2000)

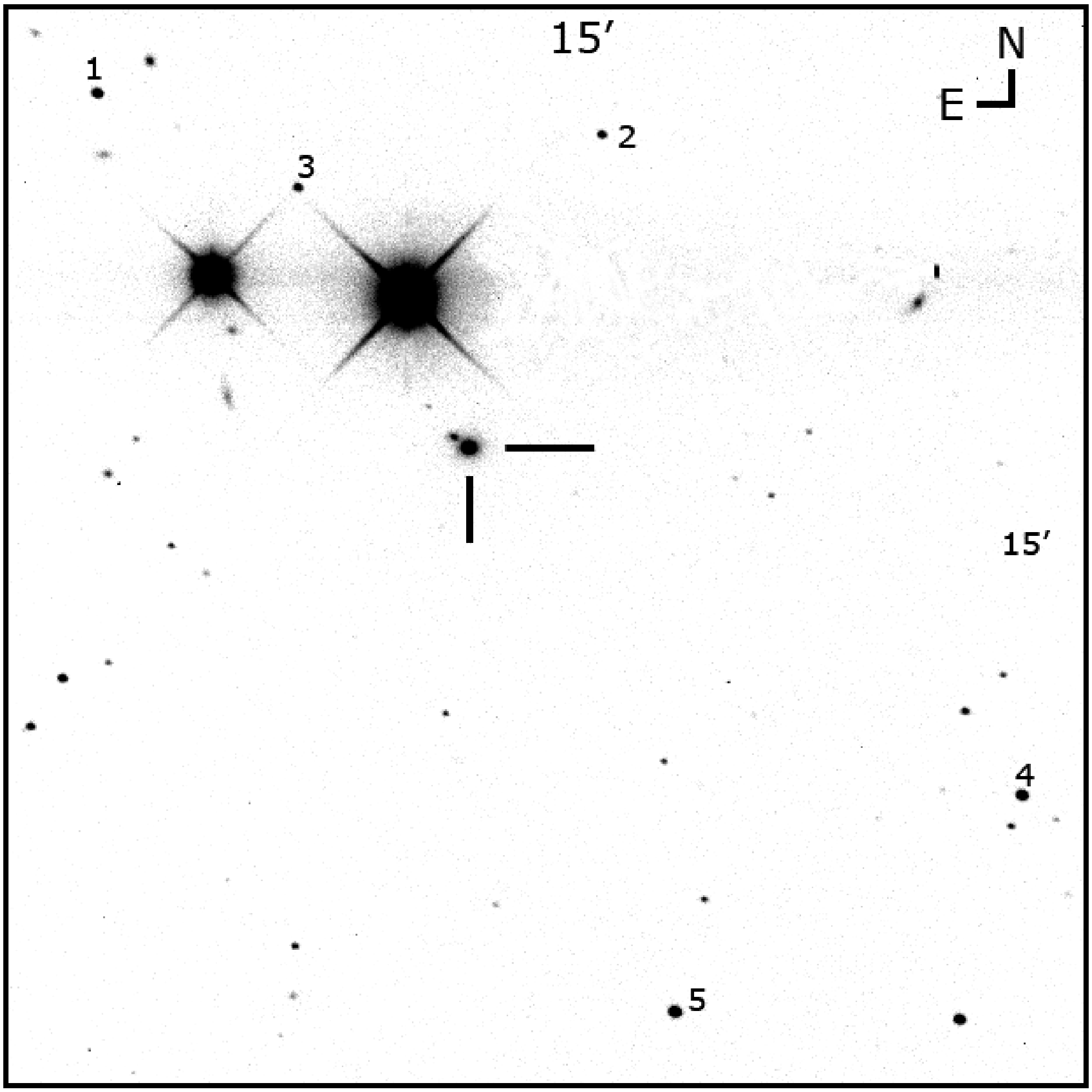

Figure A.4 MRK421 α = 11:04:27.2 δ = 38:12:32 (2000)

