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Further Lunar Occultations from the 2.4 m Thai National Telescope

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Abstract

We present the latest lunar occultation (LO) results obtained at the 2.4 m Thai National Telescope, continuing a program started in 2014. We report on 21 LO events for 20 stellar sources, yielding 7 binary stars, 1 angular diameter, and 1 star with extended circumstellar emission. These results, some of which are obtained for the first time, are discussed in the context of previous observations when available.

Key words: binaries: general – occultations – stars: fundamental parameters – techniques: high angular resolution

1. Introduction

We present new results from the lunar occultations (LO) program routinely observed at the 2.4 m Thai National Telescope (TNT). The program and its previous results are described in Richichi et al. (2014, 2016), the former of which we denote as R14 hereafter. Hence, we keep the description of instrumentation and data analysis to a minimum in the present paper.

The program is mainly aimed at detecting binary stars with projected separations as small as a few milliarcseconds (mas) and brighter than $\approx$10 mag, and at measuring stellar angular diameters. In spite of the obvious limitations in the choice of the targets and times of observation, the LO technique is attractive for a telescope of this class because it is simple, economical in terms of time and resources, and affords an angular resolution exceeding the diffraction limit by about two orders of magnitude.

We report here on LO results recorded in the third and fourth TNT observing cycles, between 2015 October and 2017 April.

2. Observations and Data Analysis

The observations and the data analysis follow closely what was already described in R14, and we provide here only a brief summary. We have used the ULTRASPEC instrument (Dhillon et al. 2014) operated in drift-scanning mode, with window size and rebinning as listed in columns Sub and Bin of Table 1. We have used standard SDSS r', i', z' broad-band filters, as well as a narrow-band N86 filter, centered at 8611 Å with a full-width half-maximum of 122 Å.

The data are in the form of a sequence of several thousand frames for each event, covering about 30 s around the predicted time of the event. These are converted to a FITS cube, from which a light curve is generated by extracting the signal only from within a mask tailored to include the star but to exclude most of the background. We concern ourselves only with about 1 s of data around the occultation event: the LO diffraction pattern lasts in fact less than 0.5 s. This corresponds in practice to about 2″ on the sky. Thus, we are not sensitive to, e.g., wide companions.

We analyze the data by means of both a model-independent maximum-likelihood method to derive the brightness profile of the source (Richichi 1989), and a model-dependent least-squares method to derive parameters such as angular diameters and binary separations (Richichi et al. 1996).

3. Results

The LO events are listed in chronological order in Table 1, which follows the same format as R14, where most of the columns are self-explanatory. *D* and *R* refer to disappearances and reappearances, respectively; the magnitudes and spectra are quoted from SIMBAD; τ and ΔT are the integration and sampling times, respectively; S/N is the signal-to-noise ratio, measured as the unocculted stellar signal divided by the rms of the fit residuals; in the notes, UR, Diam, and Bin stand for unresolved, resolved diameter, and binary star, respectively.

The stars with a positive determination (i.e., not unresolved) are listed in Table 2, which also follows the format used in our previous papers. Columns 2 and 3 list the measured rate of the event *V* and its deviation from the predicted rate V_t. This deviation is due primarily to slopes in the local lunar limb ψ, which can thus be computed and are listed in Column 4. Only in two cases (SAO 92922 and HD 92323) could the actual rate of the event not be determined, and therefore, we report in Table 2 merely the predicted geometrical values. We expect that the real PA might differ from the predicted value on average by few to $\approx$10°. Columns 5 and 6 list the Position Angle and the Contact Angle of the event, with the limb slope already included. For the sources found to be resolved, column 7 lists the best-fitting angular diameter in the uniform disk approximation. For the binary stars, columns 8 and 9 list the projected separation (along the PA direction) and the brightness ratio, respectively. The last column reports for convenience the filter, already listed in Table 1.

We discuss our results, also in the context of available previous studies, in the subsequent subsections, which follow the chronological order of Table 1.

