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Coordinated Micro-Variability CIRCE Polarimetry and SARA JKT Multi-Frequency Photometry Observations of the Blazar S5 0716+71

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Abstract: A critical observation for testing the KRM jet model, in development at FIU, is to observe high time resolution, high accuracy photometry and polarimetry over a wide range of frequencies in the optically thin portion of the synchrotron spectrum. The detection of micro-variability during these observations would be ideal so the background and flaring components could be separated. Target of opportunity H-band photometry and polarimetry observations on the Gran Telescopio Canarias (GTC) 10.4-m with the Canarias InfraRed Camera Experiment (CIRCE) instrument were made in conjunction with the Southeastern Association for Research in Astronomy (SARA) JKT observing in the optical VRI bands in order to test the model. Here we present simultaneous micro-variability observations of Blazar S5 0716+71 made on 14 April 2017, with the CIRCE instrument on the GTC 10.4-m telescope and optical observations made with the 1.0-m SARA JKT in La Palma. The CIRCE observations consisted of high time resolution polarimetric observations in the H band over a period of 2.4 h on source, measuring both the H-band flux and the polarization degree and angle. Simultaneous observations with the SARA JKT 1.0-m yielded VRI light curves with about three minute time resolution over ~4 h. 0716+71 showed only small amounts of variability during the observation. We present here the resulting data and a comparison to previous observations.

Keywords: Blazars; micro-variability; optical astronomy; KRM jet model; relativistic turbulence

1. Introduction

Blazar S5 0716+71 is one of the most interesting blazars because its duty cycle for micro-variations is on the order of 80–90% [1]. Thus it is an obvious choice to observe with a large telescope. The intent of the observation was to observe micro-variations with not only unprecedented time resolution (on the order of seconds), but also to monitor the polarimetric and multi-frequency variability at the same time. The motivation for the observation is to test the KRM turbulent jet model under development at Florida International University (cf. [1,2]). Micro-variability is defined as small-amplitude (~0.1 mag), short-duration (<1 day) oscillations, which the model describes as being caused by a shock propagating down a turbulent jet. The KRM model is a two-zone, shock-in-jet model inspired by the work of Kirk, Reiger and Mastichiadis [3]. In the model, the shock front accelerates upstream electrons which cool downstream by emitting synchrotron radiation.

Micro-variability is explained by breaking the jet into turbulent cells with randomly directed magnetic fields, so that when a shock encounters a turbulent cell, the flux is increased. These temporary increases, during the encounter with the cell, are referred to as pulses or flares. The duration of a pulse is indicative of the size of the turbulent cell, and the amplitude is related to the density and magnetic field properties of the cell.

Several predictions of the model can be tested with multi-wavelength and polarimetric micro-variability observations. Solutions to the particle kinetic equations with synchrotron cooling allows us to predict the shape of a pulse emitted at a particular frequency as the result of the shock interacting with a turbulent cell. The pulse shapes are predicted to be different for different frequencies, inducing variability in the spectral index, and this provides a method to test the model if we can adequately observe micro-variations at widely separated frequency bands. As the model also predicts the direction of the magnetic field would be randomly oriented within cells, the strength of the synchrotron emission and the degree of polarization would be variable as well, and predictions on these variations would allow for further testing of the model.

The observations presented in this paper were planned for February, 2017, when 0716+71 would be placed optimally in the sky for long time series observations. The Florida International University (FIU) 24'' telescope was used to monitor brightness levels and the SARA JKT and SARA Kitt Peak telescopes were used to monitor the level of micro-variability activity before using time on the GTC 10.4-m. Unfortunately, all through January and February, the object went through a faint minimum, and attempts to detect micro-variability oscillations were fruitless. While the simultaneous CIRCE/JKT observation was postponed indefinitely, 0716+71 started to brighten in April, and the simultaneous observations were then scheduled.

2. Observations

We observed S5 0716+71 as often as possible from 4 December 2016 (MJD 7727, with MJD = JD – 2,450,000) through 20 May 2017 (MJD 7894) using the FIU 24'' and the two SARA telescopes at Kitt Peak and La Palma. The light curve presented in Figure 1 shows the brightness of the source decreasing from around $R = 13.0$ reaching a minimum of $R = 14.96$ on 20 January 2017 (MJD 7774). The black dots represent monitoring observations with red triangles indicating a failed attempt to find micro-variability; green triangles indicate when micro-variability was detected. We define microvariability as the presence of pulses or variations with the linear trend removed. The nights shown where microvariability was seen were marginal detections and therefore unsuitable for KRM fitting which needs distinct pulses for application.

