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ON DETERMINATION OF ANGULAR SIZES OF SOME RELATIVELY HOT STARS BY LUNAR OCCULTATION OBSERVATIONS AND ON SUGGESTED INTERFEROMETRIC INVESTIGATION OF THESE STARS

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RESUMEN

Las observaciones interferométricas y lunares de ocultación de estrellas son dos técnicas eficaces que nos permiten alcanzar una alta resolución angular, a un nivel de 1 milisegundo de arco y mejorar los rangos espectrales en el visual y el IR cercano. Varias decenas de curvas de difracción fotoeléctricas de ocultaciones lunares de varias estrellas se han registrado con una resolución de 1 milisegundo y alta resolución temporal en los observatorios del Instituto Astronómico de Sternberg durante dos períodos de cerca de diez años. Entre las estrellas estudiadas con este método hay un número de estrellas relativamente calientes. Para algunas de ellas los tamaños angulares determinados del análisis de las curvas de difracción registradas durante la ocultación muestran ser diferentes a los esperados. Se sugieren posibles explicaciones de estas discrepancias. Se presenta una tabla con la información sobre las estrellas que se podrían sospechar de tener una estructura compleja en base al análisis de las observaciones de ocultación lunar y de otros datos disponibles. Los objetos estelares descritos aquí podían convertirse en un tema de investigación interferométrica por modernos sistemas interferométricos de gran alcance.

ABSTRACT

Interferometric and lunar occultation observations of stars are both the effective techniques which allow us to reach high angular resolution at a level of 1 milliarcsecond and better both in the visual and in the near-IR spectral ranges. Several tens of photoelectric diffraction curves of the lunar occultations of various stars have been recorded with a high time resolution of 1 millisecond at the observatories of the Sternberg Astronomical Institute during about two ten-year periods. Among the stars studied by this method there is a number of relatively hot stars. For some of them the angular sizes determined from analysis of the recorded occultation diffraction curves prove to be different from the expected ones. Possible explanations of such a discrepancy are suggested. A table with information on the stars which could be suspected to have complex structure on the basis of analysis of the lunar occultation observations and other available data is presented. The stellar objects described here could become a subject of interferometric investigation by modern powerful interferometric systems.

Key Words: binaries (including multiple): close — circumstellar matter — stars: fundamental parameters — techniques: high angular resolution — techniques: interferometric — techniques: photometric

1. GENERAL INFORMATION

Photoelectric observations of lunar occultations of stars allow us to reach high angular resolution at a level of 1 milliarcsecond or even better (for sufficiently bright sources) both in the visual and in the near-IR spectral ranges, and therefore permit to measure directly the angular sizes of various stellar objects and to detect their multiplicity or indications of presence of some circumstellar matter around them. Let me remind you that the analysis of the diffraction curve observed when a star is being occulted by the moon's dark limb lies at the basis of this method. In Figure 1 one can see a general view of theoretical diffraction curves corresponding to the real occultation curves usually recorded for a single star. Accurate high-speed photoelectric photometry allows us to distinguish between the diffraction curve obtained in observation of the occultation of a star having a finite angular diameter and an analogous one recorded while observing the occultation of a point-like source.

Several tens of photoelectric diffraction curves of the lunar occultations of various stars have been recorded with a high time resolution of 1 millisecond at the observatories of the Sternberg Astronomical Institute during about two ten-year periods. Observations were carried out with use of different com-

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TABLE 1

RELATIVELY HOT STARS WHICH CAN BE SUSPECTED TO HAVE COMPLEX ANGULAR STRUCTURE FROM ANALYSIS OF THE LUNAR OCCULTATION DIFFRACTION CURVES AND FROM STUDY OF OTHER AVAILABLE DATA

