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On Direct Measurements of the Angular Sizes of Stars by Lunar Occultation Observations

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Abstract

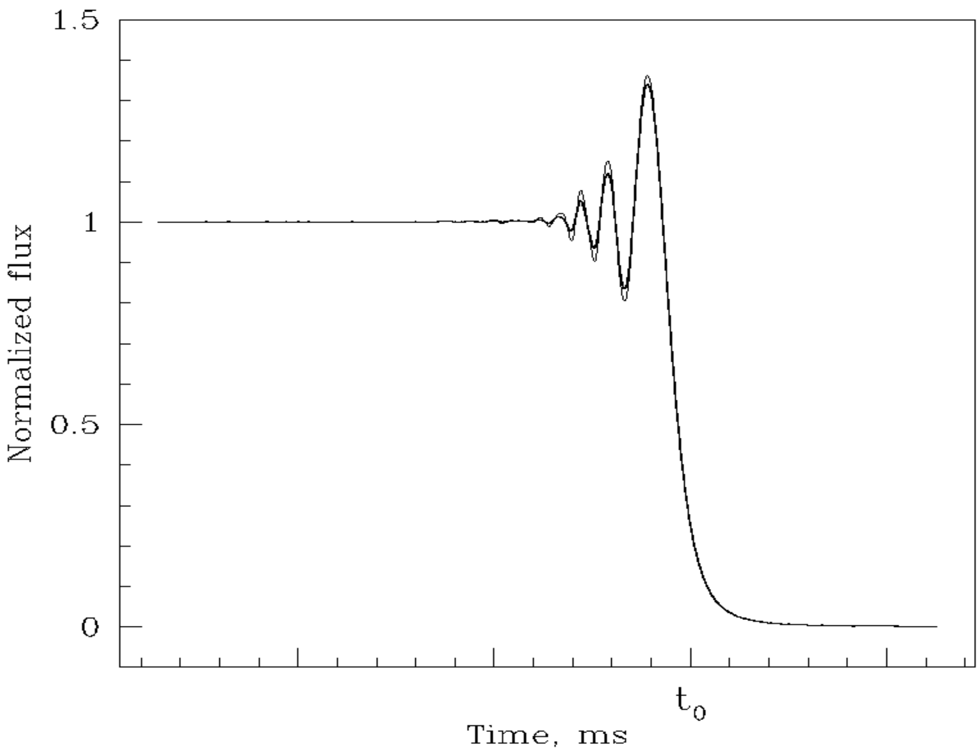
General principles of direct measurements of the angular sizes of stars by lunar occultation observations are briefly described. Some examples of the results obtained from analysis of the occultation diffraction curves recorded in the observatories of the Sternberg Astronomical Institute of the M.V. Lomonosov Moscow State University are presented.

Keywords: Lunar occultations of stars, photoelectric observations, direct measurements of the angular sizes of stars.

General Principles

When the edge of the dark part of the lunar disk covers (occults) one or another star at the movement of the Moon relatively stars in the sky, a diffraction effects arise, and as a result one can record a diffraction curve of stellar occultation. A typical duration of passing of the first Fresnel zone over line of sight of the observer for the light source having a very small angular diameter of the order of a few milliarcseconds (mas) is of the order of 20 milliseconds (ms), therefore for a sufficiently detailed registration of changes of the light flux in the diffraction pattern it is necessary to record them with a time resolution of the order of 1 ms. For that one should have a photoelectric photometer which allows to record light flux from the investigated star with the mentioned time resolution. If the diffraction curve of the lunar occultation of a star is recorded then it is possible to do it's analysis in order to distinguish it from the diffraction curve corresponding to the occultation of a point-like source (having a zero angular diameter), and thus to determine directly the angular size of the star under study. See the Fig.1 below.

Figure 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*



In case of close double star it is also possible to analyze the recorded occultation diffraction curve and to determine directly angular sizes of it, though in this case a model of the occultation process is more complex [1].

