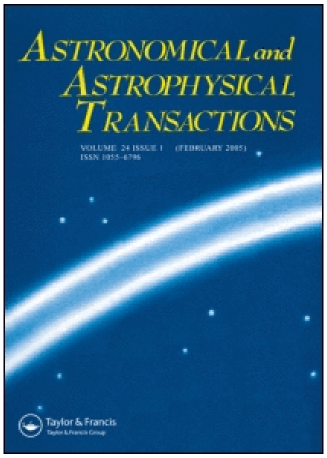

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OBSERVATIONS OF THE OCCULTATIONS OF STARS BY SOLAR SAILS

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A big solar sail is now being planned for launch in Russia. It will consist of a flat disk with characteristic dimension of about 100 m. Such a sail being launched to the near-Earth orbit will occult the stars from time to time. This will enlarge the possibilities of the occultation observation method for obtaining information about angular sizes and other physical parameters of the stars occulted. Possible applications are discussed.

Star eclipses by the sail orbiting the Earth at the height of about 40,000 km being observed by a 1.5 m-telescope will take place once in about 1100 hours with the sensitivity of $7^{m}\!.3$. This sensitivity is the limiting magnitude for recording diffraction light curves with an acceptable precision. The same observations made from the Hubble Space Telescope when the solar sail is at the 100,000 km distance from the Earth will achieve $8^{m}\!.1$ limit with an average time of about two months between successive occultations.

KEY WORDS Solar sail, occultations of stars, photoelectric observations, stellar angular sizes

The photoelectric observations of the lunar occultations of stars have become an efficient method for achieving high angular resolution and for the determination of stellar physical characteristics. They allow to measure stellar angular diameters and angular distances between close binary system components of the order of 10^{-3} arcsec, to discover new close double stars and envelopes around stars, and, under the best conditions, to derive brightness distributions over the stellar disks and stellar atmospheric structure. These observations are being conducted in many observatories as well as in Tien-Shan and Central Asian ones of the Sternberg Institute [1, 2].

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. Main shortcomings here are the limited celestial area covered by the moonpath, and a high photon background from the Moon itself. Since the lunar disk, considered from that point of view, is simply a screen moving over the sky it would be worth to try to use some artificial dark body which moves at a given orbit. By applying this we get a possibility of recording diffraction light curves at the moments of star occultations by such a screen. Its edge may be sufficiently smooth, so a possibility of distortion of the diffraction pattern due to irregularities in the limb, as it is present in the case of lunar occultations, will be excluded.

The solar sail (SS) is now being developed in Russia by the "Energiya" Space Center [3] as a part of a world-wide program. It will consist of a flat disk having $b = 100$ m in diameter, made from aluminized mylar film of several microns thickness and a small experimental package at the centre of that disk. The aluminized layers will reflect sunlight practically totally (the reflectivity is more than 99%).

The SS will be launched at the highly elliptical, near-Earth orbit with the inclination angle of $\sim 52°$ and the apogee of 40,000 km, and in 6–7 months it will reach the L_1 Moon–Earth libration point, changing its orbit under the sunlight pressure.

For the Moon, occultations take place for stars with the declinations $|\delta| \leq 28°$, but for the SS observations of such events, taking into account its inclination angle and various latitudes of observatories, will be possible for the declinations up to 60°. Moreover, the "appearance" of a star from beyond the SS edge at the end of an occultation will take place in a very short time ΔT after the occultation begins. This will substantially extend the volume and quality of the information obtained. The time ΔT can be estimated as

$$\Delta T = \theta/\dot{\phi}, \tag{1}$$

where θ is the angular size of the SS observed from the Earth, and $\dot{\phi}$ is the SS apparent angular velocity. For the distance l from the observer to the SS, say $l \approx 40{,}000$ km, we have

$$\theta = 206,265\ b/l\,\text{arcsec} \approx 0.''5, \tag{2}$$

and $\theta \approx 0.''07$ when l is about 300,000 km (the L_1 point). The apparent angular velocity can be calculated supposing a circular orbit for simplicity (this is the worst case: indeed, the SS will spend about 0.5 of time having the velocity of less than 0.5 of that for the circular orbit):

$$\dot{\phi} = 206{,}265 V/l \approx 4.12 l_{100}^{-3/2}\,\text{arcsec/s}, \tag{3}$$

where l_{100} is l in units of 100,000 km, V is the projection of the SS linear velocity onto the plane perpendicular to the line of sight. In (3), we neglect the multiplier $(1 + R/l)^{-1/2}$, where $R \approx 6{,}400$ km is the Earth radius, and also the velocity component $V_{\rm E}$ from the Earth rotation. $V_{\rm E}$ is not more than 0.5 km/s, and by neglecting it we also consider the worst case, because after the launch the SS will rotate in the same direction as the Earth does, so really V and $\dot{\phi}$ will be less than adopted values and the sensitivity will rise. For $l_{100} \approx 0.4$, we have $\dot{\phi} \approx 15$ arcsec/s and $\Delta T \approx 0.03$ s, for $l_{100} \approx 3$, we obtain $\dot{\phi} \approx 0.8$ arcsec/s and $\Delta T = 0.08$ s.

