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14 YEARS OF PHOTOMETRIC MONITORING OF MM Dra AND A SUSPECTED VARIABLE IN THE FIELD OF BLAZAR 1ES 1959+650

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1 Introduction

Photometric monitoring of blazars is almost always carried out using the techniques of CCD differential photometry. This requires the availability of several stable, calibrated comparison stars in the same field of view as the blazar. During the course of our long term monitoring program of selected blazars, we have found that two previously published comparison stars for the blazar 1ES 1959+650, identified as star 3 and star 5 in the sequence of Villata et al. (1998), are variable.

Lee et al. (2000) identified star 5 (RA2000=$19^{h}59^{m}44\overset{s}{.}84$, DEC2000=$+65°10'7\overset{''}{.}4$) as an W UMa-type eclipsing binary known as MM Dra and initially estimated its period at 0.2644 days. A subsequent study by Bachev et al. (2011) refined the period of MM Dra to 0.26548±0.00001 days and noted the presence of the O'Connell effect. Star 3 (RA2000=$19^{h}59^{m}34\overset{s}{.}5$, DEC2000=$65°06'19\overset{''}{.}5$) was first identified as possibly variable by Doroshenko et al. (2007). Pace et al. (2013) also noted the possibility that his source was variable, though the nature of variability remained undetermined. In this paper, we present the results of 14 years of photometric monitoring of both stars with the telescopes of the WKU (Western Kentucky University) BCK (Bell, Crimea, Kitt Peak) network (McGruder, et al. 2015). Observations were obtained primarily in the R_C band, with intensive intra-night monitoring in the V and I_C bands also undertaken on several occasions.

2 Data

Observations were obtained using Western Kentucky University's BCK telescope network, which includes the 0.6 meter telescope at the Bell Observatory, located 12 miles SW of Bowling Green, Kentucky; the 1.3m Robotically Controlled Telescope (RCT) at Kitt Peak National Observatory (KPNO), and the 1.3m AZT-11 telescope at the Crimean Astrophysical Observatory (CRAO). The 0.6 meter Bell Observatory telescope was equipped with a thermoelectrically cooled 1024 × 1024 KAF 1000 CCD with Apogee Ap6ep electronics and a 10' × 10' field of view. The 1.3 meter Robotically Controlled Telescope

(RCT) at Kitt Peak, Arizona was equipped with a 2048 × 2048 pixel SITe CCD with a 9.6' × 9.6' field of view and cooled using a Cryotiger (cryogenic) compressor. The 1.3 meter AZT 11 telescope at the Crimean Astrophysical Observatory in Crimea, Ukraine was equipped with a thermoelectrically cooled FLI IMG1001E camera with 1024 × 1024 CCD with a 10' × 10' field of view. Observations fall into two categories: long-term nightly observations spanning 14 years for each target and short-term continuous observations spanning a few hours on select nights to detect and characterize any short term, intra-night variability.

2.1 Long Term Monitoring

Long term monitoring of both stars was undertaken at all three observatories of the BCK network. An observation log is shown in Tables 1 and 2. A finder chart showing the location of MM Dra, star 3 and the photometric comparisons stars used is displayed in Figure 1.