No.	Name	HR (HD)	V (m_v)	Sp	Comments
1	68 δ^3 Tau - A	1389	4.311	A2 IV	There were some doubtful data on close duplicity
2	36 Gem - A	2529	5.27	A2 V	No other reliable data on close duplicity
3	SAO 77215	HD 36113	6.9	B5	The same
4	SAO 78858 - A	HD 50634	6.80	B9.5 V	The same
5	SAO 93963 - A	HD 28406	6.91	F8	The same
6	σ (57) Aqr	8573	4.825	A0 IVs	The same
7	μ Cet	813	4.27	F0 IV	There were some data on close duplicity
8	54 λ Gem - A	2763	3.581	A3 V	There were some data on close duplicity
9	23 τ Sco	6165	2.82	B0 V	No other reliable data on close duplicity

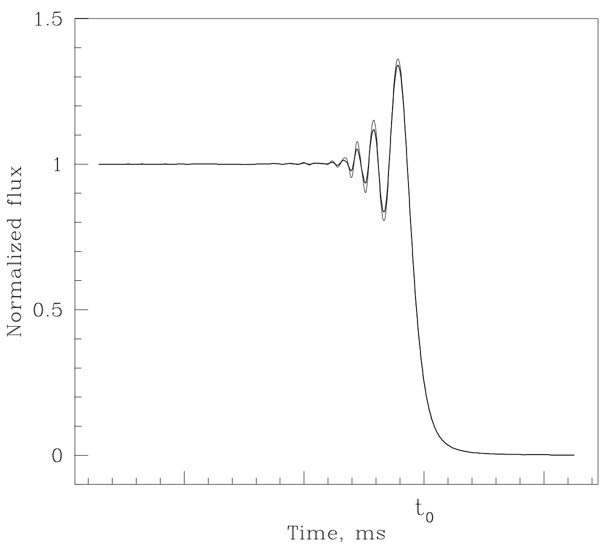

Fig. 1. Theoretical diffraction curves for a single star. The thin line is an occultation diffraction curve for a point-like source; the thick line shows an occultation curve for a star with some small finite angular diameter. On the horizontal axis time t is given, t_0 is the moment of geometric occultation of the stellar disk centre.

plexes consisting of photoelectric photometer, computer and a special interface device, at the High Mountain Observatories in Tien-Shan' (Kazakhstan) and at Mt. Maidanak (Uzbekistan), and also at the 70 cm reflector of the Institute in Moscow.

Among the stars which were studied by this method there is a number of stars having early or relatively early spectral types, i.e. relatively hot stars. For most of such stars their angular sizes have been determined from analysis of the recorded occultation diffraction curves. In a number of cases the results obtained prove to be different from the expected ones: these results are in contradiction with other direct measurements of the angular diameters of stars under study or with reasonable indirect estimates of these values for the stars of corresponding spectral types and luminosities; in some other cases there are contradictions in the results of different measurements of angular separations between components of close binary stars.

Below you can see the Table 1 where the stars which could be suspected to have complex structure on the basis of analysis of the lunar occultation diffraction curves and other available data are listed. This list is of course not finished, it is to be continued as a quantity of the ambiguous results of the lunar occultation observations is increased.

2. SPECIFIC EXAMPLES OF AMBIGUOUS RESULTS

In some cases, the processing of the data obtained by fitting an optimal single-star model results in the value of angular diameter which is much larger than its reasonable indirect estimates for a star of given spectral type and luminosity, although the quality of fitting is sufficiently good. The first example is the occultation diffraction curve of the star 68 δ^3 Tau = HR 1389 which has been recorded in the visual B spectral band ($\lambda_0 \simeq 0.44\,\mu$ m) at the High-Mountain Tien-Shan' observatory of the SAI (Figure 2). The star has a magnitude $V = 4.311$ and spectral class A2 IV, it is a variable star V 776 Tau with a period of $57^d.2$ and a visual trinary ADS 3206, in which the

