*R*esearch in
*A*stronomy and
*A*strophysics

The evolution of eccentricity in the eclipsing binary system AS Camelopardalis

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Abstract In 2002, 2004 and 2017 we conducted high precision CCD photometry observations of the eclipsing binary system AS Cam. By analysis of the light curves from 1967 to 2017 (our data + data from the literature) we obtained photometric elements of the system and found a change in the system's orbital eccentricity of $\Delta e = 0.03 \pm 0.01$. This change can indicate that there is a third companion in the system in a highly inclined orbit with respect to the orbital plane of the central binary, and its gravitational influence may cause the discrepancy between observed and theoretical apsidal motion rates of AS Cam.

Key words: binaries: close — binaries: eclipsing — stars: individual (AS Cam)

1 INTRODUCTION

As Camelopardalis (AS Cam) is a main-sequence eclipsing binary star (B8V+B9.5V components); its orbital period is ≈ 3.43 days, its orbital eccentricity is $e \approx 0.17$ and its maximum visual brightness is $\approx 8.57^{\mathrm{m}}$ (see Simbad database[1] and General Catalogue of Variable Stars, Samus et al., 2017) It was found in photographic plates by Strohmeier & Bauernfeind (1968). Hilditch (1969, 1972) conducted photoelectric observations of AS Cam, obtained its radial velocity curve and calculated the system's absolute parameters.

Khaliullin & Kozyreva (1983) discovered apsidal motion in AS Cam using *WBVR* photometry. The obtained rate of periastron movement of $\dot{\omega}_{\mathrm{obs}} = 16°$ per century was almost 3 times less than the expected theoretical value of $\dot{\omega}_{\mathrm{th}} = 44°$ per century. This discovery was independently confirmed by Maloney et al. (1991); Wolf et al. (1996). AS Cam became the second (after DI Her, see Martynov & Khaliullin 1980) eclipsing system in which the apsidal motion proved to be much slower than was predicted by theory. To explain the discrepancy between observational estimations and theoretical calculations of the apsidal motion rate in both binaries (DI Her and AS Cam), different authors introduced different hypotheses (Shakura 1985; Moffat 1989; Claret

1997, 1998). Most of their hypotheses were already discussed by Maloney et al. (1991); Claret (1997, 1998), so we do not describe them here. Zakharov et al. (1988), Khaliullin et al. (1991) explained the observed anomalies in the frames of classical and relativistic mechanics: gravitational influence of a third companion on the central binary in case of non-coplanar orbits can slow down the apsidal motion. Borkovits et al. (2007) significantly improved this idea and enriched it by numerical and analytical computations.

According to Claret et al. (2010) there is still no evidence for the existence of a third companion in DI Her, and its light equation cannot be found within existing errors of observational data. A leading idea that explains the system's slow apsidal motion is a non-coplanar axial rotation of the stars, and Albrecht et al. (2009); Albrecht et al. (2011) observed the Rossiter-McLaughlin effect in DI Her and NY Cep. This model requires very high equatorial velocities (up to $300\,\mathrm{km\,s^{-1}}$). In the case of AS Cam, Kozyreva & Khaliullin (1999) found evidence favoring the existence of a third body. They obtained high precision light curves of AS Cam in 1992–1996, accumulated 10 primary and 13 secondary minima and used them to find variations in times of minima. Based on these data and times of minima from the literature, Kozyreva & Khaliullin (1999) discovered cyclical in-phase variations of primary and secondary times of

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minima and explained their result by the influence of a third companion; its orbital period was found to be about 805 days, its eccentricity was ≈ 0.5 and its amplitude of the light time effect was ≈ 0.50 astronomical units.

After the discovery of the light equation in AS Cam in 1999, a lot of new minima times were obtained. We can test the data again (including new observations), and then we can verify the presence of a third body.

2 OBSERVATIONS

Photometric observations of AS Cam were conducted in 2002, 2004 and 2017 at Tien Shan Observatory, Fesenkov Astrophysical Institute (Kazakhstan). In 2002 and 2004 we used the 50 cm AZT-5 telescope with the photomultiplier tube (PMT) model 79 and *V* filter. The comparison star was HD 34463. In 2017 we obtained new CCD observations in *B*, *V* and *R* filters using the Zeiss-1000 telescope equipped with an Apogee U900 CCD camera. For the latest set of observations we used TYC 4347-452-1 (comparison star) and TYC 4347-682-1 (check star) as reference stars. Usual exposure times were about 10 seconds. A sample light curve of AS Cam is shown in Figure 1.

