The University of Jaén Astronomical Observatory

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Abstract. We present a description and instrumental characterization of the photometric equipment of the Astronomical Observatory of the University of Jaén. The observatory hosts a 41 cm automated telescope inside a 4 m dome located at the university main campus, in the outskirts of the city of Jaén (Spain). This facility is used for educational, outreach and occasional scientific research on bright stellar objects. Despite the observatory location in a light polluted urban area, its performance for differential photometry studies has proven to be very acceptable. The discovery of the Be star LS I +5979 as a peculiar eclipsing binary system is so far the most relevant achievement.

Key words: Telescopes – Techniques: photometric – Gamma rays: stars – Stars: individual: LS I +59 79

1 Introduction

The Astronomical Observatory of the University of Jaén (UJA) was established in 2004 as an educational facility of the Higher Polytechnic School of Jaén. It is located inside the UJA main campus of *Las Lagunillas* in the outskirts of the city of Jaén (Spain, population 120,000). A dome 4 m in diameter on top of the School building, together with a large circular classroom below it, are today one of the most representative landmarks in the campus (see Fig. 1). The observatory original purpose was to provide teaching support to different astronomy courses. Having access to this kind of resources is today a growing practice in most universities around the world (e.g. Ovcharov et al. 2014).

During its first years, the only instruments available consisted of a 250 mm Schmidt-Cassegrain (SC) telescope, a small 60 mm Zeiss refractor telescope, and a few theodolites including a Kern DKM3 unit. Practical sessions of astronomy were often carried out using them. These included activities such as telescope pointing and astronomical coordinate systems, measurement of azimuths using the Sun and Polaris, and determination of latitude and longitude through meridian transits of stars. At present, the observatory main educational role is related to the Geodetic Astronomy course offered in the context of the new UJA degree on Geomatics and Topography Engineering.

In 2014, an application was submitted by the UJA Department of Physics to the academic authorities with a request to upgrade part of the equipment with many years of use. After approval and a long selection and delivery process, the new UJA telescope, hereafter UJT, was finally installed. First light was achieved on the night of 11 to 12 May 2015 during an emotive opening ceremony conducted by the UJA Rector, Prof. Juan Gómez Ortega.

The WGS84 geodetic coordinates of the observatory central pillar measured with Differential Global Positioning System are: latitude: $+37^\circ 47' 14\overset{''}{.}35$N;

longitude: 003°46′39.″73W; altitude: 511.01 m. Further details can be accessed in the observatory web page[3].

Live images of the UJT surroundings are provided by a fish-eye camera placed next to the dome[4]. Despite the location in a light polluted urban environment, the telescope has proven to be a successful resource for both educational and outreach purposes, as well as occasional research involving bright celestial objects.

Fig. 1. External view of the UJA Astronomical Observatory on top of the Higher Polytechnic School of Jaén building, i.e., A3 building in the *Las Lagunillas* campus of Jaén.

2 The observatory education and outreach activities

2.1 Education

The educational tasks carried out at the UJA Astronomical Observatory usually have a strong component of positional astronomy as well as astrodynamics. These are the aspects that need to be strengthened when addressing engineering students with Geodesy and Topography interests. A representative example, shown in Fig. 2, is the practical determination of the site coordinates by means of meridian transit of stars observed with theodolite and chronometer. The UJT also plays a complementary role here when students are given full access to its computer control system. Concepts such as astronomical coordinates, time scales, and data acquisition procedures become easier to understand when students themselves command the telescope to slew towards a previously chosen star and its image appears on the computer screen. Moreover the teacher also encourages them to reproduce later, on their own, the coordinate transformation steps that the telescope computer performs automatically.

[3] `http://www4.ujaen.es/~jmarti/observa4.htm` (in Spanish only).
[4] `http://aljayani.ujaen.es` (in Spanish only).

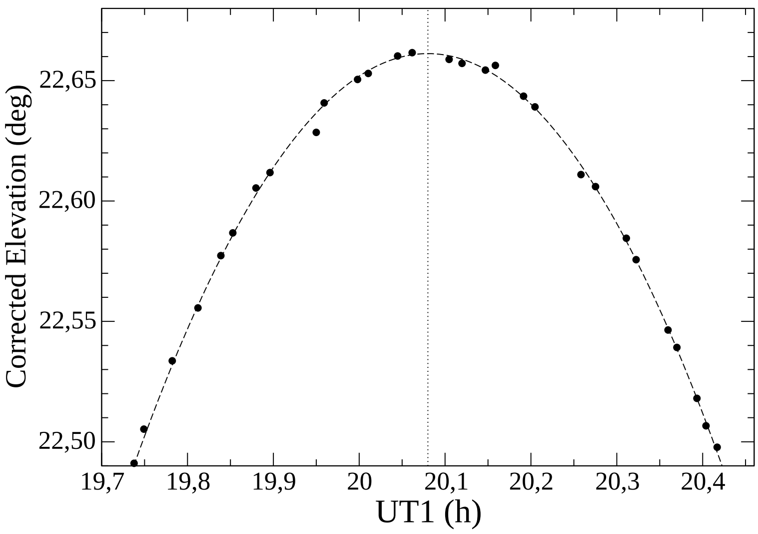

Fig. 2. An example of a meridian transit observation carried out with students from the UJA Astronomical Observatory on 7th November 2013. The star α Piscis Austrinus was observed using a Leica T105 theodolite and a chronometer adjusted to UTC. The observed elevations were corrected for refraction and the chronometer readings converted to the UT1 time scale directly related to the Earth Rotation Angle. The long-dashed line is a least squares parabolic fit that provides an estimate of the time and elevation of the transit. The astronomical longitude and latitude of the site are easily derived from these two observables. The correct result is recovered within $\pm 10''$ accuracy very suitable for teaching purposes.