3.1. SAO 163645

This binary system was first reported by van den Bos (1962) using a visual micrometer, and it was later followed up by LO (Eitter & Beavers 1979) and extensively by speckle interferometry (see Mason et al. 2010, and references therein). These latter authors also computed updated orbital elements, which, if used at face value for the epoch of our observation and observed position angle of limb scan, would place the

Table 1
List of Observed Events

Date (UT)	Time	Type	Source	V (mag)	Sp	Filter	Sub (pixels)	Bin	τ (ms)	ΔT	S/N	Notes
2015 Oct 21	13:39	D	SAO 163645	6.1	K1III	i'	8 × 8	no	6.1	6.3	81.5	Bin
2015 Nov 20	11:44	D	SAO 146419	8.5	M2III	z'	16 × 16	2 × 2	6.6	6.9	55.6	UR
2015 Nov 22	14:06	D	HD 5143	7.3	F0V	r'	16 × 16	no	11.9	12.2	45.5	Bin
2015 Nov 23	16:25	D	IRC +10023	6.6	M0	N86	8 × 8	2 × 2	3.7	3.9	32.3	Shell
2015 Dec 21	11:29	D	SAO 92922	7.1	K0	z'	16 × 16	no	11.9	12.2	11.3	Bin
2015 Dec 22	18:53	D	IRC +10046	7.6	M3	N86	8 × 8	2 × 2	3.7	3.9	40.6	UR
2016 Jan 19	17:01	D	SAO 93803	7.2	A0	r'	8 × 8	no	6.1	6.3	75.6	Bin
2016 Mar 28	20:42	R	HD 147473	6.9	F0V	r'	16 × 16	2 × 2	6.6	6.9	45.8	Bin
2016 Mar 30	21:37	R	IRC −20434	9.2	K0Ia	N86	16 × 16	2 × 2	6.6	6.9	30.5	UR
2016 Apr 18	19:28	D	HR 4418	4.9	G8IIIa	N86	8 × 8	2 × 2	3.7	3.9	28.2	UR
2016 Oct 17	22:15	R	SAO 93803	7.2	A0	r'	16 × 16	2 × 2	6.6	6.9	9.4	UR
2016 Nov 4	12:27	D	SAO 161245	8.9	B7Ib	r'	16 × 16	2 × 2	6.6	6.9	27.7	UR
2016 Nov 5	12:40	D	IRC −20539	6.6	K3III	N86	16 × 16	2 × 2	6.6	6.9	47.3	UR
2016 Nov 15	20:29	R	SAO 94830	6.6	G7Ib-II	N86	16 × 16	2 × 2	6.6	6.9	15.5	UR
2016 Nov 16	21:50	R	SAO 96172	8.1	F5	r'	16 × 16	no	11.9	12.2	36.2	UR
2017 Jan 7	16:55	D	SAO 93059	6.5	K0	i'	8 × 8	no	6.1	6.3	65.8	UR
2017 Jan 14	18:36	R	HD 92323	7.5	F5	i'	16 × 16	no	11.9	12.2	41.6	Bin
2017 Feb 20	23:07	R	IRC −20496	13.0	M8	r'	16 × 16	2 × 2	6.6	6.9	70.2	UR
2017 Mar 8	14:44	D	SAO 97472	5.6	K3III	r'	8 × 8	no	6.1	6.3	37.3	Bin
2017 Mar 20	21:07	R	IRC −20535	11.2	M6	N86	16 × 16	no	11.9	12.2	38.5	Diam
2017 Apr 4	13:37	D	SAO 97200	8.5	G5	N86	16 × 16	no	11.9	12.2	41.7	UR

companion at a projected separation of 82.1 mas, slightly discrepant with our measured value of 100.0 mas—although still within the formal error on the orbit. We also note that the secondary star in the LO light curve is clearly occulted before, and therefore to the West, of the primary. This seems off by 180° from the orbital plot of Mason et al. (2010), but in fact a recent revision of the orbital parameters by Dr. B.D. Mason (2017, private communication) has resulted in a new orbital plot that is in complete agreement with our determination both in terms of quadrant and of projected separation.

