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ESTABLISHING A LIST OF SOUTHERN HEMISPHERE BLAZARS FOR MICRO-VARIABILITY STUDIES

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ABSTRACT

We have constructed a list of southern hemisphere Blazars for inclusion in a comprehensive study into the nature of Blazar micro-variability. These objects were chosen following a specific selection criteria and utilizing the results of previous micro-variability studies. We have also included two sources that were previously observed by the FIU micro-variability group. We discuss the selection criteria and describe the sources eventually chosen for the list. We report previously unpublished observations of two of the sources chosen for the list and present new observations of one of the sources.

Subject headings: galaxies: active, blazars—quasars:photometry

1. INTRODUCTION

The Blazar micro-variability Program at Florida International University (FIU) has primarily been studying northern hemisphere Blazars from the Southeastern Association for Research in Astronomy (SARA) Observatory at Kitt Peak National Observatory since 2003. Blazars are extremely energetic quasars located at the centers of galaxies in which super-massive black holes reside. In-falling material creates an accretion disk which subsequently funnels plasma onto the black hole and into the relativistic jets that are accelerated along the rotational axes of the black hole. These jets contain relativistic electrons and protons, as well as magnetic flux.

Blazars are a member of the larger class of active galaxies called Quasars (QSOs). There are different categories of Quasars depending on the R, ratio of radio (5 GHz) to optical (440nm) flux densities. Radio-loud quasars (RLQSOs) and BL Lacs have an R>1. These objects tend to be highly polarized and feature a flat spectrum. Blazars are a sub category of radio loud QSOs which consists of very optically active RLQSOs and BL Lacertae objects (BL Lac). There are also two sub-groups within the BL Lacs; radio selected BL Lacs (RBLs) and X-ray selected BL Lacs (XBLs). These objects are sometimes called Type I quasars. Many years of multi-frequency studies indicate that Blazar jets are oriented with a small angle relative to the observer; in essence we are looking within a few degrees of the jet axis. The relativistic jets are thought to be accelerated by conversion of rotational energy of the black hole to kinetic energy of the particles which are collimated by powerful large-scale magnetic fields. Although the jets are optically unresolved, the spectral energy distribution indicates they emit optical radiation primarily by the synchrotron process. Since the synchrotron flux dominates the spectrum in the optical, the jets are thought to be the source of the optical flux variations we observe. There are four main observational characteristics that define Blazars as a class of objects: 1. They are active galaxies with intrinsically bright and unresolved nuclei. 2. They exhibit high amplitude optical variability over multiple timescales. 3. They are extremely luminous at all wavelengths of the electromagnetic spectrum with a power-law spectrum. 4. Their optical continuum is highly polarized.

Blazar variability falls into three major categories: long-term variability, short-term variability and micro- or intraday variability. Long-term variability is defined as variations over time scales of a year or more while short-term variability is commonly associated with high amplitude outbursts that occur on timescales of a few weeks to months. Micro-variability, which is the focus of this research, is defined as rapid time-resolved variations over timescales of hours to minutes (Dhalla et al. 2010). Various subgroups of QSOs are thought to have very different duty cycles (Romero et al. 1999). The duty cycle is simply defined as the fraction of time the source displays micro-variability divided by the total time observed and will be discussed in detail in §2.

Previous FIU research has mainly focused on the Blazar sub-class and looked for micro-variability in northern hemisphere objects. The FIU Blazar gorup has taken a two-pronged approach: monitoring optical micro-variability (sometimes referred to in the literature as intra-night variability) and general monitoring at different frequency bands to characterize longer timescale variations and color changes. The FIU study resulted in the creation of a new model for the physics behind the observed micro-variability (Webb et al. 2010).

Although many observations and major research programs have been conducted on northern hemisphere Blazars, few studies have been done on Blazars visible only from the southern hemisphere. The acquisition of a telescope in the southern hemisphere by SARA has opened up new possibilities for extending the Blazar micro-variability work to these previously poorly studied sources. Compiling a list of southern hemisphere

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objects to include in our study is important for several reasons. The first is efficiently utilizing the SARA South telescope. Secondly, we are now capable of simultaneous monitoring of mid-declination objects from both SARA North and SARA South to rule out variations induced by atmospheric turbulence and equipment instability in addition to obtaining simultaneous high time resolution color changes in the mid-declination sample. Finally, we are increasing our sample size by a factor of two and adding some new very interesting sources.

