Optical Photometry of High-Energy Sources from a College Observatory

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Summary. We present a technical description of the Astronomical Observatory of the University of Jaén (UJA). Equipped with a 41 cm Schmidt-Cassegrain telescope on a robotic equatorial mount, this instrument is mainly devoted to educational tasks for Astronomy students and long-term photometric monitoring for research purposes. Outreach activities are also occasionally carried out, and a live all-sky camera is also maintained. The main detector is a commercial CCD camera hosting an $UBVR_cI_c$ filter wheel. The photometric transformation coefficients, zero points and average extinction values of the observatory have been accurately determined by imaging standard stars under clear observing conditions during 2015-2016. Despite its location in a light polluted area, the instrument has performed remarkably well and differential photometry at the 0.01-0.02 mag accuracy level is regularly achieved for bright targets (V<12). Several gamma-ray binaries and related systems (LS I +61303, LS 5039, MWC656, ...) are currently under monitoring. In the past year, the UJA observatory contributed to the optical follow-up of the black hole transient V404 Cygni in outburst. More recently, these UJA facilities have been key at identifying the Be star system LS I +59 79 as an eclipsing Be star inside the error ellipse of the unassociated gamma-ray source 3FGL J0133.3+5930.

The Observatory and its Purpose

The UJA Astronomical Observatory was upgraded in 2015 with a new 41 cm Meade Schmidt-Cassegrain telescope and a Paramount MEII German equatorial mount. Its central pillar is located at latitude +37°47'14.35" N and longitude 3°46'39.73"W (altitude 511 m) in the premises of the Las Lagunillas campus. The sky background here is severely affected by the light of the nearby city of Jaén (population 100,000). However, even with this handicap the Observatory frequently undergoes astronomy teaching and outreach sessions as well as regular photometric monitoring of bright sources. For research purposes, we focus on gamma-ray binaries and related systems. Many of these sources in the frontline of modern high-energy astrophysics turn out to exhibit bright optical counterparts, often already recorded in stellar catalogues of luminous stars compiled half a century ago (e.g. Hardorp et al. 1959).

Fig. 1. Location of the UJA Astronomical Observatory

Fig. 2. External view of the dome (diameter 4.4 m).

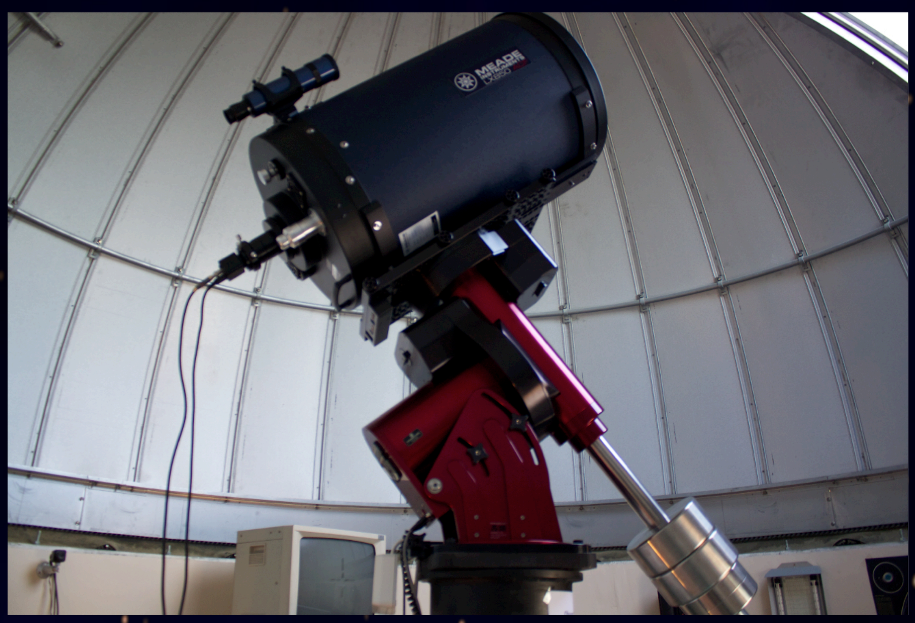

Fig. 3. The telescope and its robotic German equatorial mount.