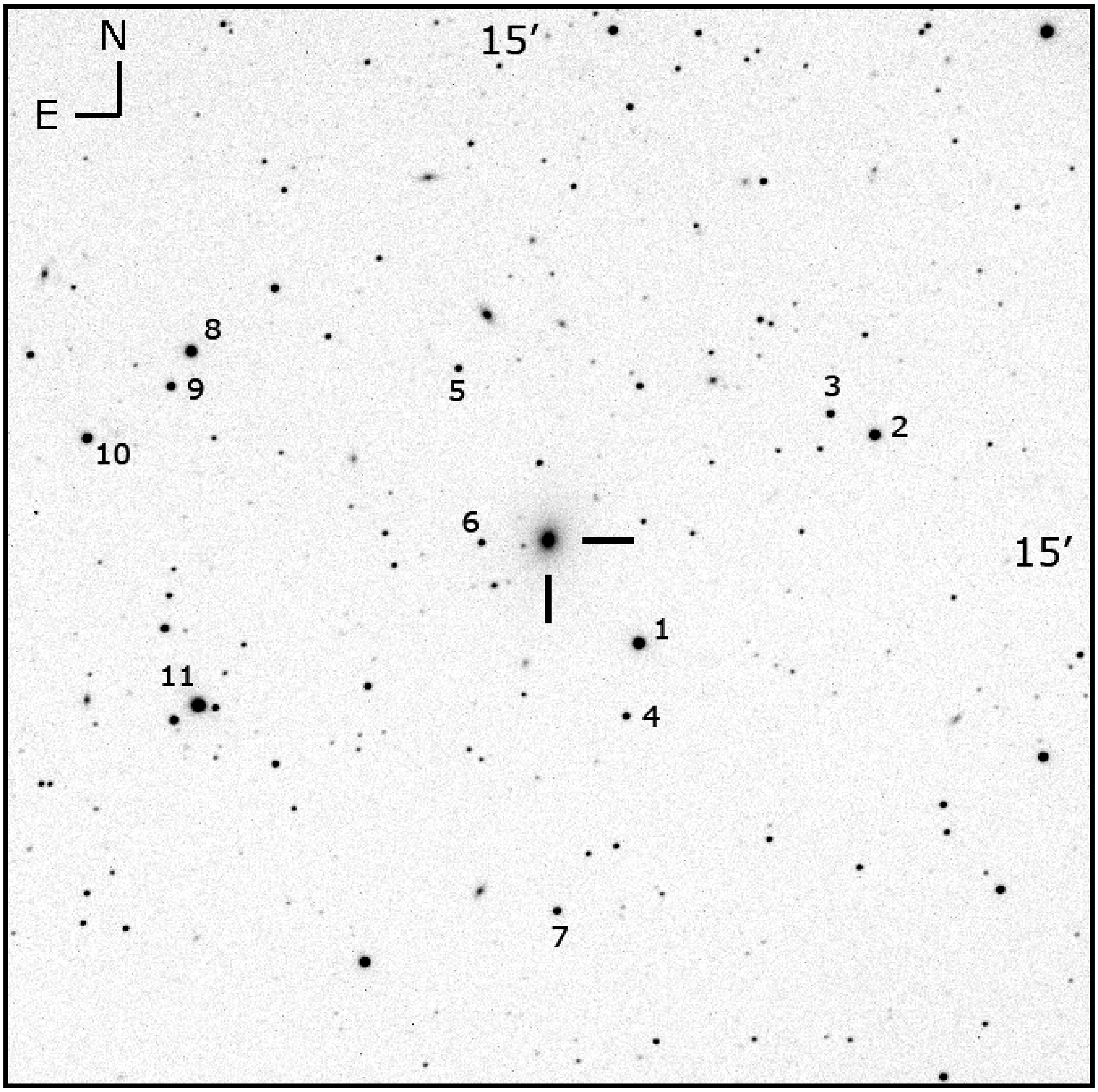

Figure A.5 MRK501 α = 16:53:52.13 δ = 39:45:36.2 (2000)

Index