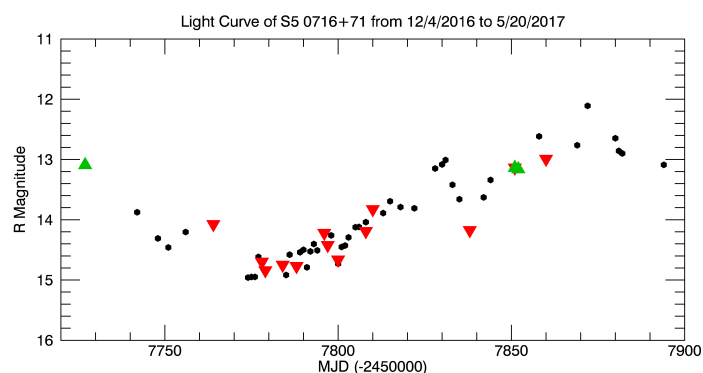


Figure 1. Light curve of S5 0716+71 from 4 December 2016 to 20 May 2017. Each black dot represents a night of observation. The green triangles represent nights with detected micro-variability while the red (inverted) triangles represent nights without.

Table 1 lists the micro-variability observations. Column 1 gives the calendar date while column 2 gives the MJD. Column 3 lists the observatory where the data was collected (“FIU” refers to Florida International University’s 24” telescope equipped with an FLI MAXCAM CCD and Johnson UBVRI filters. “SARA KP” refers to the SARA 0.9-m telescope at Kitt Peak National Observatory. “SARA JKT” refers to the 1.0-m Jacobus Kapteyn Telescope at Roque de los Muchachos Observatory on La Palma, Canary Islands). Column 4 gives the number of CCD images in the micro-variability observation and column 5 lists the results of the statistical test for micro-variability (known as the Howell test [4]). The V, R, and I average magnitudes and errors are shown in the final three columns of Table 1. The ⁺ symbol indicates a very weak detection of variability while the * denotes micro-variability pulses were visible in the light curve.

Table 1. The optical observations of S5 0716+71 from 4 December 2016 to 16 April 2017.

Date	MJD	Observatory	N _p	F-Test	Micro	V	R	I
4 December 2016	7727	SARA KP	90	3.5E9	Yes *	13.524 (0.003)	13.092 (0.002)	12.549 (0.002)
10 January 2017	7764	SARA JKT	105	5.208	No	14.454 (0.007)	14.074 (0.003)	13.525 (0.005)
24 January 2017	7778	FIU	180	0.8540	No	14.699 (0.036)	15.187 (0.068)	14.153 (0.023)
25 January 2017	7779	SARA JKT	393	5.0700	No	15.308 (0.007)	14.840 (0.005)	14.271 (0.010)
30 January 2017	7784	SARA JKT	187	0.3180	No	-	14.750 (0.006)	14.220 (0.010)
3 February 2017	7788	FIU	67	0.7320	No	15.251 (0.041)	14.770 (0.027)	14.264 (0.027)
11 February 2017	7796	FIU	200	1.002	No	-	14.220 (0.023)	-
12 February /2017	7797	FIU	99	1.1184	No	14.856 (0.048)	14.421 (0.033)	13.887 (0.025)
15 February 2017	7800	SARA KP	186	0.2329	No	-	14.663 (0.055)	14.067 (0.006)
21 February 2017	7808	SARA JKT	225	10523	No	-	14.19 (0.005)	13.604 (0.009)
25 February 2017	7810	SARA JKT	290	0.5330	No	-	13.826 (0.003)	13.306 (0.006)
25 March 2017	7838	SARA KP	110	1.1268	No	14.662 (0.004)	14.174 (0.004)	13.570 (0.004)
7 April 2017	7851	SARA JKT	96	0.4277	No –	13.137 (0.002)	13.160 (0.003)	-
8 April 2017	7852	SARA KP	63	15.918	Yes ⁺	13.601 (0.004)	13.160 (0.003)1	12.614 (0.003)
16 April 2017	7860	SARA JKT	94	0.9700	No	13.532 (0.003)	12.991 (0.002)	12.534 (0.003)