Calibrating the Photometric Equipment

$$
\begin{aligned}
U &= U_{\rm ins} - k_U X_U + T_{UBV}(B-V) + Z_U \\
B &= B_{\rm ins} - k_B X_B + T_{BBV}(B-V) + Z_B \\
V &= V_{\rm ins} - k_V X_B + T_{VBV}(B-V) + Z_V \\
R_c &= R_{c\rm ins} - k_{R_c} X_{R_c} + T_{R_cVR_c}(V-R_c) + Z_{R_c} \\
I_c &= I_{c\rm ins} - k_{I_c} X_{I_c} + T_{I_cVI_c}(V-I_c) + Z_{I_c}
\end{aligned}
$$

Fig. 4. Equations for absolute photometry

$$
\begin{aligned}
\Delta(U-B) &= T_{UB}\Delta(U-B)_{\rm ins} & \Delta U &= \Delta U_{\rm ins} + T_{UBV}\Delta(B-V) \\
\Delta(B-V) &= T_{BV}\Delta(B-V)_{\rm ins} & \Delta B &= \Delta B_{\rm ins} + T_{BBV}\Delta(B-V) \\
\Delta(V-R_c) &= T_{VR_c}\Delta(V-R_c)_{\rm ins} & \Delta V &= \Delta V_{\rm ins} + T_{VBV}\Delta(B-V) \\
\Delta(V-I_c) &= T_{VI_c}\Delta(V-I_c)_{\rm ins} & \Delta R_c &= \Delta R_{c\rm ins} + T_{R_cVR_c}\Delta(V-R_c) \\
\Delta(R_c-I_c) &= T_{R_cI_c}\Delta(R_c-I_c)_{\rm ins} & \Delta I_c &= \Delta I_{c\rm ins} + T_{I_cVI_c}\Delta(V-I_c)
\end{aligned}
$$

Fig. 5. Equations for differential photometry. The left panel shows the relation between instrumental and absolute colors. The right panel shows the relation between instrumental and absolute differences of magnitude.

The telescope is equipped with a commercial CCD camera SBIG ST10-XME. It has 16 bit digitation levels and a CCD chip with 2184×1472 pixels of 6.8 μm size. A filter wheel with $UBVR_cI_c$ Johnson-Cousins filters is also available. Both absolute and differential photometry has been performed using the equations displayed in Figs. 4 and 5, respectively. The different transformation coefficients and zero-points have been determined for each color and filter by observing equatorial standards from Landolt (1992) on clear nights. A detailed description of the process is given in Martí et al. (2017). Figs. 6, 7, 8 and 9 display representative plots of the calibration procedure that yields the coefficient, atmospheric extinction and zero-point values, always taking into account the colour dependences. The results do not change significantly from night to nigh and average values are used to calibrate the data if standards cannot be observed.

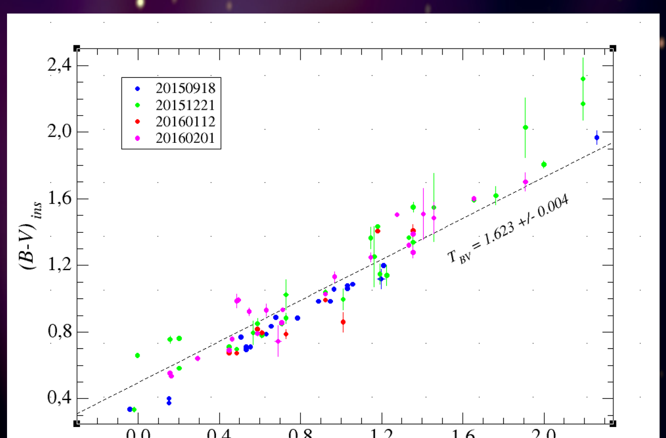

Fig. 6. Dependence of instrumental versus absolute values of the *(B-V)* colour. The slope of the linear fit is the T_{BV} transformation coefficient. Colour of points correspond to the dates listed in the legend (YYYYMMDD).

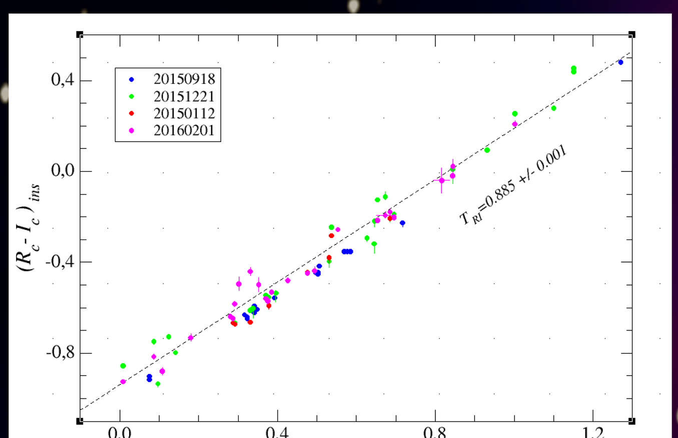

Fig. 7. Idem as in previous figure for the *(R-I_c)* colour.