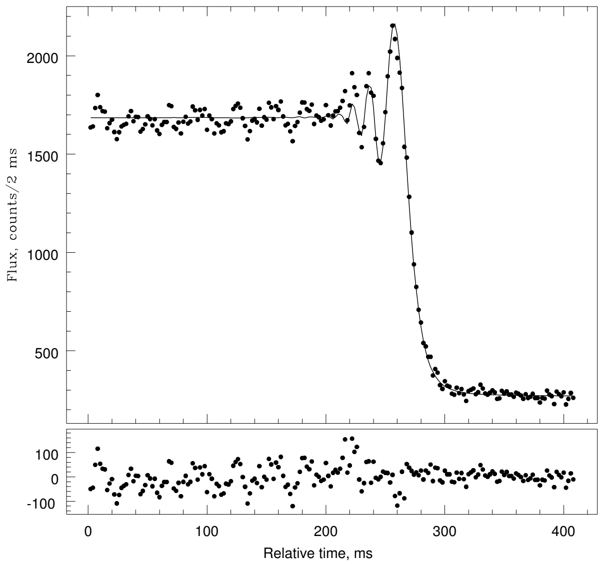

Fig. 2. Occultation diffraction curve of 68 δ^3 Tau = HR 1389 in the B band. Tien-Shan' observatory of the SAI, 48 cm reflector. Observer: E.Trunkovsky. The dots represent the data of the flux measurements (the photometer counts in the interval of 2 ms), the solid line is the optimal model curve for the occultation of a single star. Horizontal axis: relative time in ms; vertical axis: flux (counts in 2 ms); second vertical axis: deviations of the recorded counts from the optimal model diffraction curve (counts in 2 ms).

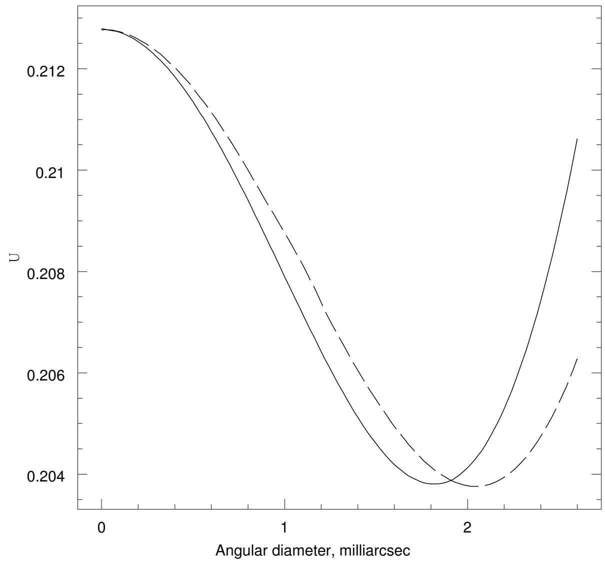

Fig. 3. Dependence $u(d)$ obtained in the processing of 68 δ^3 Tau's occultation curve for $\mu = 0$ (solid line) and $\mu = 1$ (dashed line).

angular distance between two most bright components "A" and "B" is $1''.4$ and magnitude difference between them is $3^m.3$ (Dommanget & Nys 2002).

The occultation curve presented here is related to the main component "A"; its angular diameter was estimated by different indirect methods, which yielded the values d of $0''.0006$, $0''.00046$ and smaller (Fracassini et al. 1981, 1973). The primary "A" star itself was known for a long time as a close spectral binary with a period of $57^d.2$ (Hoffleit & Jaschek 1991), however some relatively recent spectroscopic observations did not show evidence for the spectral binarity; so information on the primary's structure is rather inconsistent.

In the data processing by fitting an optimal single-star model diffraction curve we have obtained a dependence $u(d)$ of the sum u of the normalized deviations squared of the recorded data from the best model curve on the given value of angular diameter d (Figure 3); this dependence clearly shows a pronounced minimum near the value $d = 0''.00182$ (for a uniformly illuminated stellar disk with a limb-darkening coefficient $\mu = 0$) or $d = 0''.00204$ (for a fully limb-darkened stellar disk with $\mu = 1$).