The low brightness levels during January and February of 2017 represented a “plateau” similar to those seen in 2003 and 2006, only at a much fainter base brightness level [5,6]. The earlier short-duration plateaus lasted only several hours, while the plateau we observed here lasted for several months. During this low period, fifteen micro-variability observations were made: nine showed statistical variability while six exhibited no signs of variability. Of the nine nights, only two nights showed actual micro-variability pulses in the light curves.

2.1. The SARA JKT Observation

A confluence of good weather and accessibility of both the GTC 10.4-m and SARA JKT telescopes occurred on the night of 16 April 2017. Since S5 0716+71 was only well positioned for the first half of the night, the total observing duration was only 3.61 h. Although the Moon was at 71%, it was more than 90° away in declination, and thus did not significantly affect our measurements. We took 320 total images with the SARA JKT telescope, 94 in the R-band sequencing between the V, R, and I filters. Each individual image was exposed for 30 s. The resulting time resolution, per frequency band, was about ~2.5 min after readout time and changing filters. Figure 2 shows the SARA JKT micro-variability light curve in the R-band. The photometry was calibrated with the Heidelberg comparison sequence using stars 3, 4, 5, and 6. Star 8 was used as a check star. The initial Howell test returned a positive result for micro-variability with an F-test for variability value of 3.285 (the critical value being 1.4), which indicates a 95% probability of variability, as is attested to visually in Figure 2. When the linear trend ($y = -0.1557x + 0.5848$, with an R^2 of 0.58) was removed, the Howell test returned a negative result for micro-variability. Thus, we did not observe the micro-variability pulses

that we were hoping for to test the model. While no pulses were seen, the light curve shows similar variations in all three frequency bands.

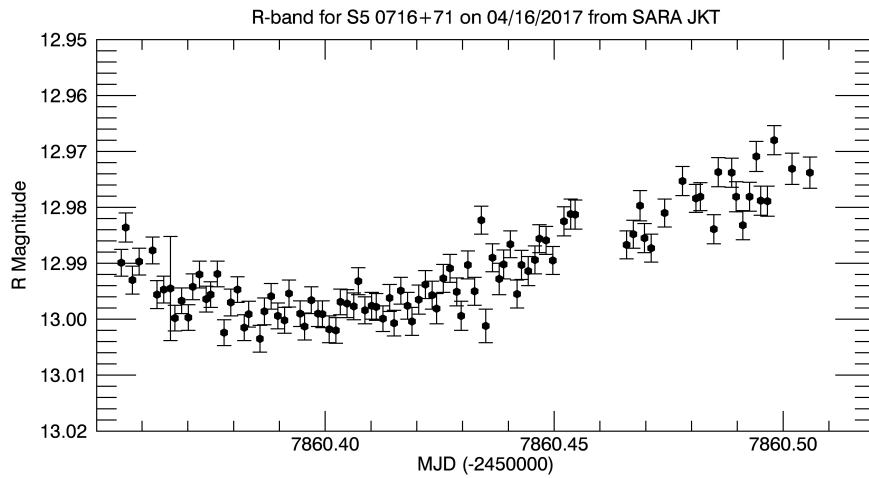


Figure 2. The light curve of S5 0716+71 in the R-band. Though some distinct short-term variability is present, no measurable pulses are seen.

The resulting VRI light curves are plotted in Figure 3, with the V magnitudes offset by -0.571 and the I magnitudes offset by $+0.04882$. The V and I data were much noisier than the R data. All photometry data presented in Figures 2 and 3 are differential and calibrated using the sequences found at the Heidelberg Blazar monitoring site.