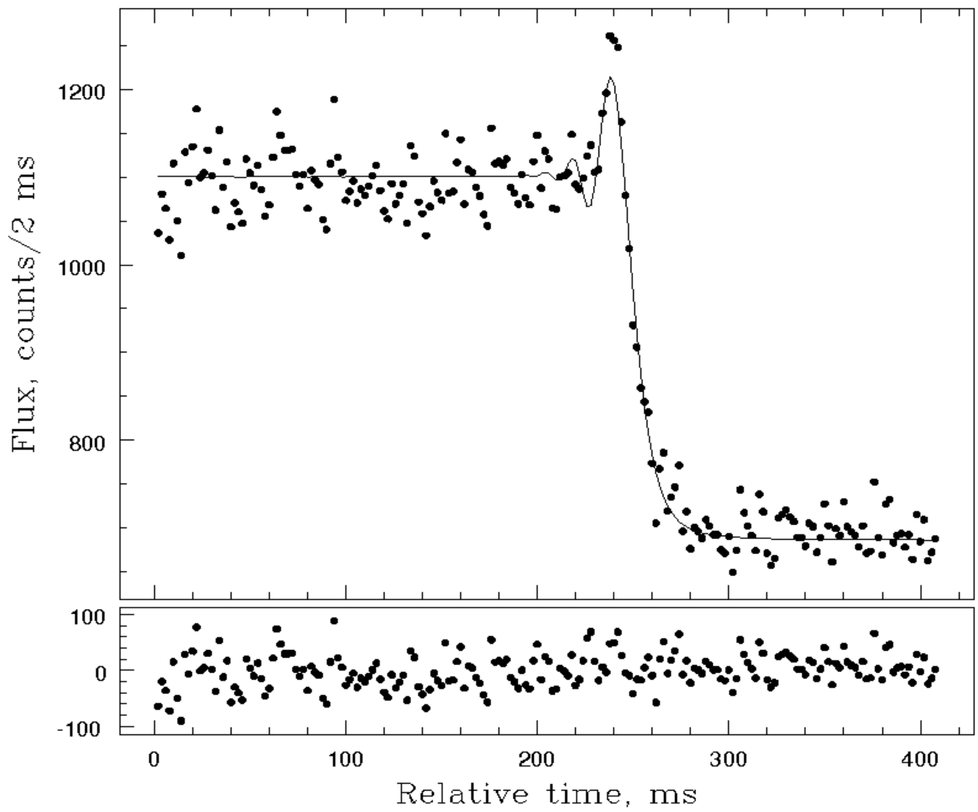
Some Examples of the Results Obtained from Analysis of the Occultation Diffraction Curves Recorded in the Observatories of the Sternberg Astronomical Institute

During about 20 years in the observatories of the Sternberg Astronomical Institute of the M.V.Lomonosov Moscow State University a several tens of occultation diffraction curves of various stars have been recorded with a time resolution of 1 ms. When processing the data obtained the angular diameters of some stars have been determined directly, and in some other cases a close binarity of stars under study has been discovered, and the angular distances between their components and their luminosity ratios have been measured. Several examples of such results are presented below.

The Carbon Star Y Tauri

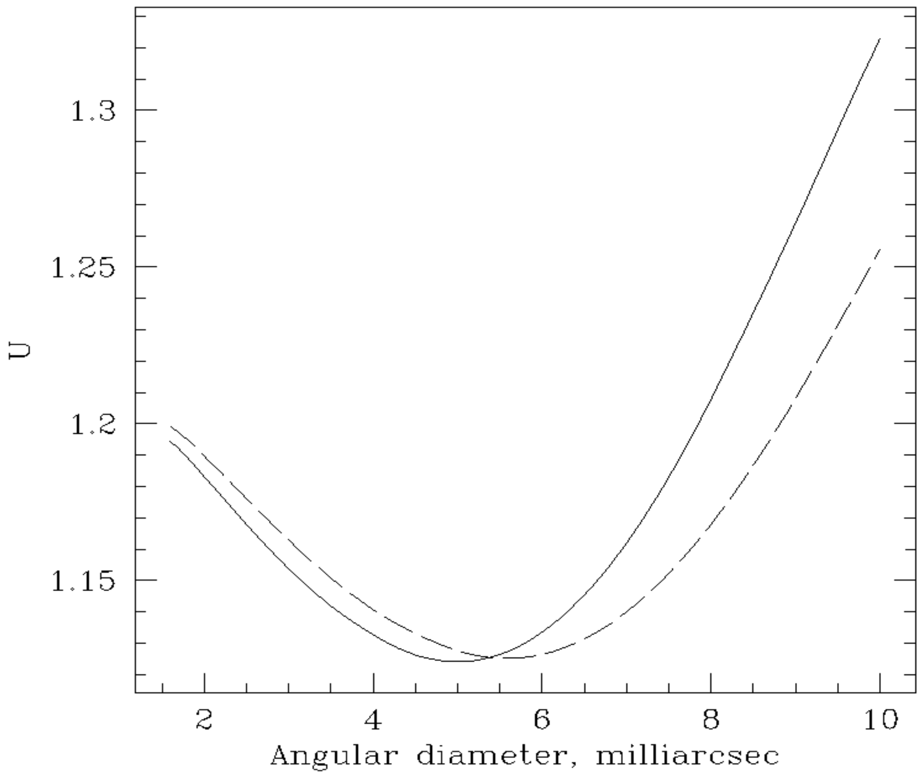
The occultation diffraction curve of the very interesting carbon star Y Tauri has been recorded by the author with a time resolution of 1 ms in the “R” spectral band of optical range on February 4, 1982, with the 48-cm telescope-reflector AZT-14 of the High-Mountain Tien-Shan’ Observatory of the Sternberg Astronomical Institute located near Alma-Ata (Kazakhstan) [2]. Figure 2 shows the recorded occultation curve and the optimal model diffraction curve corresponding to the determined value of the star’s angular diameter.