Since the relative rms deviation of the recorded data from the optimal model curve (expressed as a percentage of the signal drop during occultation) is reasonably small (in comparison with other observations) and accounts for about 3.2%, one may consider the quality of this occultation curve as rather high, and, consequently, the result obtained as sufficiently reliable. Besides, as it follows from our numerical experiments, a possible error in determination of the d value due to effect of the stochastic noise, which was being present during observation, on the solution found from the recorded occultation curve, should not as a rule exceed noticeably $0''.001$ and, at the actual noise level in the given specific case probably accounts for a value of not more than $0''.0007$.

Thus the d value obtained in the occultation data processing exceeds significantly a reasonable indirect estimates of angular diameter of the main component, and therefore can be considered as some effective angular size of the object which possibly has a compound nature. I.e. this could mean that the primary star of 68 δ^3 Tau is actually a very close binary or multiple system, especially if we take into account the evidences of the spectral binarity mentioned earlier. On the other hand, since information on the binarity of the main component is somewhat ambiguous, one may presume also a presence of extended envelope or some disk-like structure around the star itself. The angular size of the emitting region which has been determined from the occultation

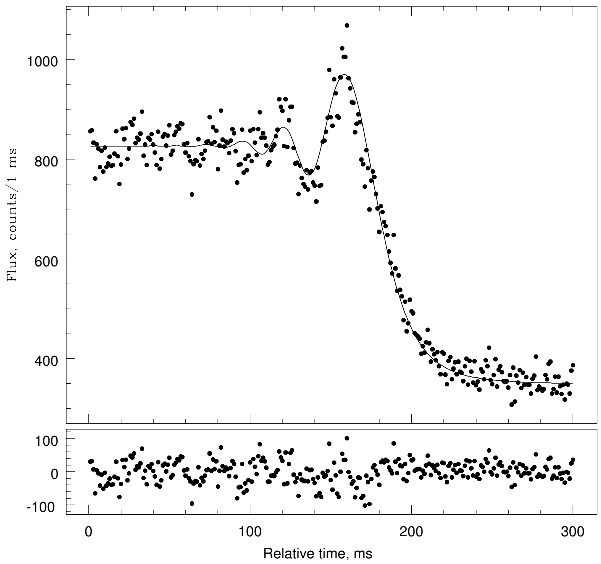

Fig. 4. Photoelectric occultation curve of σ Aqr = HR 8573 in the V band. Mt. Maidanak observatory of the SAI, 60 cm reflector. The dots represent the data of the flux measurements (the photometer counts in the interval of 1 ms), the solid line is the optimal model diffraction curve for the occultation of a single star. Horizontal axis: relative time in ms; vertical axis: flux (counts in 1 ms); second vertical axis: deviations of the recorded counts from the optimal model curve (counts in 1 ms).

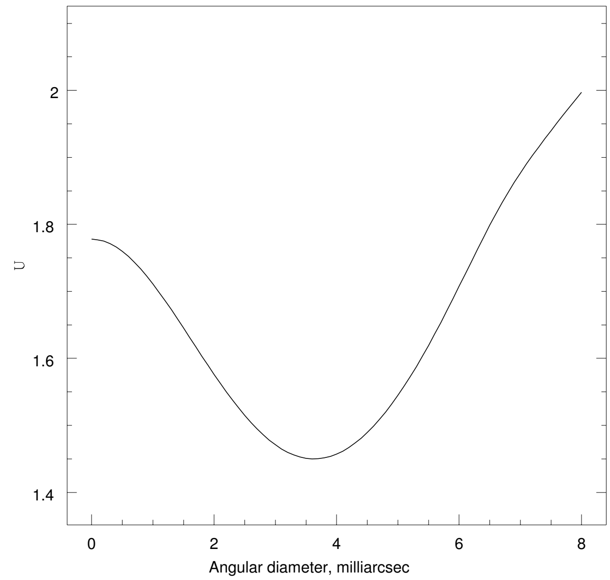

Fig. 5. Dependence $u(d)$ obtained in the processing of σ (57) Aqr's occultation curve.

data corresponds to the linear dimension of about 0.1 a.u.