This highlights the potential that accurate LO measurements can still hold in refining orbital elements of binary stars even when these can be, in principle, well studied by other techniques. Another useful constraint added by LO is the very precise flux ratio, in this case accurate to 0.2% in the i' filter, which can be used to constrain the mass ratio. The spectral types are K1/2III and F, and the combined mass is $2.08 \pm 0.49\, M_{\odot}$ (Mason et al. 2010), but the dynamical masses could not yet be resolved by Malkov et al. (2012).

3.2. HD 5143

This bright, relatively wide binary has been observed extensively both by visual observers (starting with Muller 1954) and speckle interferometry, of which we cite only the latest namely Tokovinin et al. (2015). No LO of this system were reported until the present work. One peculiarity of our observation is that the predicted contact angle was almost zero (−1°), so that the relatively large limb slope that we determine from the data could be with equal probability positive or negative. We report the negative ψ value and associated PA in Table 2. Interestingly, both the negative and positive values lead to a good agreement with the expected projected separation that we compute using the revised orbital elements published by Tokovinin et al. (2015). Even allowing for the formal errors in the orbit, the range is 88–98 mas, to be compared with our measurement of 91.6 mas. In this case, the LO result does not add valuable constraints to the orbit, and the chief benefit is in the flux ratio determination.

3.3. IRC+10023

This star is classified as M4 by Kwok et al. (1997) on the basis of IRAS LRS spectra, which is consistent with its visual and near-IR colors. No previous high angular resolution measurements are available, which includes any previous LO events.

Our LO light curve is only marginally fitted by a point-source model (normalized $\chi^2 = 1.3$), while a more satisfactory fit ($\chi^2 = 0.9$) is achieved with the model of a star surrounded by extended circumstellar emission. The emission extends over ≈100 mas and contributes about 9% of the total flux at 0.86 μm. It also appears to be shifted to the West, with the star actually lying at the edge of the emission. This could be indicative of a bipolar nebula, not uncommon in the case of AGB stars.

McDonald et al. (2012) have indeed reported a 96% IR excess over the model photospheric flux for this star using data from visual to 25 μm, adding plausibility to our finding. The peak of the IR emission is estimated at 4.6 μm, so that high angular resolution studies at near-IR wavelengths would be desirable. We also note that the best fit to our LO curve provides an upper limit on the angular diameter for the central star ≈2 mas. This is in general agreement with the value of 2.3 mas, which can be deduced from the estimates by McDonald et al. (2012) for the distance, luminosity, and $T_{\rm eff}$ of the central star.

3.4. SAO 92922

This binary was first detected by means of LO by Edwards et al. (1980) but not confirmed in a subsequent event observed by Schmidtke & Africano (1984). Further speckle observations eventually confirmed the binarity and added several measurements (Mason 1996; Hartkopf et al. 1997; Mason et al. 2001);

Table 2
Summary of Results: Angular Sizes (Top) and Binaries (Bottom)

(1) Source	(2) V (m/ms)	(3) $(V/V_t)-1$	(4) $\psi(°)$	(5) PA (°)	(6) CA (°)	(7) ϕ_{UD} (mas)	(8) Proj. Sep. (mas)	(9) Br. Ratio	(10) Filter
IRC+10023	0.5829	−8.2%	9.7	158.7	31.7	≈100 (shell)	⋯	⋯	N86
IRC−20535	−0.4540	9.7%	4.1	45.1	130.1	3.20 ± 0.03	⋯	⋯	N86
SAO 163645	0.6292	7.2%	−8.6	268.4	20.4	⋯	100.0 ± 0.2	2.817 ± 0.005	i'
HD 5143	0.5943	−11.7%	−27	212.0	−28.0	⋯	91.6 ± 0.1	2.708 ± 0.002	r'
SAO 92922	0.3700	⋯	⋯	304.0	60.0	⋯	8.3 ± 0.2	3.67 ± 0.05	z'
SAO 93803	0.5290	0.0%	0.0	310.0	45.0	⋯	75.6 ± 0.2	8.35 ± 0.02	r'
HD 147473	−0.4109	−8.1%	−5.8	244.2	137.2	⋯	62.6 ± 0.6	1.199 ± 0.001	r'
HD 92323	−0.6380	⋯	⋯	105.0	170.0	⋯	416.5 ± 0.7	2.231 ± 0.002	i'
SAO 97472	0.4970	−8.1%	7.8	319.8	35.8	⋯	4.60 ± 0.02	11.47 ± 0.04	r'

however, orbital elements have not been determined yet. Our LO event took place about 17 years after the last available speckle determination, therefore providing a useful constraint both in terms of projected separation and flux ratio. Note however that we could not determine the actual lunar limb slope due to poor sampling, leaving a small uncertainty on the position angle.