Romero et al. (1999) and Romero et al. (2002) conducted some preliminary studies of southern hemisphere Blazars with the 2.15-m CASLEO telescope at El Leoncito, San Juan, Argentina. These studies were focused on measuring the duty cycles in a large sample of quasars. The duty cycle is defined as the fraction of time spent in the "on" state divided by the total fraction of time observed. The "on" state is defined when the single nights observation shows variations of 0.1 magnitudes during the course of the night. Equation 1 gives the simple definition of the duty cycle (DC):

$$DC = \frac{\tau}{T} \tag{1}$$

where τ is the total amount of time source is exhibiting micro-variability and T is the total time spent observing source. Romero et al. (1999) altered the definition of the DC intending to correct for different observation lengths and their formulation is given as:

$$DC = 100\frac{\Sigma_{\text{ı}=1}^{n} N_i(1/\Delta t_i)}{\Sigma_{\text{ı}=1}^{n}(1/\Delta t_i)} \tag{2}$$

where $\Delta(t_i) = \Delta t_{i,obs}\ (1+z)^{-1}$ is the duration corrected for the redshift. The value of N_i is 0 if the object is non-variable and 1 if it is variable (Romero et al. 1999). This formulation gives significantly different values for the DC than equation 1 when the observing times were of unequal length for different observation periods. For consistency we will refer to the DC defined in Equation 2 since our objects were chosen based on the (Romero et al. 1999) paper.

Early studies of northern hemisphere quasars indicated a difference in duty cycles between RLQSOs and Radio Quiet QSOs (RQQSO)(Romero et al. 1999). Observations of RQQSOs imply that these sources do not eject strong relativistic jets so the optical variability is most likely due to in-homogeneities in the accretion disk. Theoretical models imply that RQQSOs should have significantly lower DC compared to RLQSOs Blazars since their emission is dominated by the more stable disk. Romero et al. (1999) observed a list of twenty-three southern QSOs that contained RQQSOs, RLQSOs and Blazars. RLQSO's showed micro-variations 60% of the time while no micro-variability was detected in any of the RQQSOs. Of the radio selected objects, 67% of the radio loud objects showed micro-variability. For the three XBLs chosen, one (2155-304) showed micro variations.

Romero et al. (2002) then studied twenty gamma-ray Blazars that were detected by the EGRET telescope on the Compton Gamma-Ray Observatory. Overall results of micro-variability showed DCs of 71.5% for the RBLs and RLQs, 27.9% for XBLs and only 2.7% for RQQSOs (based on Equation 2). These results correlate with previous results where the highest percentage of duty cycles falling under the RLQ and RBL class. These results were verified by (Cellone et al. 2000), who take into account minor seeing fluctuations, contaminants such as light from the host galaxies, and instrumental effects. The Romero publications also gave extensive backgrounds on most of the objects, including finder charts, comparison star sequences, and photometric light curves. From the total of 40 objects in their lists, 50% were RLQ, 22% RBLs, 20% RQQs and 8% XBLs.

In §2 we will present a table of the southern hemisphere objects chosen for our program and discuss the background information for each object. We also outline the criteria which we used to choose the sources and then present a brief summary of observations already made at SARA north (Kitt Peak Observatory) and SARA south (Cerro Tololo) for four of the objects that we included on our list. In §3, we present new observations of five of the objects chosen for our list during the past summer. Section 4 contains a brief discussion of the underlying model of optical micro-variability. We summarize the work in §5.

2. SAMPLE AND OBSERVATIONS

We decided on five criteria for choosing the sources to be included on the FIU/SARA Blazar micro-variability program: 1) They must be located between declinations $-90°$ and $0°$, given the location of SARA south (-04 43 15 (hms) West, -30 09.9 (dm) North), 2) They must fall into categories of RBLs and RLQs to have a high probability of displaying micro-variability based on previous observations, 3) Objects must to be spread out over right ascension in order to have availability of at least one Blazar throughout the year, 4) Visual magnitudes should be on the order of 17 or brighter, 5) All of the objects selected need to have finder charts and calibrated comparison stars. Once the objects were chosen, finder charts from several sources including the NASA Extragalactic Database (NED), SIMBAD Astronomical Database, and the Extragalactic Astrophysics web pages at Heidelberg University (http://www.lsw.uni-heidelberg.de/projects/extragalactic/charts/) were found and cataloged. The sample is presented in Table 1 where we list the object name, the coordinates (RA and DEC) at epoch J2000.0, magnitude in visual (V) band, the name of source in the Third EGRET Catalog name, and the redshift. This list, while not forming a complete sample, will allow observers at FIU to be able to observe at least one object on any night of the year with a high probability of seeing micro- variations in the resulting light curve.