2.2 Outreach

Outreach towards the society and the general public is also an important duty of the UJA Astronomical Observatory that is being carried out on a best effort basis. Whenever possible in coincidence with astronomical events (eclipses, bright comets, asteroid fly-bys, ...) both Jaén citizens and the university community are invited to attend outreach sessions in the observatory premises under the guidance of UJA astronomers. The UJT live images are projected and commented to the audience in the classroom below it. Access to visit the dome and the telescope is also granted for groups up to ten people at once. The outreach tasks are always supported by the UJA communication staff who ensures a broad circulation in advance of open activities in local and regional media. In addition, these tasks were recognized in 2010 with the 1st UJA Scientific Outreach Prize awarded to some of the authors.

3 The telescope and its instrumentation

The new UJT is a Meade SC telescope with 41 cm diameter and f/8 focal ratio (see Fig. 3). It is supported by an automated Paramount MEII equatorial mount of German type from Software-Bisque Inc. The telescope main instrument is also a commercial CCD camera SBIG ST10-XME. It has 16 bit digitation levels and a CCD chip with 2184×1472 pixels of

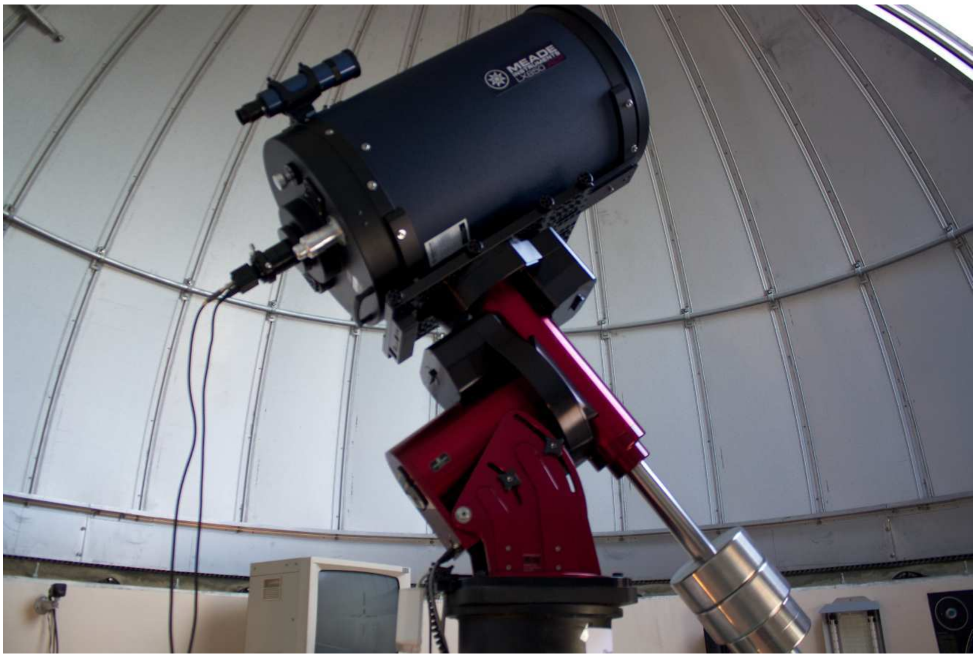

Fig. 3. Appearance of the UJT inside the dome enclosure during its comissioning phase. A simple video camera was used at this stage for the alignment of the equatorial mount and building of the first pointing models.

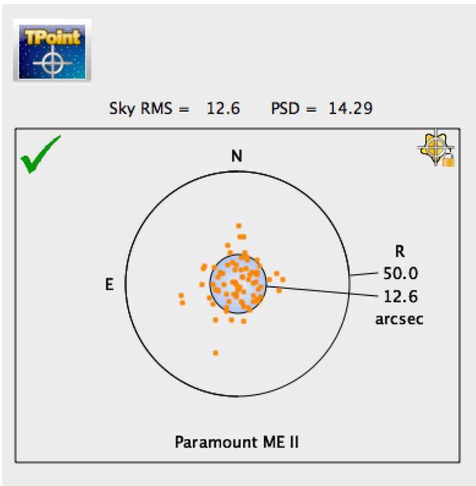

Fig. 4. Screen capture of the *TheSky* control software showing the excellent pointing capabilities of the UJT equatorial mount (rms below 15 arc-second).

6.8 μm size. The pixel gain amounts to 1.2 e^- per count and the pixel scale at the focal plane without binning is $0\farcs42$ pixel^{-1}. The corresponding field of view covers $15' \times 10'$. The camera works with a CFW-8 filter wheel mounting $UBVR_cI_c$ Johnson-Cousins filters for broad band photometry (Johnson & Morgan 1953; Cousins 1974a, 1974b). These glass filters are manufactured according to the Bessell (1979) prescription. Their central wavelengths are 0.366, 0.438, 0.545, 0.641 and 0.798 μm, respectively. Cooling of the camera, up to 30° below ambient temperature, is possible with a build-in Peltier system. The hardware ensemble is operated using *TheSkyX* program of Software-Bisque Inc. provided by the equatorial mount manufacturers. The computer controlling the telescope is next to it inside the dome, but remote control from other computers in the local network is also possible.

The equatorial mount has been remarkably aligned with the Earth polar axis to within less than one arc-minute. With an appropriate pointing model, the root mean squared (rms) deviation of objects from the CCD frame center is routinely below $15''$ as illustrated in Fig. 4. The maximum duration of a single unguided exposure is about three minutes with the current setup. This time interval will be significantly increased soon when full periodic error and autoguiding corrections become fully implemented. The observatory enclosure is the same 4 m Ash Dome originally installed in 2004 when the Higher Polytechnic School of Jaén building was erected.