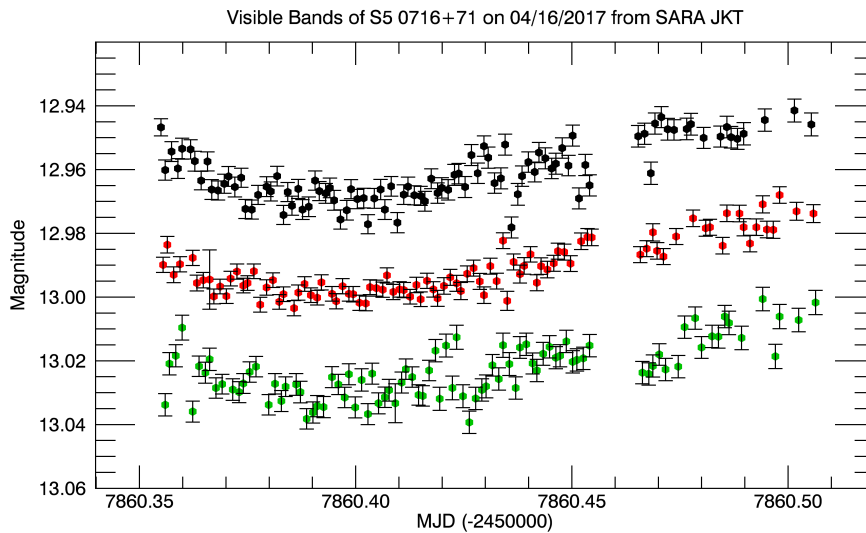


Figure 3. The SARA JKT observations. The V data (black) is offset by -0.571 and the I data (green) by $+0.04882$. Due to lack of substantial variability, the spectral index variability cannot be tested.

2.2. CIRCE Observations

The University of Florida's near-infrared astronomical imager, polarimeter, and spectrograph, CIRCE, was built for the GTC 10.4-m telescope [7]. CIRCE is a dual Wollaston Prism polarimeter which returns the linear Stokes parameters in a single image. The H magnitudes were calibrated with star 5 from the Heidelberg sequence. The H-band observations were taken at ~ 1 s time resolution and binned to about 45 s time resolution. The total observing duration was 2.365 h. Figure 4 shows the binned H-band magnitude light curve. Due to the beam splitting in CIRCE, the photometric

errors bars are larger than the SARA errors which did direct imaging. Both the polarization degree and the position angle were obtained with a frequency of about 1 per second. The binned polarization degree and polarization angle light curves are shown in Figures 5 and 6.

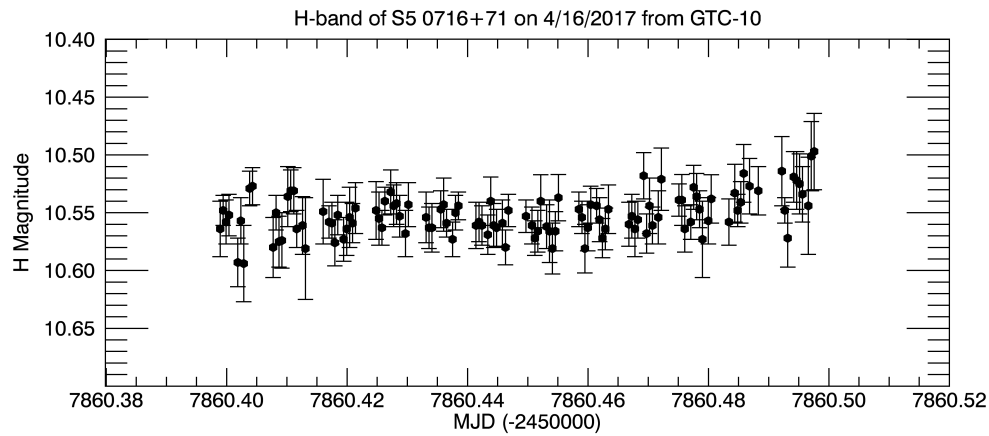


Figure 4. H-band magnitudes from CIRCE during the 16 April 2017 joint observation. The data showed a hint of an upturn at the end similar to that seen in the optical.