2.1. *Individual Sources Selected*

Our sample consisted of thirteen sources, eight of which were radio-BL Lacs and five were radio-loud quasars. Within the thirteen objects there were six gamma-ray Blazars. The average magnitude of these objects was 16.5. There were gaps in right ascension between 07:00-10:00 hours, 17:00-20:00 hours, and 22:00-24:00 hours due to various reasons including the location of the galactic plane. The average redshift of the group was approximately 0.55. Both 1510-089 and 1622-297 were already monitored at FIU, but were not included in the previous

TABLE 1
List 13 Southern Hemisphere Blazar Object

Number	Object	α	δ	m_v	Type	EGRET Name	z
1	PKS 0521-365	05 22 58.0	−36 27 31	14.5	RBL	J0536-3626	0.055
2	PKS 0537-441	05 38 50.4	−44 05 09	15.5	RBL	J0541-4402	0.894
3	PKS 0637-752	06 35 46.5	−75 16 16	15.7	RBL	···	0.065
4	PKS 1034-293	10 37 16.1	−29 34 03	16.4	RLQ	···	0.312
5	PKS 1144-379	11 47 01.4	−38 12 11	16.2	RBL	···	1.048
6	PKS 1253-055	12 56 11.2	−05 47 22	17.8	RLQ	J1255-0549	0.538
7	PKS 1334-127	13 37 39.8	−12 57 25	17.2	RLQ	J1339-1419	0.539
8	PKS 1349-439	13 52 59.6	−44 13 25	16.4	RBL	···	0.050
9	PKS 1510-089	15 12 50.3	−09 06 00	16.5	RLQ	J1512-0849	0.361
10	PKS 1519-273	15 22 37.7	−27 30 11	17.7	RBL	···	1.294
11	PKS 1622-297	16 26 06.0	−29 51 27	20.5	RLQ	J1625-2955	0.815
12	PKS 2005-489	20 09 25.4	−48 49 54	13.4	RBL	···	0.071
13	PKS 2254-204	22 56 41.2	−20 11 40	16.6	RBL	···	···

micro-variability study. Below are summaries of each object from previous and current studies:

0521-365: The radio source was identified optically as an active elliptical galaxy by (Bolton et al. 1965). PKS 0521-365 is one of the brightest radio sources in the sky at 2.3 GHz (Wall 1994). VLBI images show that the compact radio source has a jet-like component that extends north-west at a position angle of ∼310°. It is known as an active radio source, located in an elliptical galaxy (Romero et al. 1999). The jet has been attributed to shock-in-jet-model. It was known to show variability in Romero study from December 1989-April 1990. It also has an asymmetric radio structure (Danziger et al. 1979). This source is also an EGRET gamma-ray Blazar.

0537-441: $VBLI$ observations suggest a compact core with jet-like component extending towards the north at a position angle of 3°. It is sometimes classified as a highly polarized quasar. Micro-variability was confirmed in this source by (Romero et al. 1999), with amplitude of 7.7%, on 12/21/97-12/22/97. It was also noted as one of the most variable sources in the Romero et al. (2002) study. The intra night duty cycle was ∼58.2%, while the internight was 81.6%. Multi-frequency campaigns were conducted by groups using ROSAT, Einstein, and EXOSAT x-ray telescopes (Tanzi et al. 1986). It is violently variable and thought to be gravitationally lensed. It is highly variable at large frequencies and the source is bright at 352 GHz. It also seems to transition from BL Lac to quasar (Tornianinen et al. 2005). It is a compact EGRET (gamma-ray) object.

0637-752: This object is a strong flat-spectrum source. It shows a compact radio structure with a prominent jet lying at approximately 90°. This object was deemed non-variable according to the Romero et al. (1999) study, from observations on 12/21/97-12/22/97. This object was also imaged with the Spitzer Space Telescope using the IRAC camera which confirmed the synchrotron nature of the radio-optical continuum (Uchiyama et al. 2005).