Data reduction is performed using IRAF software package[5] in the same control computer and also offline. Since we deal with image data, this only includes subtraction of dark frames and flat field correction. IRAF tasks and scripts are also used for aperture photometry purposes. To give an idea of the system performance, the limiting magnitudes achievable at the 5σ level with a 20 s exposure time are approximately 13.0, 16.3, 16.8, 16.8 and 16.0 for the U, B, V, R_c and I_c filters, respectively. These illustrative values have been estimated using real CCD frames acquired under regular observing conditions (2.5 arcsecond seeing at an airmass of 1.3).

4 Photometric coefficients and atmospheric extinction

To obtain scientifically useful results, the measurements of star brightness need to be transformed into one of the absolute or calibrated photometric systems used in professional astronomy (in our case $UBVR_cI_c$). For this purpose, here we adapt and follow the formalism and expressions given in the *CCD Photometry Guide* of the American Association of Variable Star Observers (AAVSO)[6]. The raw instrumental magnitude is computed according to:

$$m_{ins} = -2.5 \log N + Z_0, \tag{1}$$

where N is the number of counts per second inside the star photometric aperture, corrected for background, and Z_0 the default value of the zero point (+25.00 in the IRAF package). Eq. 1 applies to the instrumental magnitudes obtained in all $UBVR_cI_c$ filters. Assuming that the filter set

[5] http://iraf.noao.edu/

[6] https://www.aavso.org/ccd-photometry-gude

closely matches the original Johnson-Cousins system, the transformation towards calibrated magnitudes can be based on linear equations of the following kind. Starting with the photometric colors:

$$(U-B) = T_{UB}(U-B)_{\rm ins} + Z_{UB} \quad (2)$$
$$(B-V) = T_{BV}(B-V)_{\rm ins} + Z_{BV} \quad (3)$$
$$(V-R_c) = T_{VR_c}(V-R_c)_{\rm ins} + Z_{VR_c} \quad (4)$$
$$(V-I_c) = T_{VI_c}(V-I_c)_{\rm ins} + Z_{VI_c} \quad (5)$$
$$(R_c-I_c) = T_{R_cI_c}(R_c-I_c)_{\rm ins} + Z_{R_cI_c}, \quad (6)$$

where the T and Z-terms with color subscript are the color transformation coefficients and the additive constants fixing their zero point, respectively. In addition, the appropriate equations for the true magnitudes are:

$$U = U_{\rm ins} - k_U X_U + T_{UBV}(B-V) + Z_U \quad (7)$$
$$B = B_{\rm ins} - k_B X_B + T_{BBV}(B-V) + Z_B \quad (8)$$
$$V = V_{\rm ins} - k_V X_B + T_{VBV}(B-V) + Z_V \quad (9)$$
$$R_c = R_{c\rm ins} - k_{R_c} X_{R_c} + T_{R_cVR_c}(V-R_c) + Z_{R_c} \quad (10)$$
$$I_c = I_{c\rm ins} - k_{I_c} X_{I_c} + T_{I_cVI_c}(V-I_c) + Z_{I_c} \quad (11)$$

where the k-terms with filter subscript represent the atmospheric extinctions in each filter, the X-terms the air masses of the observed star in each filter, the Z-terms with filter subscript the constant zero points of the transformation, and the T-terms with filter-color subscript account for their possible color dependence.

Determination of the different transformation coefficients requires observing as many as possible standard stars with a wide range of colors and air masses. In the UJT case, equatorial standards from Landolt (1992) have been observed on selected nights with good weather conditions. Several of them could be often fitted into a single CCD frame, thus speeding a wider coverage of color index values. Unless instrumental changes are introduced, the transformation coefficients are expected to remain nearly constant over time. Therefore, their determination can be improved by combining measurements from different nights. Only for the extinction values, that are mainly dependent on the changing atmospheric conditions, it is more advisable to derive them on a individual nightly basis.

The transformation coefficients for the UJT telescope, camera and filter set have been determined so far by combining observations of Landolt standards on four different dates (18 Sep and 21 Dec 2015; 12 Jan and 01 Feb 2016). A least squares approach was applied for this purpose to all previous equations, implemented through a custom-made FORTRAN code. The corresponding results are presented in Table 1 for the color coefficients, Table 2 for the extinctions of each night, and Table 3 for zero points and their color dependence terms. The first observing night did not cover a sufficiently wide range of air masses. Consequently, the standards stars of that night contributed to the determination of the color coefficients only.

In the Appendix Figs. 7, 8, 9, 10, and 11 we also display the plots corresponding to the fits of color transformation terms. The atmospheric extinctions obtained are plotted in Fig. 12. They turned out to be very similar for the three different nights available. Fig. 13 of the Appendix illustrates the constancy of the zero points for all filters. For example, for the filter V we plot in this figure the quantity $Z_V = V - V_{ins} + k_V X - T_{VBV}(B - V)$ as a function of air mass, and so on for the rest of filters.