Figure 2. *Occultation Diffraction Curve of Y Tau Recorded on February 4, 1982. Observer- E. Trunkovsky. Horizontal Axis- Time in Milliseconds Relative to a Certain Conditional Moment. Vertical Axis- Signal Values Proportional to the Measured Flux. Dots- Photometer Counts Corresponding to the Accumulation Interval of 2 ms (Obtained by Adding Each two Consecutive Counts Accumulated over 1 ms); Solid Line- Optimal Model Curve for the Occultation of a Single Star. The Lower Part of the Figure Shows the Deviations of the Counts from the Optimal Model Curve*



In the processing of the photoelectric occultation curve the dependences of *u*- the sum of the squared normalized deviations of photoelectric counts from the model curve—on the angular diameter value *d* under different limb-darkening assumptions have been obtained. Figure 3 shows these dependences.

Figure 3. *u(d) Dependences Obtained in the Processing of the Y Tau Occultation Curve Recorded on February 4, 1982. Solid Curve- for a Uniformly Illuminated Stellar Disk (the Limb Darkening Coefficient μ = 0), Dashed Curve- for μ = 1*



The following angular diameter values were obtained from these dependences (in milliseconds of arc, abbreviated as mas): d = 5.0 mas for a uniformly illuminated stellar disk, and d = 5.6 mas for a fully limb-darkened disk. The error of d was estimated in the paper [2] by the value $\sigma_d \approx 1.2$ mas; this estimate was obtained by constructing “quasi-observed” realizations based on the disturbances of the obtained optimal model curve corresponding to the recorded occultation area [2].

In paper [3] the analysis of the available results of direct angular diameter measurements of this carbon star in different spectral bands of the optical and near-IR spectral ranges has been carried out. Currently, the author is aware of the results of seven (7) direct measurements of the angular diameter of Y Tau obtained from the analysis of photoelectric lunar occultation curves. The occultation curves of Y Tau were recorded both before and after the mentioned observation by Trunkovsky [2]. It should be emphasized that among the known occultation observations only two were made in the optical range (in the red part) of the spectrum. All the remaining occultation observations of this star were conducted in the near-IR spectral range.

The catalog [4] gives the following variability ephemeris based on the photometric data for this star:

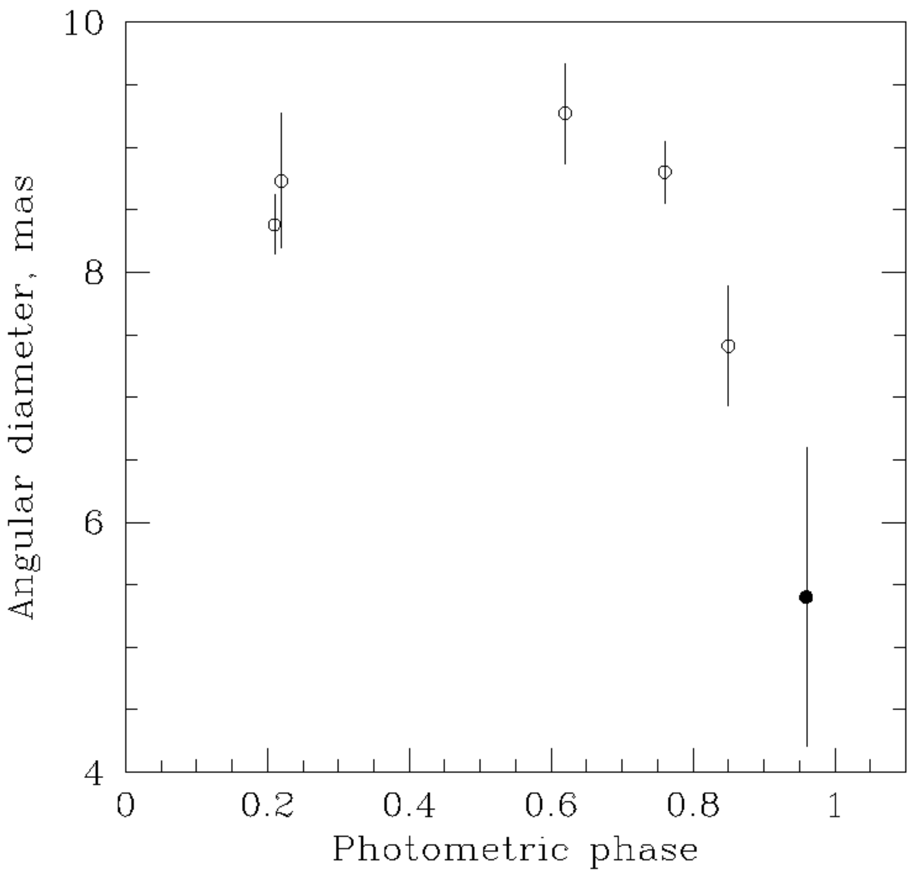
$$JD_{max} = 2437065 + 240^{d}.9\ E. \qquad (1),$$

where $240^{d}.9$ is a period (or quasi-period) of the photometric variability.

One can assume (with certain reservations) that the ephemeris (1) represents fairly adequately the typical characteristics of the photometric variability of Y Tau in those years when the mentioned photoelectric lunar occultation observations of Y Tau were carried out. Having made such an assumption, one can compute the corresponding phases φ of this photometric variability bearing in mind that $\varphi = 0$ at photometric maximum.

The dependence of angular–diameter values d of Y Tau, obtained from the known lunar occultation observations in the near-IR H spectral band and R spectral band of the optical range, on the phase of its photometric variability φ is shown in Fig. 4; also shown are the corresponding errors for these values.

Figure 4. *Values* d *of Angular Diameter of Y Tau, Obtained from Lunar Occultation Observations in the "H"* and "*R"* Spectral Bands*, as a Function of the Phase* φ *of Photometric Variability of the Star. The Values* d *Correspond to the Adopted Limb Darkening Model. The Value of* d *Obtained from the February 4, 1982 Observation in the "R"- Band is shown by the Black Circle*



It is sufficiently clearly seen that the dependence of *d* on the phase of photometric variability, shown in Fig. 4, suggests the presence of periodic or quasi-periodic variations of the star's diameter. The angular diameter measurement of Y Tau based on the data of the February 4, 1982 observation was carried out near the phase of photometric maximum, and the obtained angular diameter *d* turned out to be the smallest of the known values. Also, other measurements in the $\varphi > 0.6$ region clearly show that *d* tends to decrease as the maximum phase approaches. Also noteworthy is the fact that the values of *d* obtained from the August 31, 1975 and February 20, 1994 observations, and corresponding to the almost coincident phases of the star's variability φ, proved to be quite similar.

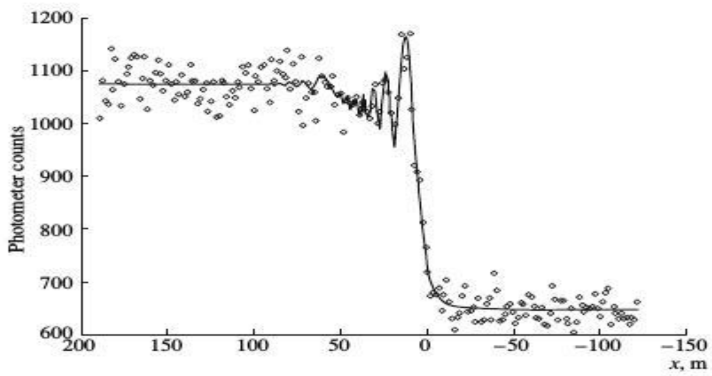
Thus, one can suggest that Y Tau is a pulsating star, and that the decrease of its diameter is accompanied by an increase of its luminosity. If this dependence really takes place, this may indicate that the nature of the pulsations is such that the contraction of the star leads to a substantial increase of its effective temperature.