Due to a small apparent SS angular size, the question arises whether it is possible to consider the SS edge as a straight one in comparison with the linear diameter of the stellar disk projection onto the plane perpendicular to the line of sight and placed at the distance of the SS. A stellar disk having $d = 0.''005$ in angular diameter will have a linear diameter of about 1 m being projected onto that plane at the $l_{100} \approx 0.4$

distance, and 7 m, at $l_{100} \approx 3$. This means that the disk linear diameter will be about 0.01–0.07 of that of the SS. But really the diffraction pattern is formed by a greater part of SS edge and a straight-line edge approximation may not henceforth be correct, especially in the case of $l_{100} = 3$. Thus, curved-edge calculations should be used in real analysis.

In the case of a straight-line edge, the angular dimensions of the Fresnel zones from a point-like monochromatic source can be written as

$$\alpha_m \approx 206{,}265(m\lambda/l)^{1/2}[1 - (m-1)^{1/2}/m^{1/2}]\,\mathrm{arc\,s}, \tag{4}$$

where $m = 1, 2, 3\ldots$ is zone number, and λ is the wavelength. For $m = 1$, we have

$$\alpha_1 \approx 206{,}265(\lambda/l)^{1/2} = 2.06 \times 10^{-2}\lambda_1^{1/2} l_{100}^{-1/2}\,\mathrm{arc\,s}, \tag{5}$$

where λ_1 is the wavelength expressed in micrometers. For observations in the V band ($\lambda_1 = 0.55$):

$$\alpha_1 \approx 1.53 \times 10^{-2} l_{100}^{-1/2}\,\mathrm{arc\,s}. \tag{6}$$

In the case of lunar occultations, when l is equal to the mean Earth–Moon distance $l_0 \approx 3.8 \times 10^8$ m, $\alpha_1 \approx 0.''008$. For $l_{100} \approx 0.4$, α_1 is $0.''024$, and for $l_{100} \approx 3$, $\alpha_1 \approx 0.''009$. It is clear that α_1 should not exceed much the angular size of a stellar disk, since otherwise very high precision is needed for detecting small deviations from the theoretical diffraction point-like source curve. So the determination of stellar diameters of several milliarcseconds will be much easier for $l_{100} = 3$.

One should take into account also a finite dimension of the telescope primary mirror. It smooths the diffraction curve with an average window of $d = 206{,}265 \times D/l\,\mathrm{arc\,s}$, where D is the telescope diameter. For $l_{100} = 0.4$ and $D = 0.5$ m, d will be $0.''003$, and for $D = 1.5$ m and the same l_{100}, $d \approx 0.''008$. One possible solution of this difficulty for improving angular resolution up to $\sim 0.''001$ (but with decreasing sensitivity) might be to put a mask on the primary mirror which opens to the stellar light only a strip of ≈ 20 cm width; the strip itself should be oriented parallel to the SS edge.

For estimating the solar sail occultation sensitivity, we shall determine the pass time of the first Fresnel zone from (5) and (3):

$$t_1(s) = \alpha_1/\dot{\phi} \approx 5 \times 10^{-3} l_{100}\lambda_1^{1/2}. \tag{7}$$

One should choose the integration time Δt as $\Delta t \leq 0.1 t_1$ for the registration of the diffraction curve with a sufficient temporal resolution. Let us suppose that we observe occultations in the V photometrical band with $\Delta\lambda \approx 1000$ Å wavelength band around $\lambda = 5500$ Å, and the detector quantum efficiency is $\epsilon \approx 0.01$.

The solar sail should be oriented by its "dark" side to the observer. Calculations show that, for the sail surface reflectivity of 99% and $\Delta t < 1$ ms, the number of counts from the sail itself (i.e., the background counts for the diffraction curve) will not be greater than ~ 5 for one Δt bin, so it is a case when sensitivity is limited by the statistics of pulses detected from the source. Our previous experience in analysing the photoelectric diffraction curves obtained in Tien-Shan and Central Asian observatories [1, 2] shows that one may use a 5σ level for a minimal number of counts from the star detected at one time bin as a measure of diffraction curve which will be processed properly afterwards. So the precision of each measurement in the diffraction curve should be better than 20%. At the 5σ level, we have to detect $N_{\rm min} \approx 30$ pulses in one time bin. Hence, the minimal detectable flux can be written as

$$F_{\rm min} = 4N_{\rm min}hc(\lambda\epsilon\pi D^2\Delta t)^{-1} \approx 7.6\times10^{-9}\lambda_1^{-1}D^{-2}\Delta t^{-1}\,{\rm erg/s/cm^2}. \qquad (8)$$

By putting $\Delta t = 0.1t_1$ and t_1 from (7), in (8) we have

$$F_{\rm min} \approx 1.52\times10^{-5}\lambda_1^{-3/2}D^{-2}l_{100}^{-1}\,{\rm erg/s/cm^2}. \qquad (9)$$