Table 1. Coefficients to transform from instrumental to true color

Coefficient	Value	Additive term (mag)	# of standard stars used
T_{UB}	2.00 ± 0.06	-7.1 ± 0.2	21
T_{BV}	1.623 ± 0.004	-0.806 ± 0.003	85
T_{VR_c}	0.987 ± 0.002	-0.300 ± 0.001	86
T_{VI_c}	0.942 ± 0.001	$+0.602 \pm 0.001$	85
$T_{R_cI_c}$	0.885 ± 0.001	$+0.831 \pm 0.002$	84

Table 2. Atmospheric extinction values at the UJT urban site

Date	Extinction coefficient	Value (mag airmass^{-1})	# of standard stars used
21 Dec 2015	k_U	–	–
	k_B	0.310 ± 0.004	30
	k_V	0.199 ± 0.002	30
	k_{R_c}	0.151 ± 0.002	30
	k_{I_c}	0.099 ± 0.002	30
12 Jan 2016	k_U	–	–
	k_B	0.32 ± 0.01	9
	k_V	0.228 ± 0.003	9
	k_{R_c}	0.162 ± 0.003	9
	k_{I_c}	0.116 ± 0.003	9
01 Feb 2016	k_U	0.49 ± 0.01	11
	k_B	0.329 ± 0.005	26
	k_V	0.225 ± 0.002	25
	k_{R_c}	0.162 ± 0.003	26
	k_{I_c}	0.110 ± 0.003	26

With the transformation coefficients in hand, it is possible to use them on regular observing nights for differential photometry work once the calibrated magnitudes of suitable comparison stars in the field have been previously determined. In this case, only the color and magnitude differences between the target and the comparison stars matter. Having all the same airmass, the k-terms obviously cancel out as also do the zero points. The previous equations become then noticeably simplified when expressed in incremental form.

For the differences in color, one gets:

$$\Delta(U - B) = T_{UB} \Delta(U - B)_{\rm ins} \tag{12}$$

$$\Delta(B - V) = T_{BV} \Delta(B - V)_{\rm ins} \tag{13}$$

Table 3. Zero points and color terms

Zero point	Value* (mag)	Color term	Value	# of standard stars used
Z_U	-7.14 ± 0.02	T_{UUB}	$+0.46 \pm 0.01$	11
Z_B	-3.92 ± 0.01	T_{BBV}	$+0.24 \pm 0.01$	65
Z_V	-3.70 ± 0.01	T_{VBV}	-0.044 ± 0.004	64
Z_{R_c}	-3.52 ± 0.01	$T_{R_cVR_c}$	-0.07 ± 0.01	65
Z_{I_c}	-4.56 ± 0.01	$T_{I_cVI_c}$	$+0.008 \pm 0.003$	65

(*) Appropriate for instrumental magnitudes computed with the IRAF default zero point of magnitude scale (+25.00).

$$\Delta(V - R_c) = T_{VR_c}\Delta(V - R_c)_{\rm ins} \quad (14)$$
$$\Delta(V - I_c) = T_{VI_c}\Delta(V - I_c)_{\rm ins} \quad (15)$$
$$\Delta(R_c - I_c) = T_{R_cI_c}\Delta(R_c - I_c)_{\rm ins} \quad (16)$$

Similarly, for the differences in calibrated magnitude:

$$\Delta U = \Delta U_{\rm ins} + T_{UBV}\Delta(B - V) \quad (17)$$
$$\Delta B = \Delta B_{\rm ins} + T_{BBV}\Delta(B - V) \quad (18)$$
$$\Delta V = \Delta V_{\rm ins} + T_{VBV}\Delta(B - V) \quad (19)$$
$$\Delta R_c = \Delta R_{c\rm ins} + T_{R_cVR_c}\Delta(V - R_c) \quad (20)$$
$$\Delta I_c = \Delta I_{c\rm ins} + T_{I_cVI_c}\Delta(V - I_c) \quad (21)$$

Differential photometry is the main use given the transformation coefficients of Tables 1, 2 and 3 in a long-term program of regular monitoring of variable stars, as described in the next section. Future observations will improve the obtained values and allow to assess how stable they are on very long time scales (years).

Alternatively, in case Landolt-based comparison stars are not available for some field, one can always rely on a very powerful resource such as the AAVSO Photometric All-Sky Survey (APASS[7]). The differential photometry equations above, and the color-dependent coefficient values, can be directly used with the APASS B, V, and the duly transformed g', r' and i' magnitudes. The APASS sky coverage has significantly increased in its latest data releases and provides a high density of comparison stars, reaching up to $\sim 10^4$ deg^{-2} in some regions of the Milky Way plane. The only APASS disadvantage is the lack of U-band magnitudes.

5 Astronomy research with an educational telescope

Although it is not its primary goal, the UJT can also be eventually used for research astronomical observations. A weak point here is the observatory location in an urban and therefore highly light-polluted area. This is unavoidable given the need to provide easy hands-on direct access to the

[7] https://www.aavso.org/apass

telescope for students in the campus. However, a strong point is the permanent availability of the telescope for long-term monitoring projects of bright objects appropriate for small instruments. Interested students are given the opportunity to witness and participate in some of the data acquisition sessions devoted to research.

The UJA astronomers are structured around a research group focused on high energy sources in the Galaxy (reference code FQM-322). In this context, optical monitoring of the new class of so called γ-ray binaries, and possible candidates, appears as an excellent long-term project for the UJT. The reader may refer to Dubus (2013) and Paredes (2013) for extensive reviews on this kind of interesting stellar systems that provide one of the hottest topics in modern high energy astrophysics. The optical counterparts of γ-ray binaries are typically luminous, early-type stars with a circumstellar envelope producing strong emission lines in their spectrum. Optical brightnesses easily reach the $V = 10$-12 mag level and ~ 0.1 mag variability associated with the orbital period is naturally expected. Multi-colour photometry of these systems is thus perfectly within reach of educational telescopes such as the UJT, even under light-polluted skies by using differential photometry techniques. The topic is also timely considering the present day debate about the physical environment where relativistic particles are accelerated up to TeV energies. Models based on the relativistic wind of a pulsar interacting with the companion circumstellar disc compete with those invoking relativistic jets from an accretion disc in a microquasar scenario. In any case, ample room for contribution exists given that only a handful of confirmed systems are currently known.