1034-293: This Blazar was deemed to be non-variable in the Romero et al. (1999) study. PKS 1034-293 has a variable flux density between 1.0 and 3.0 Jy (Shen et al. 1998). Object is known to have longer internight variability (Chudczer et al. 2001).

1144-379: Known to be a highly variable source, it has been observed in radio frequency bands at 13 cm and 6 cm. It has been confirmed to be a BL Lac object because of its rapid radio variability, its infrared, optical and featureless power law index of 1.5 (Nicolson et al. 1979).Source has an average magnitude of ∼17.7. It was observed to display micro-variability on March 1984-April 1985 (Bozyan et al. 1990).

1253-055: Also known as 3C 279. It is widely studied source. It was first identified by (Sandage & Wyndham 1965) as an optically violent variable (OVV) quasar at redshift $z = 0.538$ (Webb et al. 1990). It is known to emit gamma-rays, and have major flaring episodes. It has been observed by the MAGIC telescope (Aleksic et al. 2011). This sources was the first object to show superluminal motion (Li et al. 2009).

1334-127: ($z = 0.539$) was classified as a highly polarized quasar by Impey and Tapia (1988). It is also a EGRET source and has a flat radio spectrum in the radio to millimeter range (Lister et al. 1998). The source is very bright up to 352 GHz (Tornianinen et al. 2005).

1349-439: This Blazar is a low latitude, radio source with a compact structure. It has a high degree of polarization (Impey & Tapia 1988), and is observed at $V = 16.37$, $B - V = 0.58$, and $U - B = -0.54$ (Veron P. 1996). Featureless spectrum indicates its a BL Lac object. This source has a companion that is radio-quiet which is located only 0.7 arc minute south of the main blazar (Veron P. 1996).

1510-089: Although this source was identified as non-variable according to both Romero papers, recent observations done by FIU group showed marginal micro-variability in several cases (see section 3). It showed an average magnitude of approximately 13.29. This object is also an EGRET gamma-ray blazar, and X-ray variable. It is an extreme blazar in all wavebands. Object was observed over three epochs at 8.4 GHz. The core flux density varies of about 50%, while the scatter in the jet flux density is within 10%. The jet and core components polarization fluctuate from 2%-9% (Orienti et al. 2011). A 15 year light curve was constructed, showing a highly active blazar (Xie et al. 2008).

1519-273: Observed to be an intraday variable source, it also shows strong variability in circular and linear polarization. The polarization has been noted to vary on timescales of hours to days at frequencies of about 1.4 and 8.6 GHz (Macquart et al. 2000). It was noted to be variable, with amplitude of 3.3% as measured on 9/97 by Romero et al. (1999). Observations showed that interstellar scintillation were the cause of the inter-day radio variability (Carter et al. 2009).

1622-297: This is a flat spectrum radio QSO. Object is known to be a weak X-ray source. X-rays are probably produced via inverse Compton process (Meyer et al. 2008). Object was also observed via Compton gamma-ray observatory and at Cerro Tololo Inter-American observatory and is known to show gamma-ray variations on an intra-day basis. SARA South will be obtaining a more sensitive CCD camera on site within the next few months which should increase the S/N for this faint source and allow microvariability observations. Blazar PKS 1622-297 was included on the list although its average magnitude is very faint because of its extremely interesting gamma-ray flares and the fact that it has been observed at SARA north for a number of years.

2005-489: It was initially discovered as a strong radio source in the Parkes 2.7GHz survey (Wall 1975). This object is one of the brightest and contains the highest frequency peaked BL Lac objects in the southern hemisphere. Multi-year studies have shown large flux and spectral variations in the X-ray region (Kaufmann 2009). Multiwavelength monitoring campaigns of PKS 2005-489 have discovered a complex flux and spectral variability. This variability fluctuated from timescales from days to minutes (Rector 2002).

2254-204: This object was declared variable according to the Romero papers with amplitude of 3.3%. It is a BL Lac object and exhibits variability at high frequencies. It also exhibits variability at low frequencies and the spectrum is flat and inverted during short-term flares (Tornianinen et al. 2005).