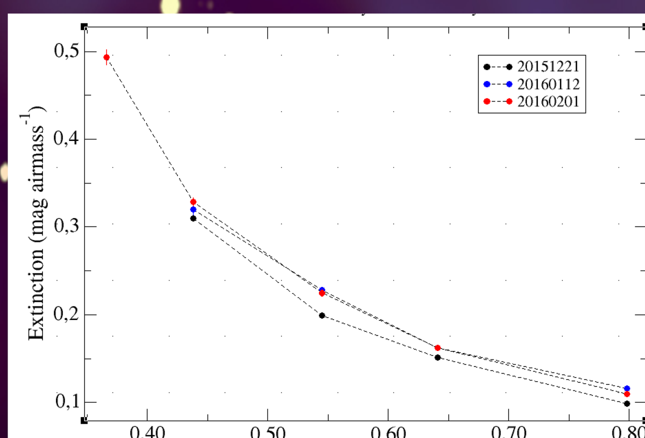

Fig. 8. Values of atmosferic extinction coefficients for three different dates. The central wavelengths of the filters are used in this plot.

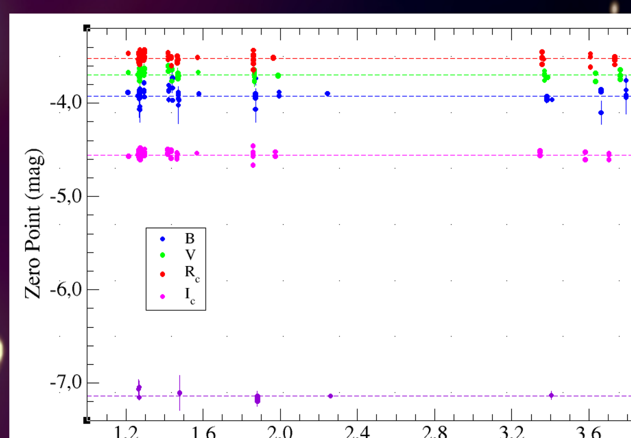

Fig. 9. Zero-point values for all filters from observations on different nights.

First Scientific Results and Discoveries

In the summer of 2015, the UJA telescope contributed to the optical follow-up of the black hole transient V404 Cygni in outburst. The VR_cI_c light curves were found to be consistent with an scenario based on the ejection of non-thermal emitting, relativistic plasmons with their synchrotron emission contributing at optical wavelength (see Fig. 10, adapted from Martí et al. 2016a). The observatory has also played a role in the efforts of our group aimed to identify unassociated sources of gamma-rays at low galactic latitude. The *Fermi* LAT source 3FGL J0133.3+5930 is one of them (Acero et al. 2015). We selected it as a possible gamma-ray binary candidate given the presence of the luminous Be star LS I+59 79 (a.k.a. TYC 3684-95-1) in its 95% confidence ellipse . This star is also consistent with the position of the X-ray source 1RXS J013326.9+ 592946 detected by *ROSAT* (Voges et al. 2000). From September 2015 to January 2016, multi-colour photometry of LS I+59 79 was intensively collected with the UJA telescope. This allowed us to discover its eclipsing binary nature with an orbital period of of 1.9402 ± 0.0006 d (see Fig. 11). Phase zero is set at HJD 2457378.306. Modelling of the light curves suggests that we are dealing with a semi-detached system where one of the components fills its Roche lobe (Martí et al. 2016b). An active galactic nucleus in the field appears as an alternative counterpart to the *Fermi* source, but its blazar nature is not yet confirmed by current data. Even if the LS I +59 79 turns out not to be a high-energy emitter, the discovery of a new eclipsing binary from a light polluted site is a remarkable achievement for a College observatory.