As a proof of the previous statement, we provide here a short account about the Be star LS I +59 79 (Martí et al. 2016a, 2016b). Also known as TYC 3683-985-1, this object represents the first UJT astronomical discovery from the urban skies of Jaén. A deep R_c-band image of its field of view is displayed in Fig. 5. LS I +59 79 was originally classified as of B1/2Vnne spectral type by McCuskey et al. (1974), and remained poorly studied since then. We selected it as a UJT target because of its location inside the 95% confidence ellipse of the unidentified γ-ray source 3FGL J0133.3+5930 detected by the *Fermi*-LAT observatory (Acero et al. 2015). Moreover, the star is also consistent with the *ROSAT* X-ray source 1RXS J013326.9+592946 (Voges et al. 2000).

The UJT multi-colour light curves, accumulating so far nearly 50 nights between 2015 autumn and 2016 spring, clearly display a noticeable modulation with a 1.9402 ± 0.0006 d period. The observed variability is well accounted for using the PHOEBE software package for modelling different kinds of binary systems (Prša & Zwitter 2005). Therefore, we interpret this period as the orbital cycle in the context of a binary Be star. The phase folded magnitudes were calibrated thanks to the photometric coefficients reported in this paper and are displayed in Fig. 6. Even if the association with the γ-ray source is not confirmed, the new Be binary LS I +59 79 appears a sa remarkable system worth of study by itself. Another fainter candidate counterpart to 3FGL J0133.3+5930 has been also found (see Fig. 5). Additional multi-wavelength data is still being analyzed to discriminate among them. Meanwhile, the star LS I +59 79 remains under intensive follow up including spectroscopic monitoring lead by astronomers of the Institute

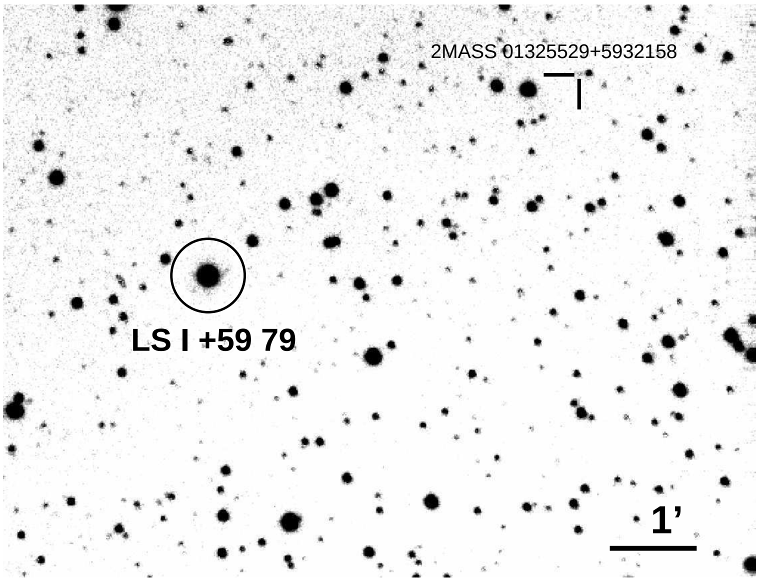

Fig. 5. Image of the binary system LS I +59 79 obtained with the UJT in the R_c-band. The binary star is the object inside the circle. The magnitude limit of this CCD frame is $R_c \simeq 18.5$. A faint 2MASS near infrared source is also marked which has also been proposed as an alternative counterpart candidate to 3FGL J0133.3+5930 (Martí et al. 2016a, 2016b). North is up and East is left. The horizontal bar shows the angular scale.

of Astronomy with NAO, Bulgarian Academy of Sciences (AINAO,BAS). A fruitful IANAO,BAS-UJA collaboration linked to optical observations of γ-ray binaries has been going on in the past for many years (e.g. Zamanov et al. 2013, 2016).

Another scientific contribution resulting from UJT work was its participation in the photometric monitoring of the low-mass X-ray binary V404 Cygni during its strong outburst of June 2015. This black hole system was intensively monitored during several nights by many astronomical observatories around the world. Its quiescent brightness level increased by several magnitudes, up to $R_c \simeq 11$, thus rendering it an easy target even for small telescopes. In the UJT observations, hints of a synchrotron optical emission component in the V404 Cygni flares were detected and reported in Martí et al. 2016c. APASS comparison stars were used in this work.

Conclusions

The UJA Astronomical Observatory has been described and its equipment characterized for calibrated photometric observations. Extinction measurements in the UJT site have been also reported. While the main driver of this kind of university facilities is training of students and outreach activities towards society, their scientific usefulness in some topics of professional astronomical research is also feasible. In the era of large and extremely large telescopes in privileged observing sites, there are still reasons for profes-