To process raw CCD data we used the MAXIM-5 program. The aperture was constant during one night. Its differences from night to night were not significant. Maximum errors for a single exposure were in the range $0.003^{\mathrm{m}} - 0.006^{\mathrm{m}}$ for the different nights. Reference stars were assumed to be constant during observations. For the values in Table 1 we used only the best light curves in *V* filter with standard deviation less than 0.007^{m}. Standard dark and flat field corrections were made. In order to obtain the maximum possible precision in times of minima, we used only full light curves between their maxima. Our values obtained for 2002, 2004 and 2017 observations are shown in Table 1.

Table 1 AS Cam times of minima obtained in this study; see Equations (1) and (2) for $(O-C)_1$ and Equations (6) and (7) for $(O-C)_2$. HJD is Heliocentric Julian Date and the "Min" column describes the type of minimum (primary (I) or secondary (II)).

HJD-2400000	Min	$(O-C)_1$ (d)	$(O-C)_2$ (d)
52542.2593	I	–0.01436	–0.00145
52547.2206	II	0.01406	0.00134
53252.4673	I	–0.01659	–0.00296
53266.1925	I	–0.01526	–0.00161
53271.1555	II	0.01486	0.00137
57757.3284	I	–0.01554	0.00289
57762.2973	II	0.02046	0.00220
57769.1602	II	0.02143	0.00316

3 LIGHT EQUATION

A computer code was used to find orbital elements and system parameters. A description of the method used in the code to solve light curves can be found in the section "Algorithms and models" in the paper by Kozyreva & Zakharov (2001), and a similar model was described by Khaliullina & Khaliullin (1984). The code seeks the photometric parameters and orbital elements using a simple model of two spherical stars (with a linear limb darkening law) that move around a common center of mass in elliptical orbits. The parameters are: the radii of the primary and secondary components $r_{1,2}$, the limb darkening coefficients for the components $u_{1,2}$, the luminosities of components in fractions of the system's total luminosity $L_{1,2}$, the inclination of the orbit of the binary with respect to the plane of the sky i, the orbital eccentricity e, the longitude of periastron of the primary star's orbit ω, the epoch of the primary minimum corresponding to the epoch of the observations analyzed and the system's third light parameter L_3.

AS Cam is a pair of definitely detached stars, therefore the model of two spherical stars with limb darkening is quite reasonable. The solution was accepted as adequate only when "observed minus calculated" value was the lowest and it had no systematic deviations within the minima. The values of parameters were found in a free search excluding the limb darkening coefficients. The values of limb darkening coefficients (0.46 ± 0.03 and 0.31 ± 0.05 for the primary and secondary respectively) were taken from the paper by Khaliullin & Kozyreva (1983). These values were computed using the high quality light curves of AS Cam obtained in 1981. The values of other parameters are slightly different from year to year, and are within the error bars of their values in table III in Khaliullin & Kozyreva (1983), except for i and e (see Table 2).

Table 2 The eccentricity e and inclination i for the orbit of AS Cam calculated using the full dataset.

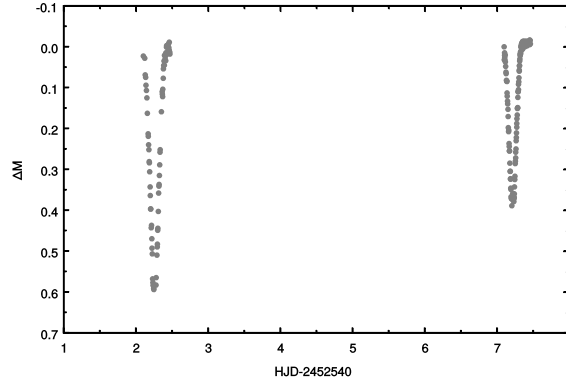| Year	e	i
1967–1968	0.147 ± 0.010	$88.3 \pm 0.4°$
1981	0.167 ± 0.008	$88.6 \pm 0.4°$
1992	0.161 ± 0.015	$88.8 \pm 0.5°$
1993	0.166 ± 0.010	$88.6 \pm 0.6°$
1994	0.166 ± 0.013	$88.9 \pm 0.5°$
1995	0.170 ± 0.010	$89.0 \pm 0.5°$
1996	0.164 ± 0.016	$88.8 \pm 0.5°$
2002	0.164 ± 0.010	$89.3 \pm 0.5°$
2017	0.178 ± 0.008	$89.5 \pm 0.5°$

Fig. 1 A sample light curve of AS Cam. ΔM is the change of its magnitude and HJD is the Heliocentric Julian Date.