2.2. *Summary of existing SARA Observations*

The FIU Blazar group has previously observed PKS 1510-089, PKS1622-29, 2005-489, and 1519-273. PKS 1510-089 has been observed on a total of ten different nights, but only five nights had a sufficiently long observation period to allow us to look for micro-variability. Micro-variations were marginally detected on two out of five nights. Average magnitude was approximately $R = 16.4$, representing a duty cycle of 23% according to Equation 2. We need many more micro-variability observations in the future to more accurately determine the duty cycle.

Gamma-ray Blazar 1622-29 has been observed on numerous occasions from SARA since 1995. It was initially observed because of intense gamma-ray burst that was seen by EGRET gamma-ray telescope where it increased in flux by a factor of 5 (Maddox et al. 1997). During the gamma-ray burst it brightened in the optical by nearly three magnitudes. It is normally very difficult to obtain high quality photometry because it is generally extremely faint ($R \sim 18$ mag.) and it is in a very crowded field with near-by stars (∼6 arc sec. north) are so close that the photometric apertures for the object and the sky must be chosen very carefully for each image. In total, we have observed this source 27 times since 1995 and we re-reduced and calibrated those historical images for this paper. The full 15-year light curve for PKS 1622-297 is presented in Figure 1. There is significant optical variability in the light curve although it has yet be seen as bright in the optical as it was during the gamma-ray flare.

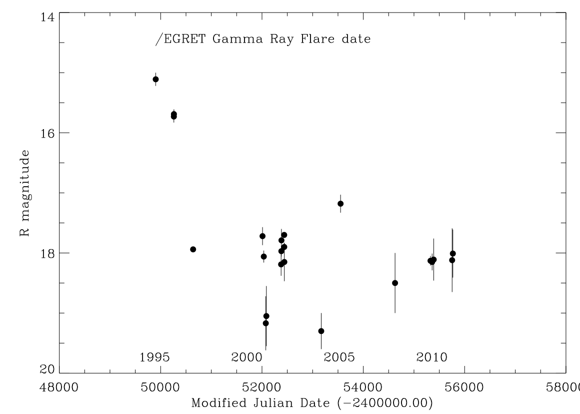

Fig. 1.— The long-term light curve for object PKS 1622-297. Some of the error bars are large indicating that the object was near the plate limit for those observations. The gamma-ray flare occurred at JD 2449894 (June 26, 1995). The source has never again been detected showing such a large gamma-ray flux.

3. NEW OBSERVATIONS

New observations were carried out at the Southeastern Association for research in Astronomy (SARA) Observatory at Kitt Peak National Observatory located near Tucson, Arizona and the SARA Observatory located at Cerro Tololo, Chile. The images were taken using the SARA 0.9m f/7 Ritchey Chretien telescope equipped with the CCD Apogee AP7 camera containing a SiTE chip. The objects chosen to observe were 1510-089, 3C 345, 1622-297, 2005-489 and 1519-273. They were observed in V, R, and I filter bands. Only observations with long enough duration were tested for micro-variability in order to insure that the variations are statistically significant, We also required high signal-to-noise before considering a detection as positive for micro-variability.

We observed 1622-297 on the nights of 7/10/2011 and 7/24/2011.The average R magnitude recorded was 18.07 ± 0.01. This object was too faint for micro-variability observations; the observation was mainly for monitoring the long-term variability (see Figure 1). Objects 1510-089 and 3C 345 were observed on June 1-June 4, 2011 on-site. The Blazar 3C 345 is part of the Northern sample we routinely observe in our micro-variability studies. Sky conditions were less than ideal on all nights. On July 10, 2011 clouds came in halting observations after midnight. 1519-273 was observed on 7/25/2011. 2005-489 was monitored again on the night of 7/25/2011. It displayed marginal micro-variability based on a statistical test first published by Howell et al. (1988). This test compares the variations in the target with those of the comparison stars, taking into account the different brightnesses and the CCD characteristics. Blazar 2005-489 was observed on 7/10/2011 and 7/25/2011 and it displayed an average magnitude of $R = 13.25$ on both nights. On the 25th, it displayed a small amount of micro-variability. Blazar 1519-273 was observed for only 1 night on 7/25/2011. It was very faint with an average magnitude of $R = 20.44 \pm 0.10$.