3.5. SAO 93803

This star was detected as binary by LO (Edwards et al. 1980; Radick & Lien 1982) but could not be resolved by speckle (Hartkopf & McAlister 1984; Mason 1996). The missed detections by speckle could have been due to the relatively large flux ratio.

About 37 years separate the first LO detections from our measurement, shown in Figure 1, making a direct comparison impossible. However, we note that all LO projected separations are in the range 40–70 mas, indicating a possible true separation of order 0″1, or ≈20 au at the distance of ≈200 pc (from *Hipparcos*). Assuming a system mass of ≈3 $M_\odot$ from the A0 spectral type and luminosity, the period could be of order 50 years, so that the intervening 37 years could possibly bracket a significant fraction of the orbit.

We recorded a second LO event of SAO 93803 a few months later, in the same filter. Unfortunately, this time the SNR was only 9.4, so that detecting the 8.3-times fainter companion was at the limit. For this reason, we listed this second event as unresolved in Table 1. We note however that the data could indeed be fitted with a binary model, yielding a 13% decrease in the standard deviation. This solution would result in a companion having a 1:5.9 flux ratio, with projected separation 53 ms along position angle 272°. If real, and neglecting orbital motion in the intervening 9 months, combining the two measurements would result in a true position angle of 318° and separation 76 mas. Given the low SNR of the second LO measurement, we cannot give full credibility to this result, and we quote it only as a reference for future more accurate observations.

3.6. HD 147473

This is another example of a binary first discovered by LO (Radick et al. 1982) and then extensively followed up by speckle. Without quoting all references, we mention the results by the CHARA group (six papers, the most recent being Hartkopf et al. 2000), and the ones by Horch et al. (2015) and Tokovinin et al. (2015), with measurements obtained in 2014. Incidentally, we note that these two latter references are very

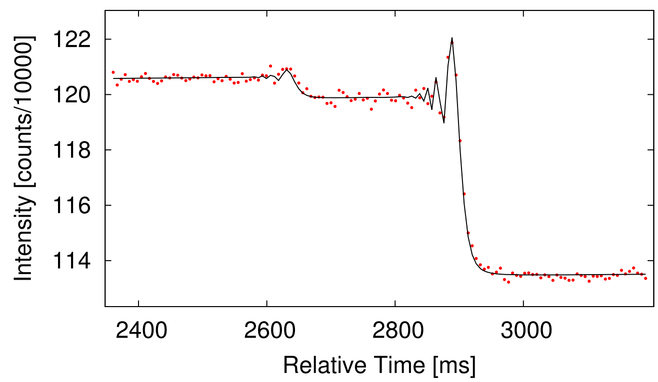

Figure 1. Occultation data (dots) for the January 19 event of SAO 93803, and best fit by a binary source model (solid line).

much in agreement between themselves except for a 180° discrepancy in the position angle.

Our measurement puts the secondary in the same quadrant as Tokovinin et al. (2015). These authors observed HD 147473 in 2014.30, almost 2 years before our LO event. Adopting their values for position angle and separation (227°.1 and 90.6 mas, respectively), the projected separation at our event should have been 86.6 mas. Our significantly smaller value of 75.6 mas can probably be largely attributed to orbital motion in the intervening 2 years, given that the period is estimated at 35.7 years (Malkov et al. 2012). Additionally, the magnitude difference is largely consistent, being quoted as 0.4 mag by Tokovinin et al. (2015) in a y filter, against 0.197 mag found by us in a r' filter. This would indicate a secondary redder than the primary, which is quite plausible as the primary is F0V.