We took into account all times of minima from Table 1 and from the B.R.N.O. database[2]. The apsidal motion of AS Cam is slow; its period is about 2400 yr. During 55 years of observations, this rate yields only $\approx 8°$ of the total cycle (360°), therefore it is possible to use linear approximations instead of sinusoidal changes in times of minima to investigate the possible light equation in the system. We obtained the following ephemerides for the primary and secondary minima with the same orbital period as the central binary

$$C_1(\text{Min I}) = \text{HJD } 2440125.60300$$
$$+3.43096730 \times E, \qquad (1)$$
$$C_1(\text{Min II}) = \text{HJD } 2440123.67395$$
$$+3.43096730 \times E. \qquad (2)$$

where E is the number of orbital cycles since the initial epoch and HJD is the Heliocentric Julian Date of the initial epoch.

The presence of a third body in an eclipsing binary system can observationally appear as periodical variations of its times of minima in comparison with the system's linear ephemerides. Such variations arise from motion of the center of mass of the binary star system around the center of mass of the triple system. The amplitude of variations for primary minima is given by a light equation

$$(O - C)_1 = \frac{a_3 \sin i_3}{c}(1 - e_3 \cos E_3) \sin(v_3 + \omega_3), \quad (3)$$

where v_3 is the true anomaly of the third companion's orbit, E_3 is its eccentric anomaly, a_3 is the semi-major axis of the third companion's orbit, i_3 is the inclination of this orbit with respect to the plane of the sky, e_3 is its eccentricity and ω_3 is the pericentric longitude.

Figure 2 shows the reference frame for the third body's orbit. The value of E_3 is connected with other
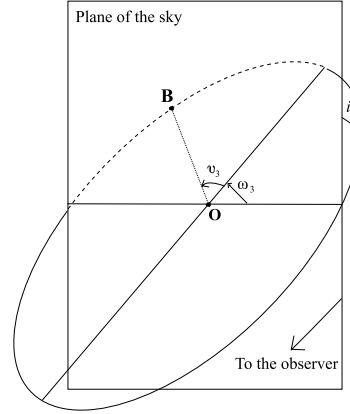
Fig. 2 A reference frame for orbital elements of the third body. Here "O" is the center of mass of the triple system, "B" is the third body within the orbit around "O", i_3 is the inclination of the orbit, ω_3 is the periastron longitude and v_3 is the true anomaly.

elements as follows:

$$\frac{2\pi}{P_3}(t - T_3) = (E_3 - e_3 \sin E_3),$$

where T_3 is the time of the periastron passage by the third body, t is the time and P_3 is the orbital period of the third body.

$(O - C)_1$ experiences periodical variations on a time scale of ≈ 2 years (see Figs. 3 and 4). These variations have the same phase for the primary and secondary minima. It is essential that both sets of observations (1968–1973 in Fig. 3 and 1980–2017 in Fig. 4) can be described by the same light equation curve. Estimations of the parameters in Equation (3) that we obtained (we applied the least-squares method for $(O - C)_1$) are listed in Table 3, and ephemeris for the third companion is

$$\text{Min III} = \text{HJD } 2444265.036 + 805.9 \times E_1, \quad (4)$$

where E_1 is the number of orbital cycles of the third body since the initial epoch.
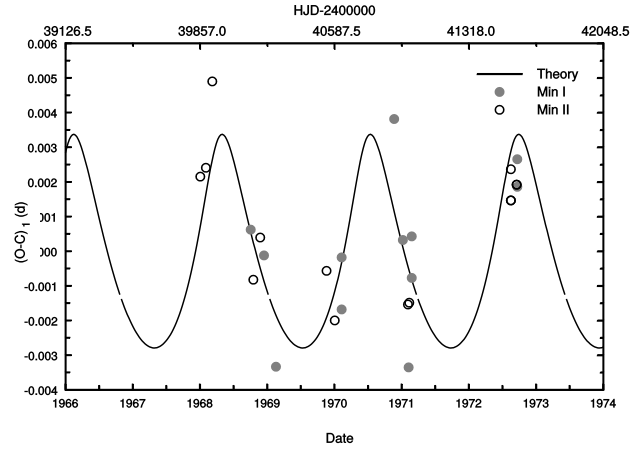
Fig. 3 The light equation curve ("Theory" as labeled in the figure) for $(O - C)_1$ calculated as the difference between observed times of minima (Min I and Min II) and values computed using Equations (1)–(2) for observations in 1967–1973. See Table 3 for parameters of the third body's orbit. HJD is the Heliocentric Julian Date. The bottom horizontal axis expresses time in years.
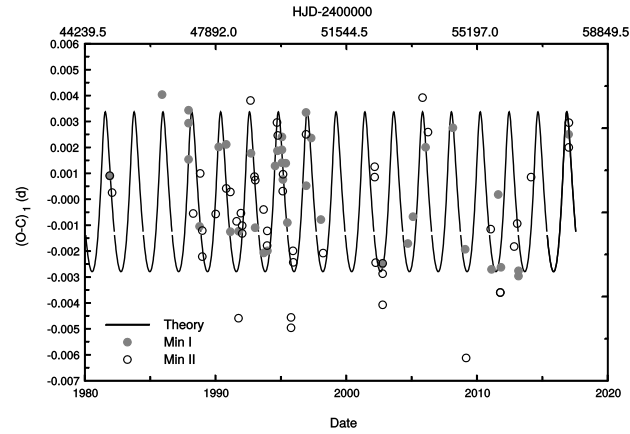