The most substantial data acquired were for PKS 1510-089. This source was bright enough to obtain reasonably high signal-to-noise micro-variability observations

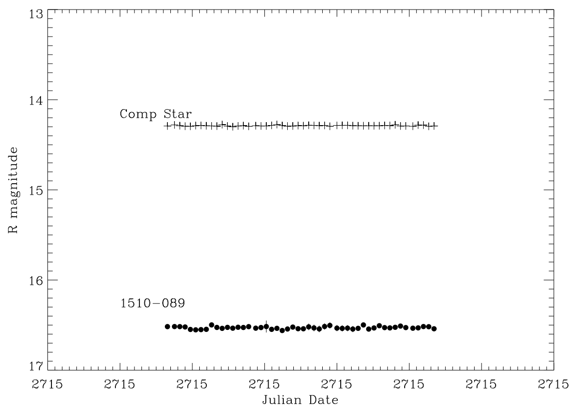

FIG. 2.— The light curve for object 1510-089 on 6-3-2011 that resulted from approximately an hours worth of monitoring. The Howell statistical test indicated that the light curve showed marginal statistical micro-variability. Bars indicate approximately 0.02 average errors for the magnitude. Average magnitude of the QSO was 16.53. For most of the objects the error bars are much smaller than the symbol of the blazar.

and the resulting light curves from the nights of June 3 and June 4 are presented in Figures 2 and 3 respectively. We used 3-4 comparison stars to establish our photometry. On both days the object displayed only marginal micro-variability.

4. DISCUSSION

The list of southern hemisphere Blazars will help further the study of the Blazar phenomena and the mystery that enshrouds them. Shocks propagating down the jets accelerate electrons which emit synchrotron radiation and are thought to be the source of the optical variations on micro-variability timescales (Romero et al. 2002). Results from previous studies at FIU for northern hemisphere objects have shown that micro-variability is not correlated with either the brightness of the source or the redshift. Evidence indicates that micro-variability is an intermittent phenomena and we have suggested a new model where micro-variations result when the shocks in the relativistic jets encounter turbulent cells (Webb et al. 2010). If the jet flow is laminar, then there are no cells, thus no micro-variations. By adding the southern hemisphere Blazars to our current observing list we will have a larger variety of objects from which to build longer micro-variability light curves and help to test the turbulent cell model. We will also extend on the previous work done on these southern hemisphere Blazars.

5. CONCLUSION

In this study we have constructed a list of 13 southern hemisphere Blazars, based on Romero et al. (1999) and Romero et al. (2002) and the FIU Blazar database. The FIU team has acquired telescope time at the SARA South telescope in Cerro Tololo and plans on utilizing that time to observe southern hemisphere Blazars, which have not been observed as much as their Northern hemisphere counterparts. In this study we have begun observations for objects on the list and have analyzed them for micro-variability, making two marginal detections of micro-variability in PKS 1510-089. We also observed objects PKS2005-489, PKS1519-273 and PKS1622-297

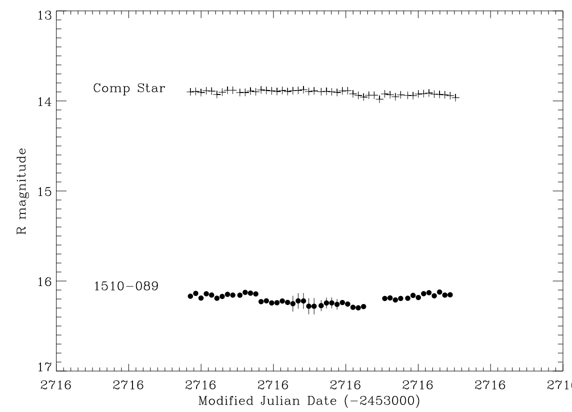

FIG. 3.— The light curve for object 1510-089 on 6-4-2011 over the course of an hour. No significant micro-variability is displayed here. Bars indicate approximately 0.02 average errors for the magnitude. Average magnitude of the QSO was 16.53. For most of the objects the error bars are much smaller than the symbol of the blazar.

and determined brightness levels for long-term variability studies of these objects.

The acquisition of the SARA South observatory at Cerro Tololo will help build the Blazar micro-variability database at FIU and keep the ongoing quest into the nature of micro-variability in Blazars moving forward.

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