The limiting magnitude is connected with $F_{\rm min}$ by the equation [4]

$$m_{\rm lim}(V) \approx -13.7 - 2.5\times\lg F_{\rm min}, \qquad (10)$$

and, if we use for D_1 the telescope diameter expressed in meters,

$$\begin{aligned} m_{\rm lim}(V) &\approx 8.3 + 3.75\times\lg\lambda_1 + 2.5\lg[D_1^2 l_{100}] \\ &\approx 7.3 + 5\times\lg D_1 + 2.5\times\lg(l_{100}). \end{aligned} \qquad (11)$$

For other photometric bands, one should use the corresponding expression for $m_{\rm lim}$ instead of (10) and (11). So for $l_{100} \approx 0.4$, Δt should not be larger than 1.6×10^{-4} s and for a 0.5-m telescope the limiting magnitude will be $4^{\rm m}\!.9$, while for a 1.5-m telescope, $m_{\rm lim} \approx 7^{\rm m}\!.3$. When the SS will reach the L_1 point, Δt will be not larger than 1.1×10^{-3} s, $m_{\rm lim} \approx 7.0$ ($D_1 = 0.5$), $m_{\rm lim} \approx 9.4$ ($D_1 = 1.5$), so the sensitivity will be rather high. Smoothing by the primary mirror for $l_{100} = 3$ and $D_1 = 1.5$ will not be large: $d \sim 0.''001$.

The frequency of the SS occultations for stars brighter than $m_{\rm lim}$ is also worth to estimate. Note first that two telescopes placed more than 100 m from each other will observe the SS occultations of different stars.

The number of stars covered by the SS per second when only one telescope observes can be determined as $\rho\dot{\phi}\theta$, where $\rho = \rho(m)$ is the density of stars brighter than m magnitude on the celestial sphere in units stars/sq.arcsec, $\dot{\phi}$ is measured in arcsec/s and θ, in arcseconds. The corresponding mean time τ between two successive occultations is then:

$$\tau = (\rho\dot{\phi}\theta)^{-1}\,{\rm s} = 1.347\times10^{-1}\rho^{-1}\dot{\phi}^{-1}l_{100}b^{-1}\,{\rm hours}, \qquad (12)$$

where b is the SS diameter expressed in meters. The function $\rho(m)$ may be approximated between $m = 4$ and $m = 10$ with a sufficient quality using the data of Allen [4] by

$$\rho(m) \approx 7.05\times10^{-12}\times10^{0.5m}\,{\rm stars/sq.arcsec}, \qquad (13)$$

so

$$\tau \approx 1.91 \times 10^{10} \times 10^{-0.5m} \times \dot{\phi}^{-1} l_{100} b^{-1} \text{ hours.} \tag{14}$$

By taking $\dot{\phi}$ from (3) and $m = m_{\text{lim}}$, from (11) we have

$$\tau \approx 1.003 \times 10^6 l_{100}^{5/4} D_1^{-5/2} b^{-1} \text{ hours.} \tag{15}$$

This means that for a 1.5-m telescope and $l_{100} \approx 0.4$, τ will exceed 1100 hours, or about once in 1.5 months. For the SS near the L_1 point, the same telescope will observe occultations once in 1.5 years. In reality, τ should be multiplied by some factor q which takes into account only night-time observations, weather conditions etc., so q is of the order of 10. One can see that for one telescope the SS occultations are very rare events. But taking into account a large number of instruments situated all over the globe, and a high probability of launching several solar sails to near-Earth orbits in one-two years, attempts in realization of such programmes seem to be realistic.

Now consider observations of the SS star occultations from the Hubble Space Telescope. These observations will have an advantage in comparison with those from ground-based telescopes because they allow to get rid of atmospheric scintillation, which is one of the main sources of errors in stellar angular diameter determination from lunar (and SS) occultations.

The HST moves in its near-Earth orbit at the velocity of 8 km/s, so its velocity with respect to the SS at the distance $l_{100} \approx 0.4$ will range from 4.5 to 10.7 km/s, depending on their relative instantaneous positions. The corresponding values for $\dot{\phi}$ lie between 26 and 61 arcsec/s, and $\alpha_1 \approx 0.0255$ arcsec (cf.(6)), so $\Delta t = (0.4 \div 1) \times 10^{-4}$ s. In the best case of $\dot{\phi} = 26$ arcsec/s, we can derive from eqs. (8), (10) and (14) the estimations $m_{\text{lim}} \approx 7.8$ and $\tau \approx 14$ d. But in that case the influence of the primary mirror on the diffraction curve will be rather strong: the effective smoothing will correspond to $0.''014$, which will make such observations impractical. The situation will be much better for $l_{100} \sim 1$, when $\alpha_1 \approx 0.''015$, and the smoothing decreases to $d \approx 0.''005$. In the latter case, $\dot{\phi} \approx 12 \div 20$ arcsec/s and $\Delta t \approx (0.8 \div 1.3) \times 10^{-4}$ s. If we choose $\dot{\phi} = 12$ arcsec/s, then $m_{\text{lim}} \approx 8.1$ and $\tau \sim 2$ months. This time should be multiplied by a factor $q \sim 1.5$ to take into account the time intervals when the Earth shadows the SS from the HST.

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