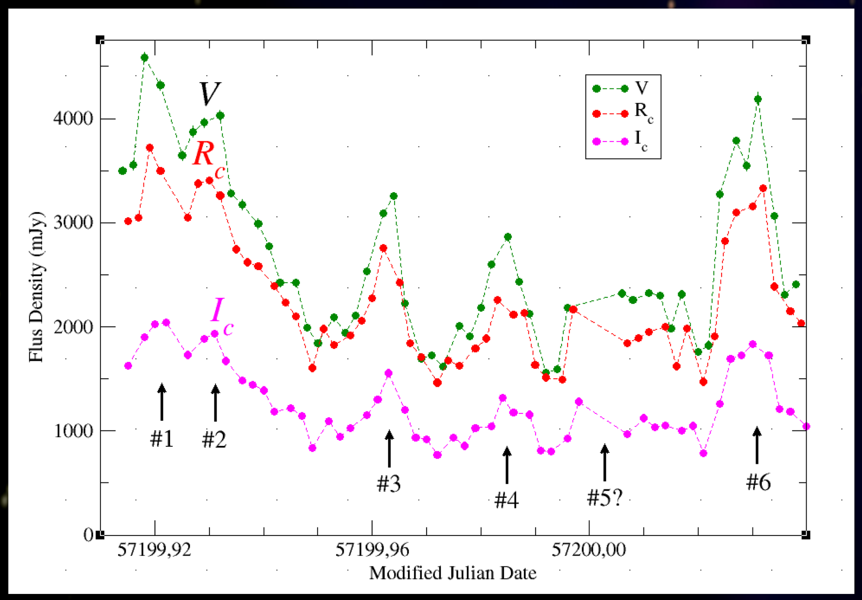

Fig. 10. Dereddned light curves of V404 Cygni observed with the UJA telescope on 26 June 2015 (Martí et al. 2016a). Vertical arrows mark individual optical flares.

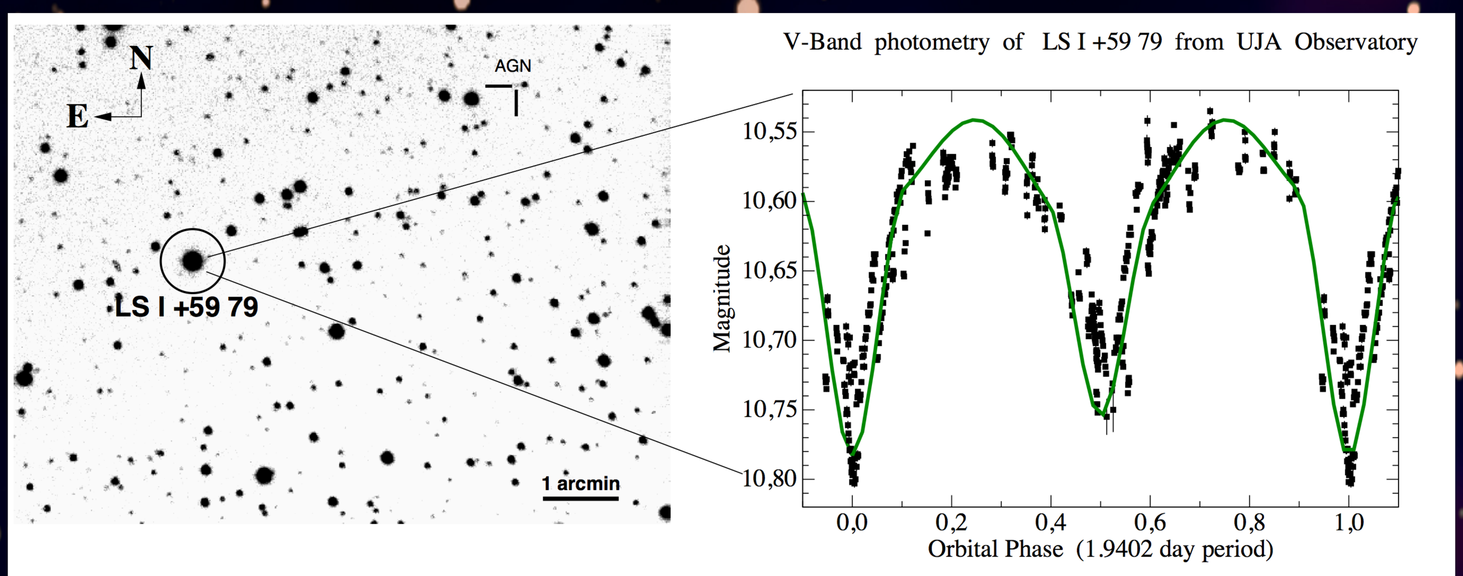

Fig. 11. Left. Deep R_c band image of the LS I +59 79 field taken with the UJA telescope. **Right.** Folded V-band light curve of the system (Martí et al. 2016b). The green curve is a tentative model fit of the eclipses using the WD code (Wilson & Devinney 1971).

References

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Web of the Observatory: http://www4.ujaen.es/~jmarti/observa4.htm (in Spanish only).