If we consider the results of the direct angular-diameter measurements of Y Tau presented in Fig. 4 to reflect the actual variations of the star's diameter, then the relative magnitude of these variations can reach approximately 40–70%. However, the number of direct *d* measurements available to date is certainly not enough for a reliable conclusion about the periodic or quasi-periodic pulsations of the star [3].

The Close Binary Star 63 Geminorum = ADS 6089

Figure 5 presents the occultation light curve of the close binary star 63 Gem = ADS 6089 obtained by the author in the *B* band of the optical range on March 5, 1982 at ~ $13^h\ 56^m\ 35^s$ UT, at the Tian-Shan high-altitude observatory, using the 48-cm reflector AZT-14 [5].

Figure 5. *"B"- Band Occultation Diffraction Curve of 63 Gem = ADS 6089 (March 5, 1982, Tian-Shan High-Altitude Observatory, 48-cm Reflector, Observer E.M.Trunkovsky). The Circles Show Light-flux Measurements (Photometer Counts Accumulated in 2 ms); the Solid Curve is the Best-fit Model Diffraction Curve Derived for a Model with Two Point-like Sources. The Coordinate x (in Meters) is measured along the Perpendicular to the Lunar Limb at the Occultation Point*



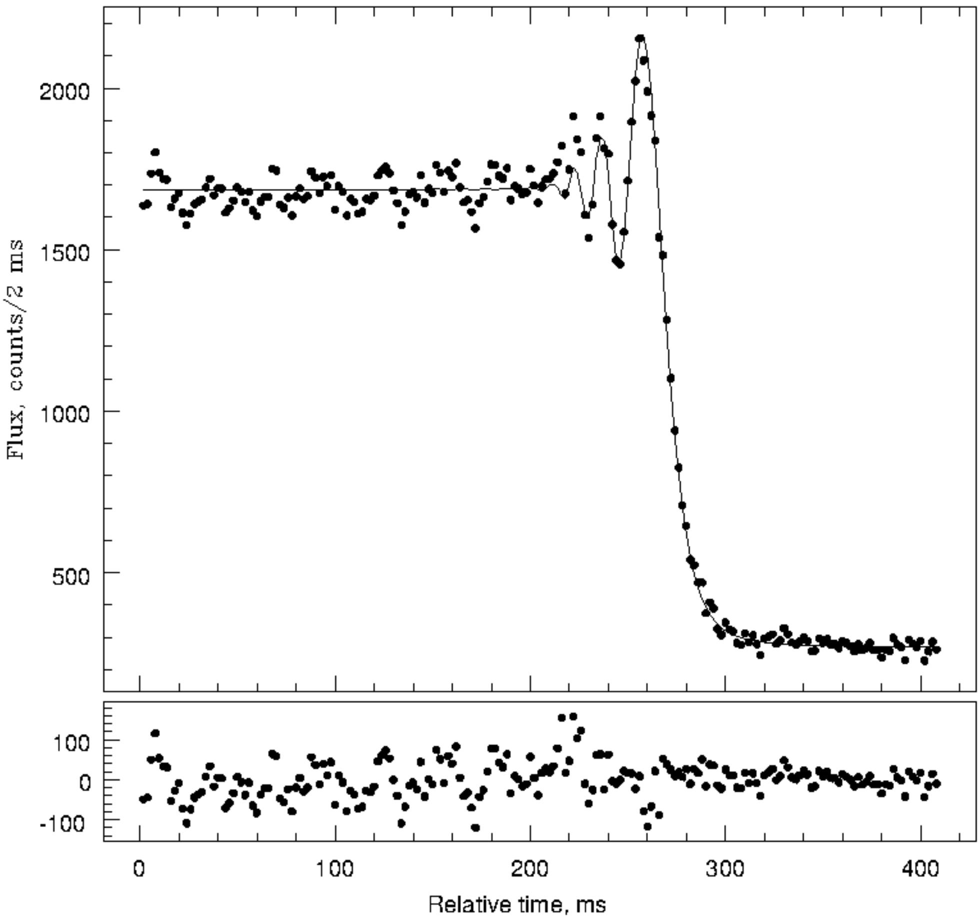
This occultation curve shows signs of binarity. The solid curve shows the best-fit model curve found for a model with two point-like sources. We determined the component of the separation between star's components perpendicular to the lunar limb, $\rho_x \approx 0.0263'' \pm 0.0005''$. We also found the magnitude difference of the components, Δm (B) = $m_1 - m_2 = 2.34^m \pm 0.10^m$, and the corresponding luminosity ratio, $L_1 / L_2 = 0.11$. Indirect estimates of the component angular diameters d result in values that are certainly below 0.001"; for the noise level of the observations, the angular-diameter uncertainty cannot be considerably smaller than the d values themselves, and the two point-source model is sufficient in this case.