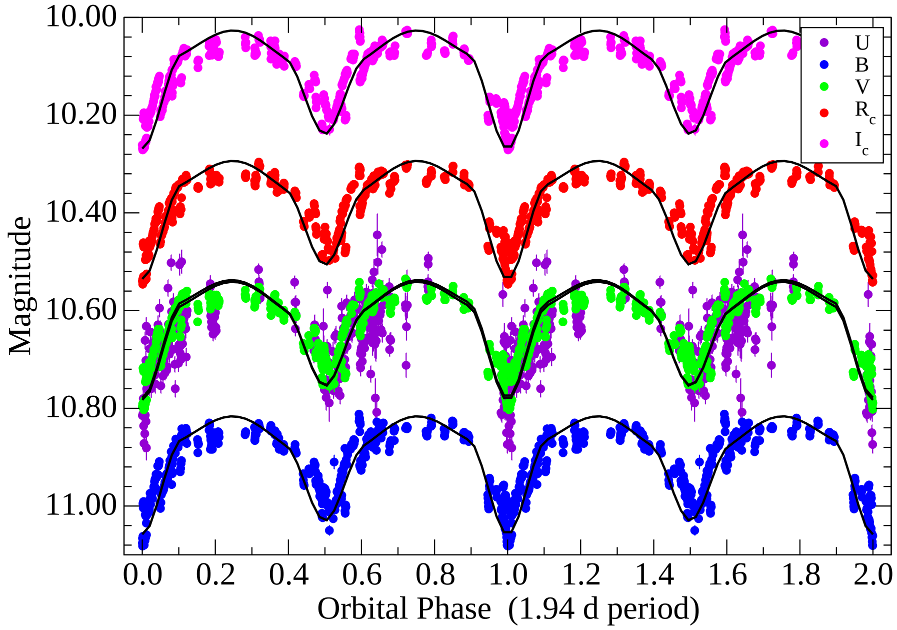

Fig. 6. Multi-color light curves of the eclipsing Be star LS I +5979 whose binary nature has been discovered using the UJT. Data points are plotted folded on the 1.94 d period believed to be the orbital cycle and shown twice. The continuous lines are a modelling attempt using the PHOEBE code (adapted from Martí et al. 2016a, 2016b).

sional usage of modest diameter telescopes. A discovery space yet belongs to them especially in dedicated long-term projects that cannot be allocated in the tight schedules of much larger facilities.

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Appendix: Photometric calibration plots.

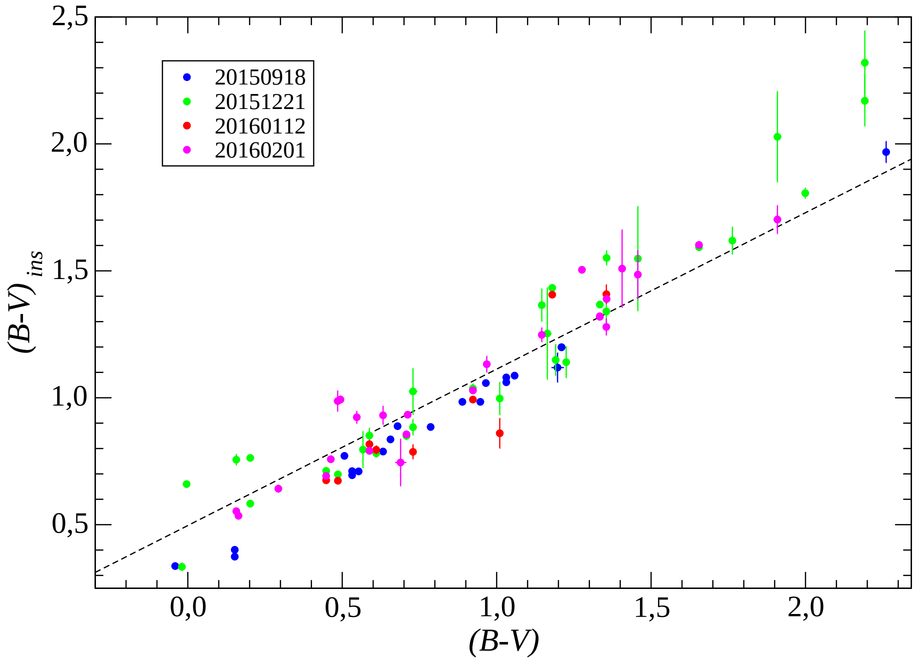

Fig. 7. Dependence of the instrumental versus true $(B-V)$ color for the UJT CCD camera and filter set. Landolt standard stars observed on different dates are combined in this plot (see legend). The transformation coefficient T_{BV} is the inverse of the slope of the least squares linear fit.

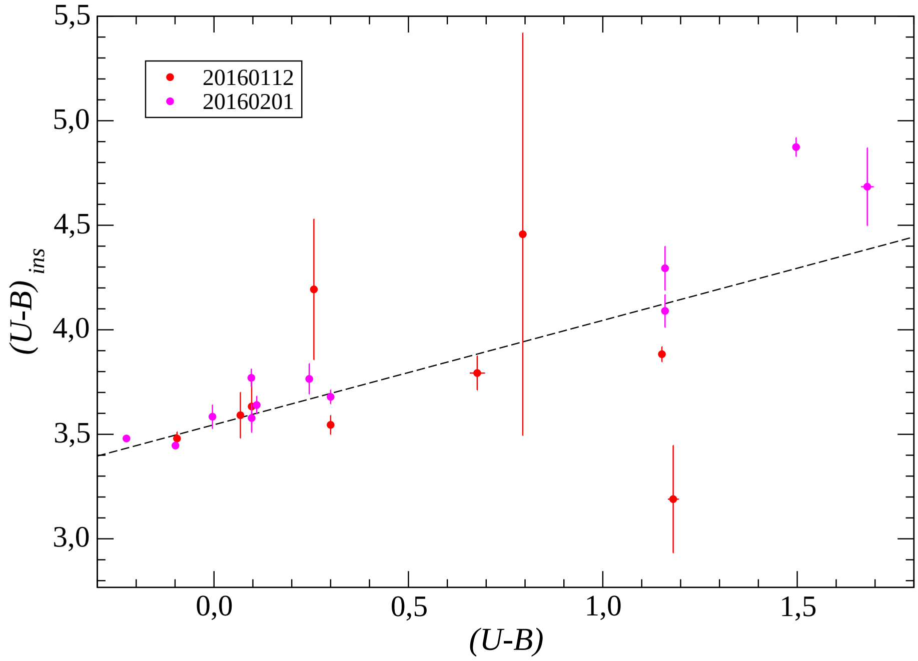

Fig. 8. Dependence of the instrumental versus true $(U - B)$ color for the UJT CCD camera and filter set. Landolt standard stars observed on different dates are combined in this plot (see legend). The transformation coefficient T_{UB} is the inverse of the slope of the least squares linear fit. This is the coefficient with largest scatter given the difficulty of U-band observations that require very long exposure times.