The next example is the occultation curve of the star σ (57) Aquarii = HR 8573 which has been recorded in the visual V spectral band ($\lambda_0 \simeq 0.53\ \mu$ m) at the Mt. Maidanak observatory of the SAI in Uzbekistan with 60 cm reflector (Figure 4).

The star has a magnitude $V = 4.825$ and a spectral class A0 IVs. It is known as spectroscopic binary (Hoffleit & Jaschek 1991) but the detailed information concerning variability of radial velocities is absent in "The Bright Star Catalogue" (Hoffleit & Jaschek 1991), as well as any data on this star were not included in the catalogue by Batten et al. (1989). This leads to suggestion that an amplitude of such variability is small, and complete radial velocity curve has not been obtained.

The processing of the occultation curve of σ Aqr has been carried out by two different methods (Irsmambetova et al. 1990). As a result of fitting an optimal model diffraction curve, we've obtained a dependence $u(d)$ (having the same meaning as explained above) which is presented in Figure 5. We can see a pronounced minimum of the function $u(d)$ near the value $d = 0''.0036$ (for $\mu = 0$). The relative rms deviation of the data from the optimal model diffraction curve (expressed as a percentage of the signal drop during occultation) is about 7%, so one may consider the quality of fitting as a satisfactory one.

We have also performed a restoration of the one-dimensional strip distribution of brightness across the object occulted from the observational data by applying the procedure of Tikhonov's regularization method in order to find a solution of the Fredholm integral equation (this approach has been first proposed by Bogdanov (1978)). As a result of this we've got the strip distribution profile along the direction normal to the lunar limb. When regularization parameter is in accord with an accuracy of the initial data, a total width of the main profile of the brightness strip distribution is about $0''.0048$ (4.8 milliarcseconds), while its width at the level of 0.5 of a peak value is about 3 milliarcsec. This result is quite in accord with the angular diameter value obtained in the best model fitting. Besides, the brightness strip distribution shows a secondary peak at the angular separation of 7.0 ± 0.5 milliarcsec from the main one. Assuming that a secondary peak corresponds to the real faint component of the source we can estimate a component luminosity ratio as about 11.5 (Irsmambetova et al. 1990).

As one can see, the d value obtained from the occultation data exceeds by several times a reasonable indirect estimate of angular diameter of a star with given spectral class and luminosity. Really, with the values of trigonometric parallax of σ Aqr $\pi = 0''.021$ (Hoffleit & Jaschek 1991) and of linear radius for A0 IV star $R \simeq 4\ R_\odot$ (an estimate can be taken from Allen 1973) we obtain $d_{\rm est} = 0''.0008$. Therefore one may suppose that d corresponds in fact, for instance, to a projection of some effective angular distance between possible components of the main complex object onto the normal to the lunar limb. Information on the spectroscopic binarity of the star (see above and in Hoffleit & Jaschek (1991)) substantiates such a suggestion.

The results presented allow us to suspect that the star σ Aqr is actually a close binary or multiple system. It is possible also that we deal with an extended shell or disk-like structure around the star itself, the more so as this star belongs to the star-forming region (Hoffleit & Jaschek 1991) and is being a relatively young object. The angular size which has been determined corresponds to the linear dimension of the emitting region (in the sky-plane projection) of about 0.17 a.u. $\simeq 37\ R_\odot$.

In the other cases, information on the binarity or multiplicity of the star being observed in occultation is available from the previous spectroscopic, photometric, interferometric, or occultation observations, however the processing of the recorded occultation curve shows that a single-star model is the best for it, and there are no evidences of presence of secondary components. Also sometimes previous occultation observations gave a perceptible angular size of the star while the processing of our data do not reveal a finite size of the stellar disk.