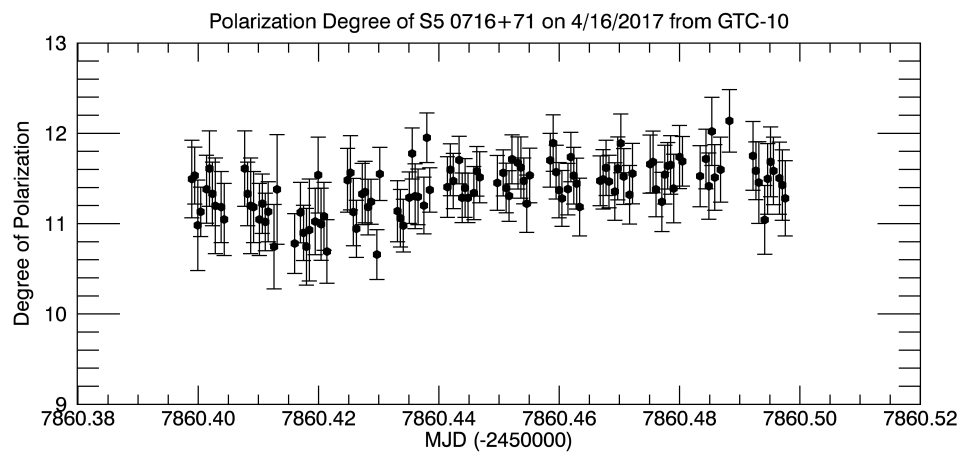


Figure 5. H-band polarization degree versus time showing possible increase with time.

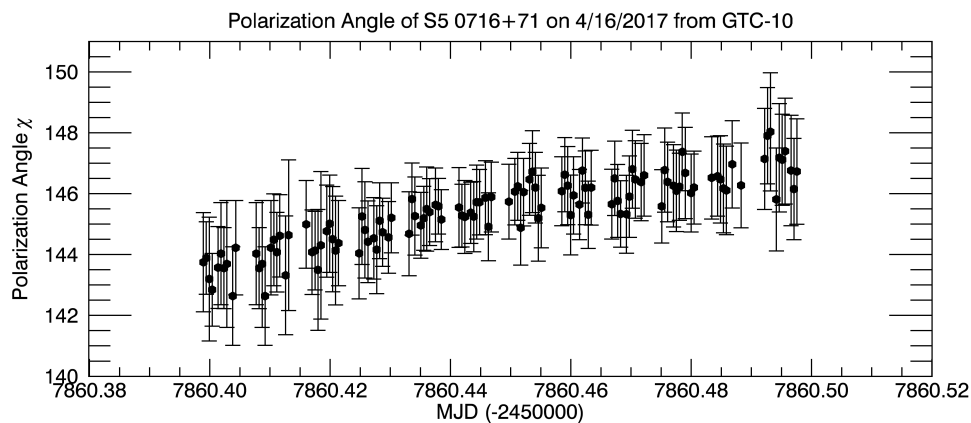


Figure 6. H-band polarization angle from CIRCE observations. The rise in angle may be due to an elevation angle effect as there wasn't sufficient time to calibrate for the effect.

2.3. Combined Observations

We have combined the CIRCE H-band and the SARA JKT VRI observations to evaluate the variability in 0716+71 for widely separated frequency bands along the optically thin portion of the synchrotron spectrum. Figure 7 shows the extension of the optical flux extrapolated into the IR from previous studies.

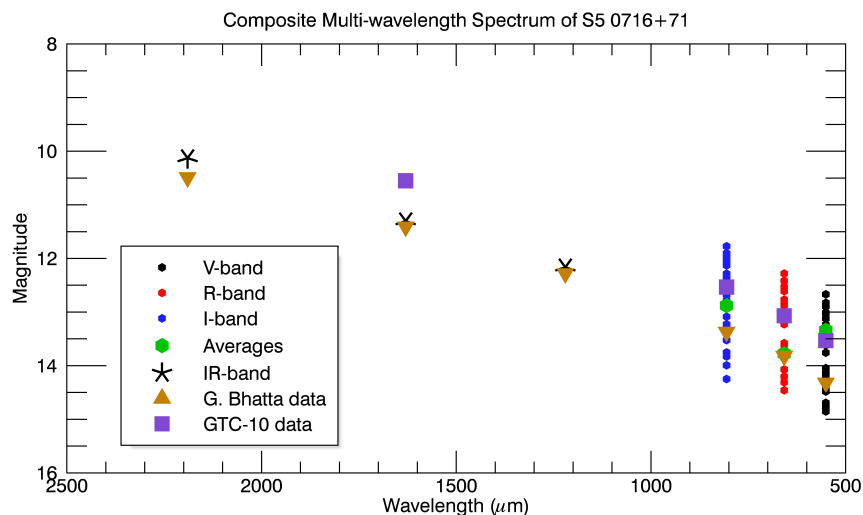


Figure 7. The composite multi-wavelength spectrum of 0716+71. The VRI data was taken by SARA telescopes. The G. Bhatta data and IR are from [2,6].