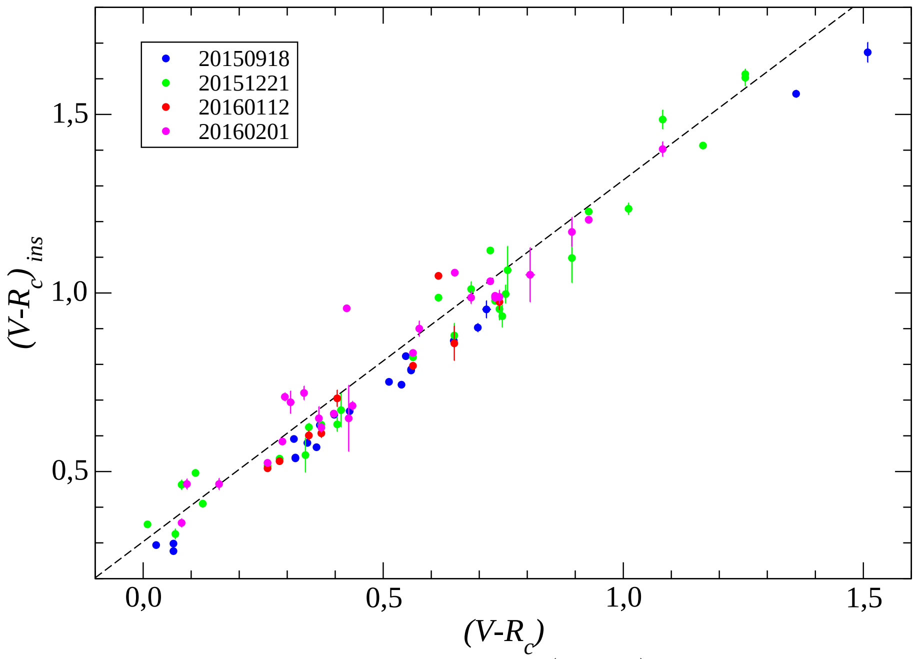

Fig. 9. Dependence of the instrumental versus true $(V - R_c)$ color for the UJT CCD camera and filter set. Landolt standard stars observed on different dates are combined in this plot (see legend). The transformation coefficient T_{VR_c} is the inverse of the slope of the least squares linear fit.

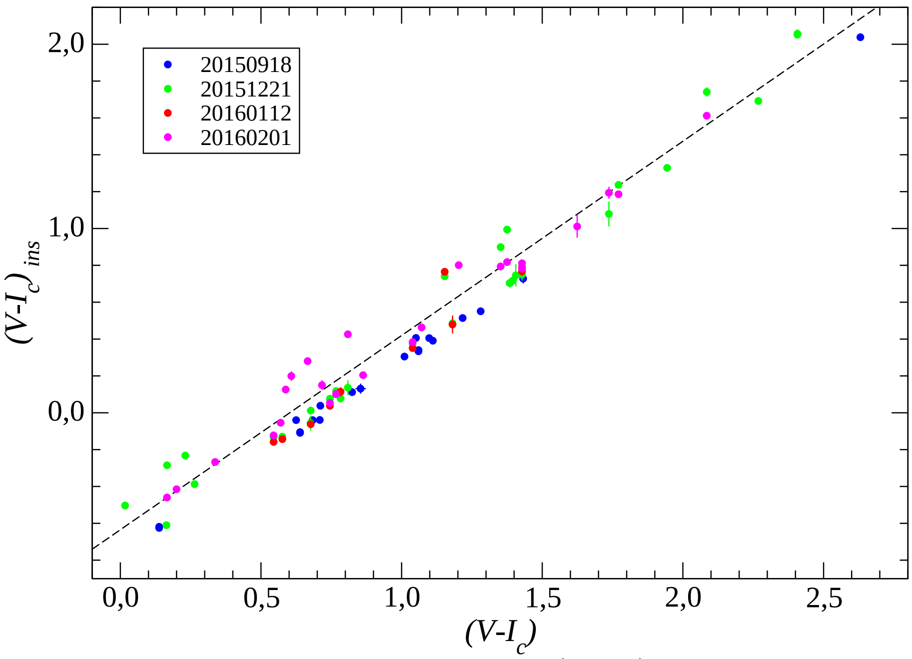

Fig. 10. Dependence of the instrumental versus true $(V - I_c)$ color for the UJT CCD camera and filter set. Landolt standard stars observed on different dates are combined in this plot (see legend). The transformation coefficient T_{VI_c} is the inverse of the slope of the least squares linear fit.