2.3. 68 δ^3 Tauri = HR 1389

There are rather many cases when a visual inspection of an occultation curve reveals no obvious indications of binarity, and the diffraction-curve analysis disagrees with other observations or indirect estimates of a star's angular size. Such discrepancies could be due to a previously unknown double or multiple nature of the star, the presence of circumstellar matter (extended envelope or atmosphere, disk-like structure, etc.) around the primary, or variations of the star's size in time (e.g., due to stellar pulsations). In some cases, analysis of a lunar occultation using a single-star occultation model result in angular diameters far in excess of any reasonable indirect diameter estimates for a star of the given spectral type and corresponding luminosity, though the agreement of the model curve with the photometric data is adequate.

Figure 6 presents the diffraction occultation light curve of 68 δ^3 Tauri = HR 1389 obtained by the author on March 2, 1982 at $14^h\ 46^m\ 29^s$ UT in the B band ($\lambda_0 \approx 0.44$ μm) at the Tian-Shan High-Altitude Observatory [5].

Figure 6. *"B"- Band Occultation Diffraction Curve of 68 δ^3 Tau = HR 1389 (Tian-Shan High-Altitude Observatory, 48-cm Reflector, Observer E.M. Trunkovsky). The Points are Light-flux Measurements (Photometer Counts for 2 ms Intervals); the Solid Curve is the Best-fit Model Diffraction Curve for the Occultation of a Single Star. The Horizontal Axis Plots the Time from an Arbitrary Zero Point (in Milliseconds); the Vertical Axes of the Upper and Lower Panels Plot the Light Flux (2-ms Counts) and the Deviations of the Counts from the Best-fit Model Diffraction Curve (2-ms Counts)*