The vertical clusters of V, R, and I points show the entire range of variability we have observed in those frequency bands over the last 11 years, the green dots giving the average value for each band during this time. The resulting slope is -0.0021 with a $>98\%$ correlation coefficient. Bhatta et al. [6] found a similar slope of -0.0023 in the simultaneous WEBT data. Our best fit simultaneous VRIH data yields a slope of -0.0027 . If one looks more closely at the 16 April 2017 data, the VRI linear fit has a significantly different slope $\alpha = -0.0039$ ($R^2 = 0.996$) and, if extended, predicts a much brighter H magnitude (~ 9.3) than was actually observed ($H = 10.55$ (0.02)). Figure 8 shows the spectrum from the 16 April 2017 data only. The blue dot is the extrapolation of the linear fit for the VRI data. This data is truly simultaneous and implies either a down-curve in the spectrum between the H and I bands, or the existence of a broken power law. Further observations are needed to confirm which.

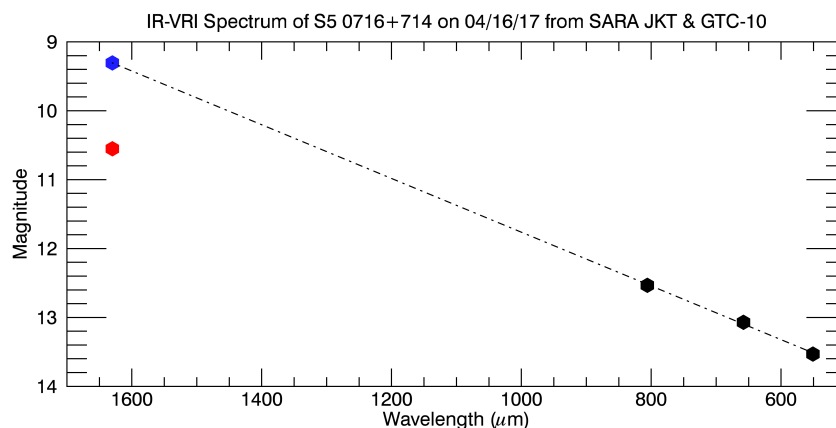


Figure 8. The VRI data (black dots) from SARA JKT averaged over the ~ 4 h observation. Can see comparison of extrapolated H magnitude vs. measured by CIRCE (red dot).

Figure 9 shows the scaled light curves plotted together so one can compare the time variability in each band. As in Figure 3, the V magnitudes were offset by -0.5712 and the I magnitudes by $+0.4888$. The H magnitudes were offset by $+2.55$. Note the GTC observations were started after the SARA JKT, due to calibration measurements after sunset for CIRCE. The SARA JKT started imaging precisely at evening twilight. The general shape of the light curves are all consistent with similar behavior throughout the evening.