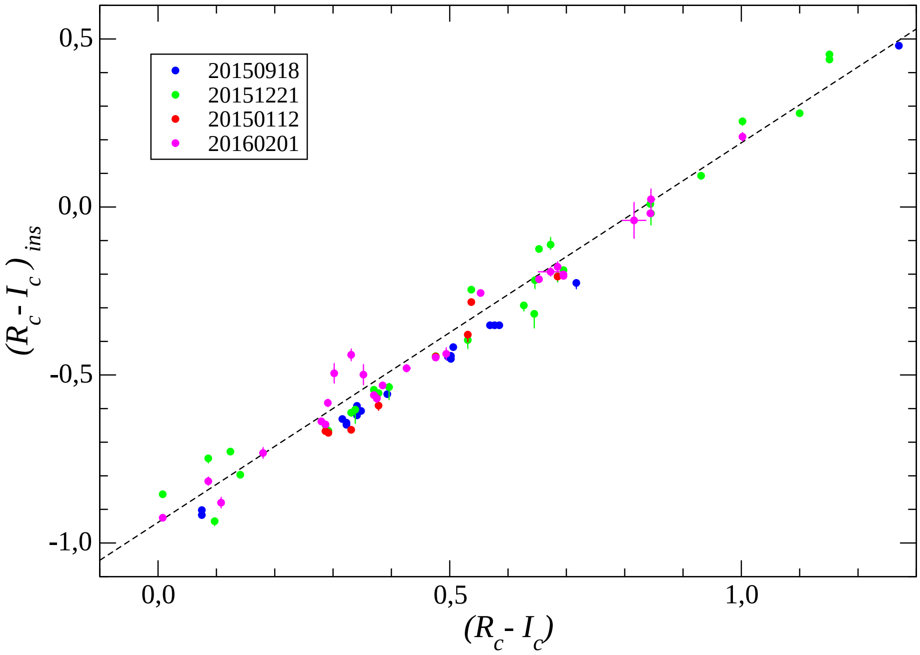

Fig. 11. Dependence of the instrumental versus true $(R_c - I_c)$ color for the UJT CCD camera and filter set. Landolt standard stars observed on different dates are combined in this plot (see legend). The transformation coefficient $T_{R_cI_c}$ is the inverse of the slope of the least squares linear fit.

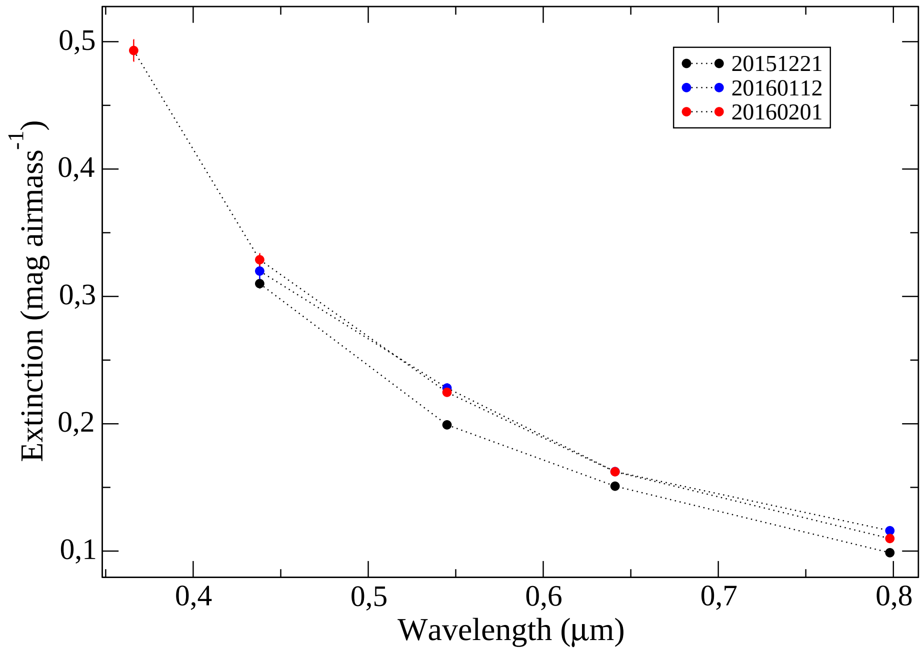

Fig. 12. Dependence of the atmospheric extinction as function of filter central wavelength observed on three different dates at the UJT urban site (see legend). The U-band extinction could be measured on one night only.

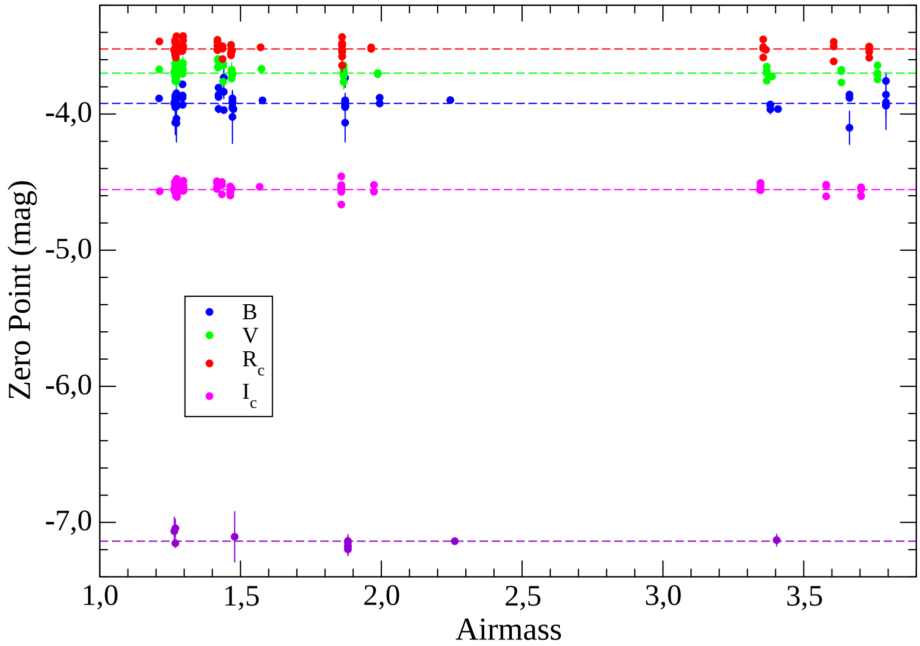

Fig. 13. Zero point of the UJT CCD camera and filter set estimated by combining observations of three different dates under similar atmospheric conditions at the UJT urban site. For all filters, the assumption of a constant zero point in all filters appears well justified. This plot assumes instrumental magnitudes previously computed using the IRAF default value of the zero point ($Z_0 = +25.00$).