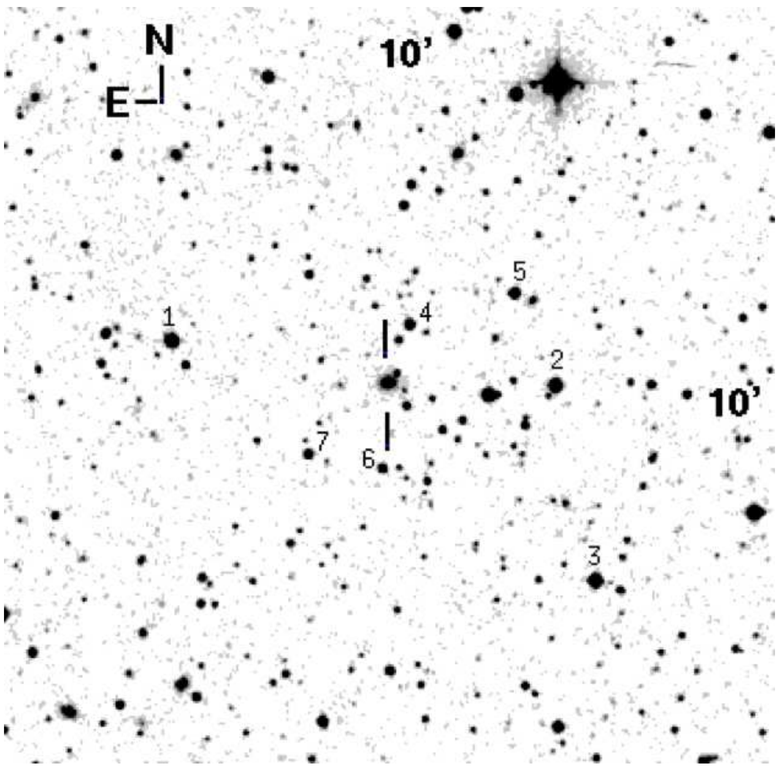

Figure 1. Finding chart for 1ES 1959+650, showing MM Dra (star 5) and star 3 from `https://www.lsw.uni-heidelberg.de/projects/extragalactic/charts/1959+650.html`

2.2 RCT Observations

The RCT observations were obtained in the R band with three consecutive exposures taken each night the source was observed from 2007 through 2014. Exposure times ranged from 90 seconds to 180 seconds; the exposure time was based upon the brightness level of the blazar since the original intent of the observations was to monitor the blazar. Each of the three exposures was flat fielded and bias corrected using IRAF. Differential aperture

Table 1: Table1. Observing log for MM Dra.

Year	Observatory	Filter	Number of observations
2001	Bell	R	21
2002	Bell	R	3
2003	Bell	R	18
2004	Bell	R	39
2005	Bell	R	57
2006	Bell	R	87
2007	Bell	R	36
2007	RCT	R	12
2008	Bell	R	3
2008	RCT	R	3
2009	Bell	R	24
2010	RCT	R	57
2010	CRAO	R	138
2011	RCT	R	192
2011	CRAO	R	42
2012	Bell	R	6
2012	RCT	R	96
2012	CRAO	R	93
2013	Bell	R	33
2013	RCT	R	153
2013	CRAO	R	24
2014	RCT	R	78

Table 2: Observing log for star 3.

Year	Observatory	Filter	Number of observations
2001	Bell	R	6
2003	Bell	R	3
2004	Bell	R	12
2005	Bell	R	9
2006	Bell	R	63
2007	Bell	R	39
2007	RCT	R	12
2008	RCT	R	3
2009	Bell	R	15
2010	RCT	R	57
2010	CRAO	R	141
2011	RCT	R	162
2011	CRAO	R	51
2012	Bell	R	6
2012	RCT	R	96
2012	CRAO	R	105
2013	Bell	R	84
2013	RCT	R	153
2013	CRAO	R	24
2014	RCT	R	78

photometry with a 5" aperture was performed on each exposure with respect to stars 1, 2, and 4 (Villata et al. 1998) to determine the R band magnitudes for MM Dra and Star 3 using the IRAF apphot package. The average of the magnitudes obtained from each of the three exposures was taken to determine final magnitudes for star 3 and MM Dra for each nightly observation.

2.3 Bell and CRAO Observations

The R band observations obtained at the Bell Observatory had exposure times ranging from 180 to 300 seconds, with three consecutive exposures obtained each night the blazar field was observed from 2001 through 2014. Three consecutive 180-second R band exposures were obtained using the Crimean telescope on each night it was observed. All exposures were flat fielded, dark subtracted and bias corrected using IRAF. Aperture photometry was used to extract magnitudes for MM Dra and Star 3 as described above for RCT observations.

2.4 Intranight observations

Continuous R, V, and/or I band exposures were obtained on several nights at the Bell Observatory. Each observing sequence lasted three to five hours. A log of these observations is presented in Table 3. Exposures were bias, dark, and flat field corrected and aperture photometry was used to extract magnitudes for MM Dra and star 3 as described above.