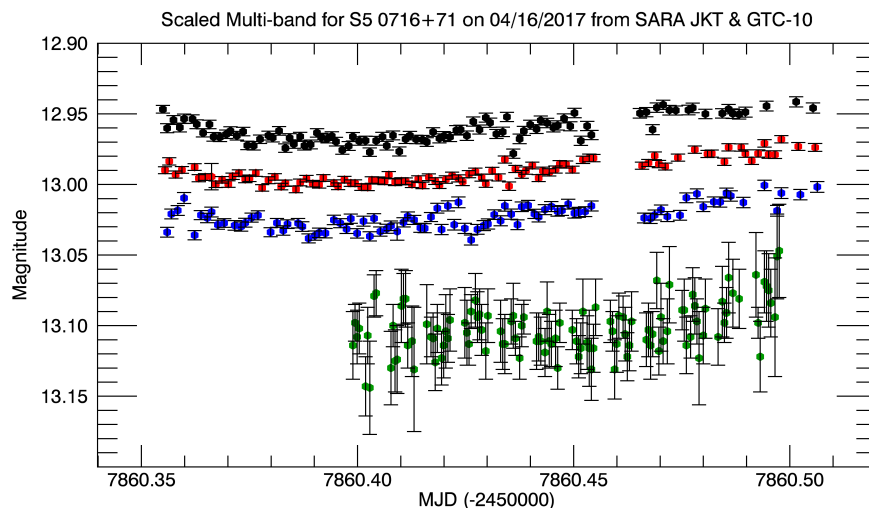


Figure 9. The composite light curve for all CIRCE-SARA data taken on 16 April 2017. All bands other than R were offset to fit easily together.

3. Discussion

We closely monitored the optical brightness of S5 0716+71 leading up to our simultaneous observation. Prior to the GTC observation, the object went through a minimum “plateau” that lasted for several months. We observed it at $R = 14.96$ (0.04) on 20 January 2017, which was maintained for over a month, until 31 January 2017. This behavior is similar to the “plateaus” discussed in [6] but over a much longer time period, and 0.7 magnitudes fainter. Several micro-variability observations were made during this time, but the source was very stable. The two micro-variability detection’s on 25 January 2017 and 15 February 2017 showed only marginal variability. The object started recovering on 16 February 2017 and continued to be very active on a night-to-night basis, peaking above 13th magnitude before falling back down to $R = 14.1$. On 15 April 2017, it then rose again to $R = 12.61$, the night before our simultaneous observations. The object would continue to brighten following our observations, reaching a brightness of $R \sim 12.1$ on 9 May 2017.

The optical polarization was measured at 9.21% (0.09) by the Boston group [8] on 26 January 2017, with an electric vector angle of $-54.91(0.3)$ degrees. The lowest percentage of polarized flux was 4.43%, occurring on 13 March 2017. The 16 April 2017 observation showed a polarization degree of about 11.3% with an angle of ~ 145 degrees. As can be seen in Figure 1, the simultaneous observations were made when the object had dropped 0.38 magnitudes from a local maximum. Table 2 summarizes the polarization data gleaned from the literature as well as the data presented here.

Table 2. Polarization Data Summary.

Group	Date	Band	Magnitude	Polarization Degree (%)	Polarization Angle (°)
Sasada (2008)	October 2007	V	12.6–12.7	27 (5) Bump 9.8 (0.5) Bckd	0–180 Var
Bhatta (2015)	March 2014	R	13.5–14.0	40–60 Var	10–20 Var
Marscher (2017)	April 2017	R	14.82	9.21	−54.95
This Work	April 2017	R	13.00	-	-
		H	10.55 (0.02)	11.3	145.4

In both [2,9], distinct events were seen in the micro-variability curve. The flare components were analyzed, separating them from a background component. It was found that the flare seemed indeed to have different polarization properties, indicating a small sub region of the jet is responsible for the flare or bump. Unfortunately our data did not show a flare or bump so we are unable to separate out the two components. Due to the lack of variability, and a comparable polarization percentage to those of the other observers, the H-band polarization is similar to the background component seen in the other studies. The idea, then, is that in the absence of micro-variations, the background jet has a rather consistent polarization degree over the optical IR region of the spectrum. In the KRM model, this is explained as laminar flow in the jet. The polarization degree changes significantly during a pulse or bump, indicating the presence of a cell or enhancement that could have vastly different properties from the background. The unchanging background polarization degree and angles are consistent with the KRM jet model, but unfortunately does not supply the critical test we had hoped for, since no pulses we observed during the observation so we could effectively separate out the pulse component.

The extrapolation of the optical VRI power-law spectrum did not match the H-band observed. This could mean either there exists a broken power law, with two different spectral indices, or the presence of significant spectral curvature. Although this behavior was not seen in previous observations, this was the first truly simultaneous VRI and H observations to date.

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Author Contributions: James R. Webb, Nankun Ming, and Douglas H. Laurence are responsible for the acquisition and reductions of the SARA observations. Steven Eikenberry and Yigit Dallier are responsible for the acquisition and reductions of the CIRCE data. The synthesis was performed by James R. Webb.

Conflicts of Interest: The authors declare there are no conflicts of interest.

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