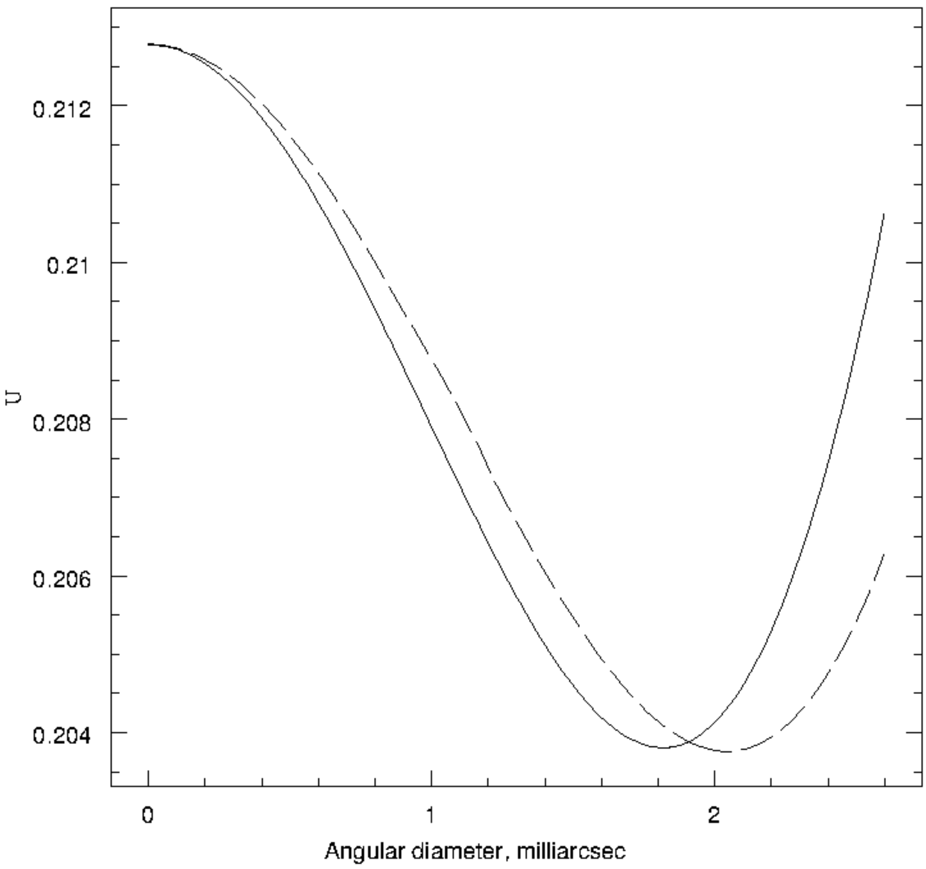


The star's magnitude is V= 4.29 and its spectral type is A2 IV; it is a visual triple star (ADS 3206), with the angular separation of the two brightest components, *A* and *B*, being 1.6", with a magnitude difference of 3.7^m [6]. The third component *C* is at an angular distance of 77" from component *A*, and its magnitude is ~ 11^m. 68 δ^3 Tauri is also known as the variable V776 Tau.

The occultation light curve presented here corresponds to the primary component *A*; its angular diameter *d* was estimated using several indirect methods as 0.0006", 0.00046", or smaller [7]. The primary *A* was itself long known as a spectroscopic binary with a period of 57.2^d [6]; however, some spectroscopic observations obtained in the 1990s did not confirm its binary nature. Thus, information about the structure of the primary is somewhat contradictory.

Our reductions of the photoelectric photometry data fitting a best-fit diffraction curve assuming occultation of a single star gave the function *u(d)*: the dependence of the sum of squared normalized deviations of the measured flux from the best-fit model curve *u* on the assumed angular diameter *d* (Fig. 7).

Figure 7. *The u(d) Relation Found from the Occultation Light Curve of 68 δ^3 Tau for $\mu = 0$ (Solid Curve) and $\mu = 1$ (Dashed Curve)*



This function clearly shows a distinct minimum near d = 0.00182" (for a uniformly illuminated stellar disk, with the limb-darkening coefficient $\mu = 0$) or d = 0.00204" (for a stellar disk with full limb darkening, $\mu = 1$).

Since the relative *rms* deviation of the photometer counts from the best-fit model curve (expressed as a fraction of the flux decrease during the occultation in percent) is fairly small (compared to many similar occultation light curves), approximately 3.2% (which is corresponding to a signal-to-noise ratio S/N ~ 30), the quality of the curve is fairly high, and our results are reasonably reliable. In addition, it follows from our numerical simulations that the possible uncertainty in the measured diameter *d* due to the influence of stochastic noise present during the observations on the solution obtained from analyzing the observed curve should not be much larger than 0.001"; for the noise level in our particular case, this is within 0.0007".

Thus, the value of *d* derived from our occultation observations is much larger than reasonable diameter estimates for the primary, and can be considered a kind of effective size of the object, which possibly has a complex structure. This could mean that the primary of 68 δ^3 Tau is actually a very close binary or multiple system, especially taking into account the indications of close binarity noted above. On the other hand, since information on the primary's binarity is somewhat contradictory, the presence of an extended envelope or a kind of a disk-like structure around the primary star is also possible. In principle, the presence of exoplanets in a hypothetical circumstellar disk is not ruled out. The angular diameter of the radiating region determined from our occultation observations corresponds to a linear size (projected on the plane of the sky) of about 0.1 AU.

Conclusions

Thus, from the above-mentioned material we can see that photoelectric observations of lunar occultations of stars with a high time resolution allow us to reach a very high angular resolution of the order of 1 milliarcsecond, and on this basis to measure directly the angular sizes of various stars and to study in detail their structure. This, of course, gives a possibility to obtain very valuable and unique information for stellar astrophysics and physics in general.

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