For example, the photoelectric occultation curve of the star 54 λ Geminorum = HR 2763 has been recorded in the visual B spectral band at the 70-cm telescope-reflector AZT-2 of the SAI in Moscow on March 11, 1995; this curve is shown in Figure 6. Quite considerable flux variations before the occultation itself due to the atmospheric scintillation are clearly seen on the curve.

The star has a magnitude $V = 3.581$ and a spectral class A3 V. It has been known from spectroscopic and occultation observations as a close binary system (in reality, as a triple one, but the third component is quite faint and considerably distant from the two main components), with the angular distance between the components $0''.045$ (at a position angle of the secondary with respect to the primary $\simeq 300°$) and magnitude difference $1^m.0$ (Dunham 1977; Hoffleit & Jaschek 1991). In the processing of our data by fitting an optimal model curve the influence of the atmospheric scintillation has been taken into account. However, we did not reveal explicitly the secondary component whose presence should be expected at the projected separation of at least $0''.038$ (Richichi et al. 1996).

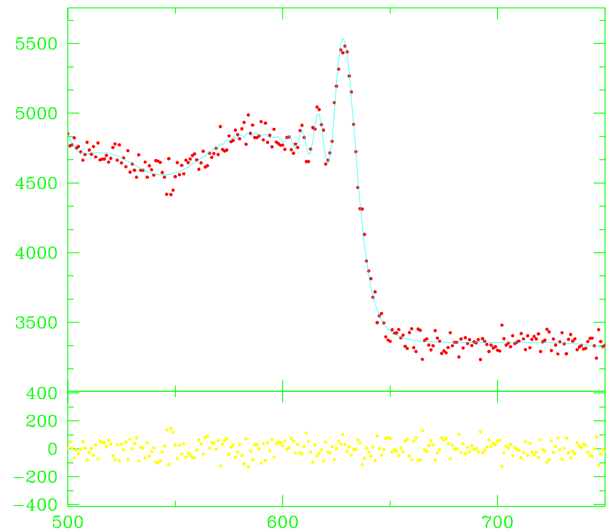

Fig. 6. Occultation diffraction curve of 54 λ Gem = HR 2763 in the B band. March 11, 1995, Moscow, Sternberg Astronomical Institute, 70 cm reflector AZT-2. The dots represent the data of the flux measurements (the photometer counts in the interval of 1 ms), the solid line is the optimal model curve for the occultation of a single star of negligible angular diameter (practically of a point-like source). Horizontal axis: time, ms (conventional values); vertical axis: flux (counts in 1 ms); second vertical axis: deviations of the recorded counts from the optimal model curve which has been fitted (counts in 1 ms).

Such a result probably could be explained by orbital motion of the components of the binary system: the secondary component had been discovered by observation of the star's occultation about 30 years ago, and possibly, it has moved considerably during this interval of time.

In such cases one may also suggest an existence of some disk-like or more complex formation near the main component. Rather complicated motion of circumstellar matter could result in changes of its visibility conditions and, eventually, in a situation when over a periods of time its detection is made difficult.

3. CONCLUSION

Since an opportunities of realizing a repeated research of the angular structure of the sources of interest by means of lunar occultation observations are strictly limited due to a strong dependence of observing chance on the path of lunar motion, an importance of interferometric study of such objects is great. The stellar objects described here could become a subject of interferometric investigation in the visible and near-IR ranges with an angular resolution of about 10^{-1} milliarcsec or better by modern powerful interferometric systems, with the purpose of obtaining reliable and independent high-quality data on their real spatial structure and of checking previously obtained results. Since different parts of the objects could radiate most effectively in different spectral ranges it is desirable during interferometric observations to get images of the sources under study at different wavelengths in order to have more opportunities to reveal substantial details of their structure.

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