Table 3: Observing log for Bell Observatory sequences

UT Date	Filter	Exposure length (sec)	Duration (hours)
2003-09-16	V & I	180	4
2003-11-04	V & I	240	4
2003-11-14	V & I	240	3
2003-11-22	R	240	3
2004-09-22	R	180	7
2005-09-07	R	240	6
2005-09-10	R	240	4

3 Results

3.1 MM Dra

The light curve of MM Dra is presented in Figure 2. Data from the Bell Observatory are in blue, data from the RCT in orange and data from CRAO in purple. The total variability amplitude is 0.53 magnitudes. The phase curve, based on the period of 0.26547863d derived as described below, is shown in Figure 3.

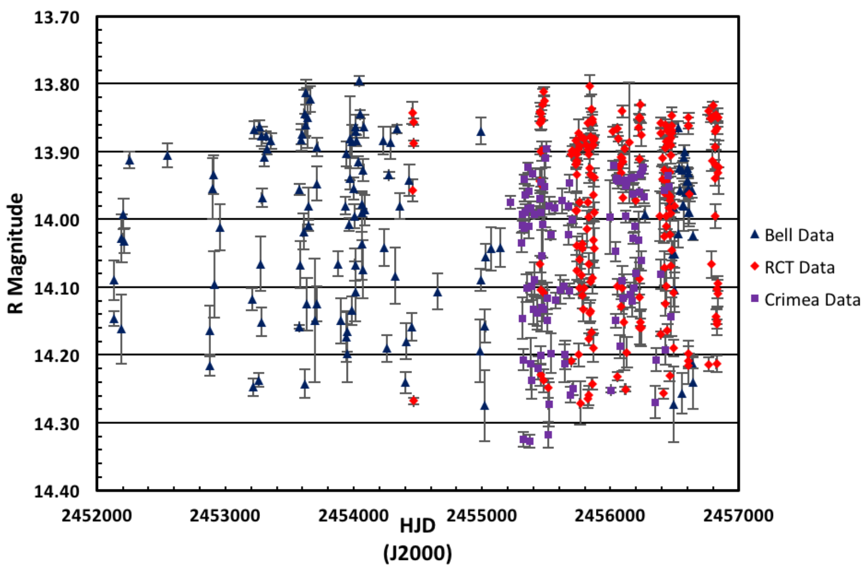

Figure 2. The long term light curve of MM Dra from 2000-2014.

A systematic analysis of the available data gives a period of 0.26547863± 0.0000003 days. Approximate determinations were made using full and quick Fourier methods together with phase binning, but the final value was refined by breaking the data into 1000-day blocks and minimizing phase shifts between blocks. Fourier fitting to the resulting light curve showed that a 6th order fit included only highly significant terms – higher order terms were not significant (less than 2 sigma). Systematic shifts were found in the R data from the three telescopes, with RCT data 0.011± 0.002 brighter and Crimea data 0.029 ± 0.008 fainter than Bell data. It was readily apparent that spurious points remained in the data, and in the end a 0.1 mag error cutoff was employed after phase shifting to a common zero point. This resulted in the elimination of 9 Bell data points, 9 from Crimea and 2 from the RCT. The eliminated points from Crimea in particular deviated significantly from the mean curve. Zero point shifts were then re-determined without the deleted data. This last correction was only about 0.001 mag, and did not affect the choice of 'outliers' to be deleted.

No spectroscopy is available for MM Dra. Given the colors from Huang et al. (2015) and the mean values for nearby stars given on the HST website[1], the VRI color indices for MM Dra suggest a spectral type of approximately K4V at primary minimum, allowing for a reddening of E(B−V) = 0.06 from Burstein and Heiles (1982). The dereddened VRI color indices at primary maximum suggest a type of K2V (Fig. 4). The $V-R_C$ and $R-I_C$ intensity means are 0.646 and 0.520, respectively, while the V, R_C and I_C intensity means are 14.649, 14.003, and 13.483. The dereddened V magnitude is 14.49, which suggests a distance modulus (Mateo and Rucinski 2017) of roughly 8.9 ± 0.3 or a distance of roughly 600 pc, implying a plausible M_V for the system of 5.5.