3.7. HD 92323

This visual binary has already been extensively measured by micrometer observers from the 1950s and more recently by speckle. The references are too numerous to be listed here. We compared our result with the latest available determination by Prieur et al. (2012), who reported a separation of 510 ± 11 mas along position angle 139°.5 at epoch 2010.30. The agreement is excellent within the error in spite of the 6.7 years elapsed. This is indeed a small amount when compared to the period of 225.3 years in conjunction with a low eccentricity (Hartkopf & Mason 2010; Malkov et al. 2012). Our measurement adds a very precise constraint on the flux ratio.

3.8. SAO 97472

LO events of this star were recorded by several authors (Eitter & Beavers 1979; Evans & Edwards 1981; Beavers & Eitter 1986), without evidence of being resolved. Beavers et al. (1981), however, reported a resolved angular diameter of 4.0 ± 1.5 mas. Mason (1996) could not detect binarity by speckle observations. This star is listed as non-binary in the multiplicity compilation of Eggleton & Tokovinin (2008).

Our light curve is not consistent with a point-source. Fits were attempted by both a resolved diameter and a binary model, with the latter giving the best solution. The projected separation of just 4.60 mas can well justify why the source was not detected by speckle and how it could mimic the angular diameter reported by Beavers et al. (1981). At a distance of 250 pc (from *Hipparcos*), our result puts a lower limit on the separation of just over 1 au so that the orbital period should be of the order of a few years.

SAO 97472 has been included in a high-precision near-IR radial velocity monitoring survey for the purpose of detecting exoplanets around giant stars (Trifonov et al. 2015). The data over 466 days show a clear RV trend in this star, which would be consistent with our binarity detection.

3.9. IRC-20535

We recorded the first LO event of this M6 late-type star, for which no other high angular resolution investigations have ever been reported. We find the source to be resolved with an angular diameter of 3.20 ± 0.02 mas, consistent with the value 2.75 ± 0.34 mas expected on the basis of its magnitude, color, and type (van Belle 1999). In the IRAS low-resolution spectra, this source shows a 9.7 μm silicate emission feature (Kwok et al. 1997) indicative of a possible circumstellar shell, which however, we do not detect in our filter.

3.10. Other Sources

IRC+10046 and IRC-20496 are late-type giants for which resolved angular diameters might have been expected (e.g., 2.3 and 3.0 mas, respectively, using the calibration of van Belle 1999). We found them unresolved with upper limits of 1.6 and 2.2 mas, respectively, which is not a significant disagreement considering that they are variable with large variations on the magnitudes used for the empirical estimates. We also found IRC-20434, which is the K0 supergiant AX Sgr, to be unresolved with an upper limit of 2.7 mas when the expected angular diameter estimate would have been at the 1.7 mas level in order to reconcile the bolometric flux modeled by McDonald et al. (2012) with the $T_{\rm eff}$ calibration by Levesque et al. (2005). In all of these cases, a faster sampling of the LO curves would have been required for better angular resolution.

HR 4418 is WDS 11279+0251, a visual multiple star with very wide separations: we did not concern ourselves with the other components.

SAO 161245 was reported as "possibly double" by Radick & Lien (1980), with $\Delta m \approx 1.5$ in a Strömgren *b* filter. The projected separation was $0\farcs62$. Speckle follow up by Mason (1996) was negative, although the companion should have been detected with the quoted minimum separation. Also, our LO curve had sufficient sampling and SNR to detect the companion, barring the very adverse effects of projection and stellar color.

4. Conclusions

Using the LO technique, we measured for the first time, the angular diameter of IRC-20535, a M6 variable star, and the circumstellar shell around IRC+10023, another M giant with an infrared excess. The bulk of our results have concerned binary stars, among which SAO 97472 has been detected as a small separation double for the first time. The projected separation was just under 5 mas, and the estimated orbital period could be of just a few years, with a potential for a quick determination of the dynamical masses if followed up with methods such as long-baseline interferometry. The other binaries were previously known, but our measurements have added some needed confirmations or exposed some inconsistencies in available orbital solutions. Our measurements provide, in most cases, accurate differential photometry to a level or in filters not previously available.

This research made use of the SIMBAD database, operated at the CDS, Strasbourg, France.

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