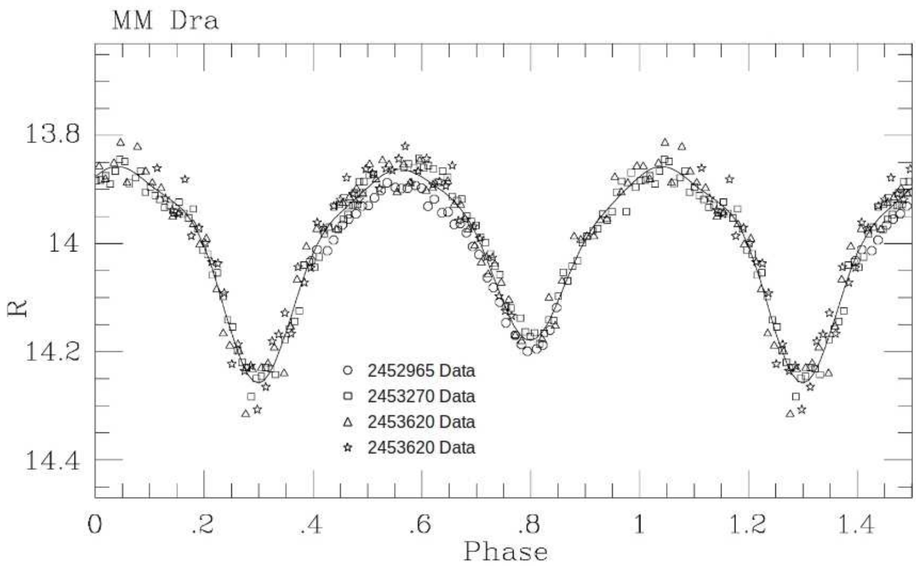

Figure 3. MM Dra data from the four nights of time series data from Bell Observatory, with different symbols for each Julian Date, showing the O'Connell effect.

MM Dra exhibits the O'Connell effect (O'Connell 1951), the phenomenon of variations in the maxima in eclipsing binary systems. Proposed theories for the explanation of asymmetrical maxima include the presence of star spots, interstellar dust and gas, and hot spots from the impact of mass transferring gas streams. (A discussion of the various models, with references, can be found in Wilsey & Beaky 2009). The MM Dra maxima vary by a range of 0.02 to 0.08 magnitude in R band, 0.02 to 0.04 magnitude in I band, and 0.06 to 0.14 magnitude in V band. Figure 3 displays the phase diagram for MM Dra plotted from continuous monitoring on three separate nights from Bell Observatory. The various marker shapes correspond to data obtained on different nights. The phase diagram shows that the observed minima converge for the four nights while a substantial

[1] `http://www.stsci.edu/ĩnr/intrins.html`

spread is observed at and near the maxima, confirming the presence of the O'Connell effect.

3.2 Star 3

The light curve for star 3 is presented in Figure 5. Data from the Bell Observatory are in blue, data from the RCT in red and data from CRAO in green. The total variability amplitude is 0.25 magnitudes. There is a noticeable dip from HJD 2455000 to HJD 2456000 of 0.2 magnitudes. The data are not sufficient to determine if this is a signature of a second object or a large star spot. A period analysis of star 3 with this 'dip interval' excluded reveals no evidence of any significant periodic components at any periods adequately sampled by our data. As with MM Dra, no spectroscopy is available for this object. VRI color indices were compared with colors given in Huang et al. (2015) and the HST compilation referred to above (Figure 4). The VRI_C color indices for star 3 most closely resemble typical values for a K7-M0 dwarf, but the separation between dwarfs and giants is not large enough to be definitive, especially given that our standards do not include any objects nearly as red as star 3. Its mean dereddened $V-R_C$ and R_C-I_C colors as determined here (0.924 and 0.904) are also very similar to those of HD146051 (0.92 and 0.92) as given for this M0.5III star in Huang et al. (2015).

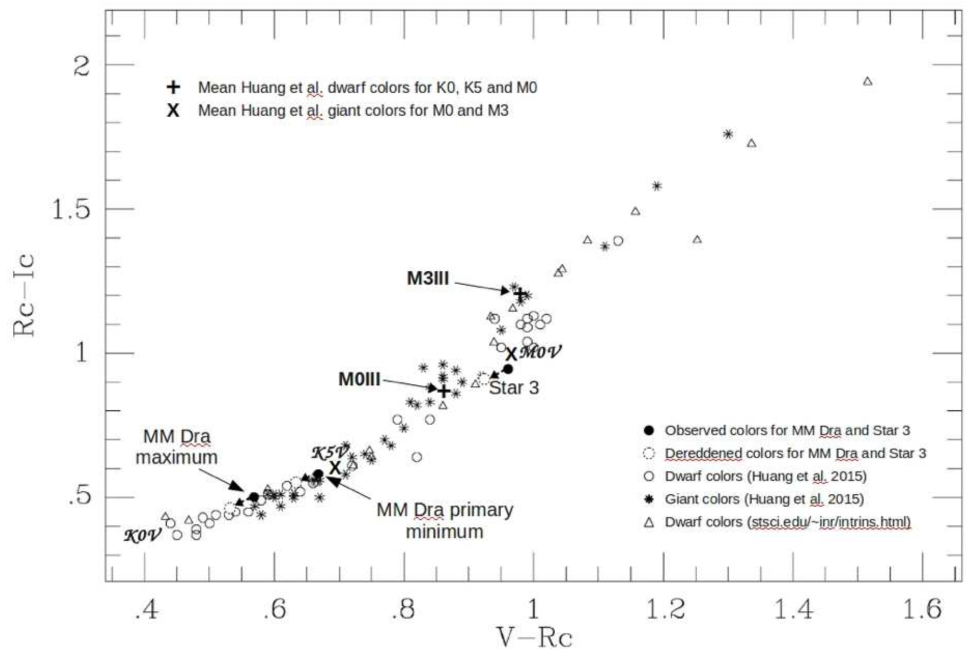

Figure 4. $V-R_C$ vs.$R-I_C$ color-color diagram showing dwarf and giant colors from Huang et al. (2015) and dwarf colors from the HST website (`http://www.stsci.edu/inr/intrins.html`), together with reddened and dereddened colors for MM Dra and star 3.

4 Conclusions

The results of 14 years of photometric monitoring of two variable stars in the field of the TeV blazar 1ES 1959+650 can be briefly summarized. For MM Dra, we confirm the eclipsing binary nature of this object and we refine the period to be 0.26547863 ± 0.0000003 days. A color analysis yields an approximate spectral type of K2 (primary maximum) to K4 (primary minimum), after a small reddening correction. The presence of the O'Connell effect is also confirmed in the phase curve for this source. For star 3, a total variability amplitude of 0.23 magnitudes was found. A period analysis does not reveal the presence of any periodic modulation in its light curve and color analysis yields an approximate spectral type of very late K or early M. Further spectroscopic observations of both of these stars are needed to refine the spectral type and (for star 3) luminosity class.

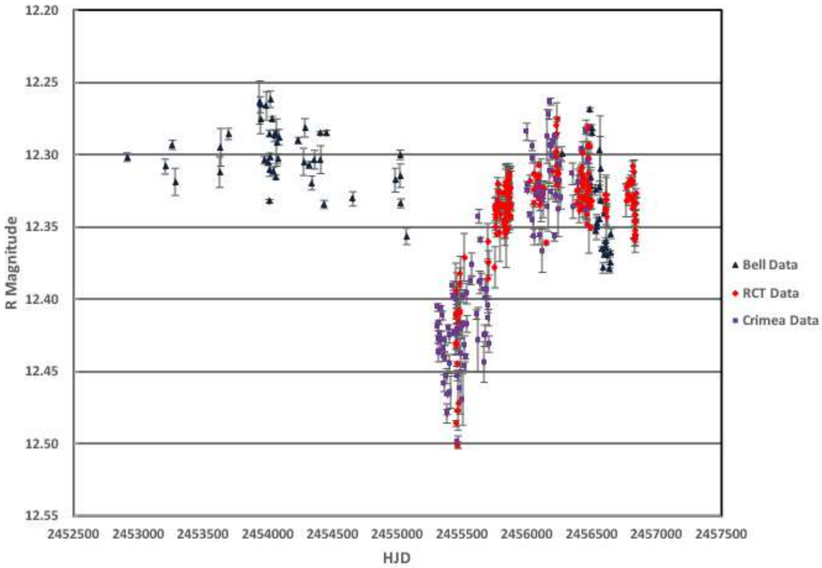

Figure 5. Long term light curve of star 3.

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