Fig. 4 The same as Fig. 3 for observations in 1981–2017.

The mass function

$$f(m) = \frac{(M_3 \sin i_3)^3}{(M_1 + M_2 + M_3)^2} = \frac{(a_3 \sin i_3)^3}{P_3^2}, \quad (5)$$

gives (after subtracting parameters of the light equation) the lower limit of the third body's mass $M_3 \sin i_3 \approx 1.1\, M_\odot$.

The light equation method only allows estimating a lower limit on the third body's mass, and the real value also depends on the angle between the plane of the sky and the orbital plane of the third companion. If the angle $i_3 \leq 30°$, the mass of the third body should be $\geq 2.2\, M_\odot$ (this value is comparable with the secondary star in the central tight binary). Our photometric solutions for the light curve can be plausible only if the luminosity of the third companion is no more than 3.5% of the total luminosity of the system. If this body is a non-degenerate main-sequence companion, its mass is less than $1.5\, M_\odot$

and $i_3 \geq 43°$. Also, the spectral lines of the third companion were not found, therefore the mass of a hypothetical main-sequence companion has an upper limit. In general, the suggested body can be a compact remnant (a white dwarf or even a neutron star) or can be a very close binary star like YY Gem.

4 RE-ESTIMATION OF APSIDAL MOTION RATE FOR AS CAM

The difference between periods of primary and secondary minima indicates the apsidal motion rate (see Fig. 5). Using the least-squares method, we compute the following ephemerides

$$\begin{aligned} C_2(\text{Min I}) &= \text{HJD } 2444939.24519 \\ &\quad + 3.43096365 \times E, \quad (6) \\ C_2(\text{Min II}) &= \text{HJD } 2444937.32569 \\ &\quad + 3.43097095 \times E. \quad (7) \end{aligned}$$
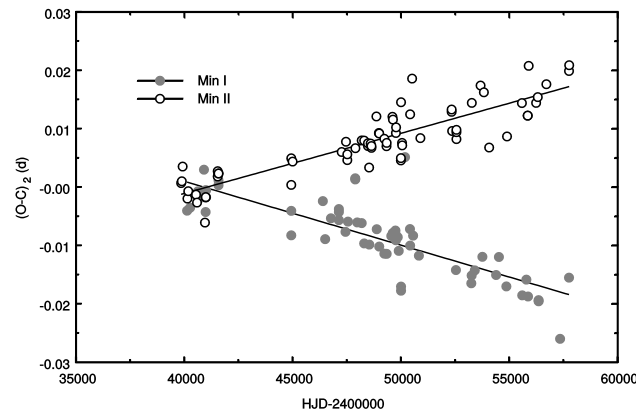
Fig. 5 The discrepancy between primary and secondary minima. The figure indicates apsidal motion in the system. $(O - C)_2$ is calculated as the difference between observed times of minima (Min I and Min II) and values computed using Equations (6) and (7). HJD is the Heliocentric Julian Date.

These equations correspond to the rate of apsidal motion $\dot{\omega}_{\mathrm{obs}} = 15.5° \pm 1.5°$ per century. The theoretical apsidal motion rate for AS Cam was found to be $\dot{\omega}_{\mathrm{th}} = \dot{\omega}_{\mathrm{cl}} + \dot{\omega}_{\mathrm{rel}} = 44°$ per century (Maloney et al. 1991).

The parameters obtained in this study coincide with the parameters of the light equation and of the apsidal motion rate calculated by Kozyreva & Khaliullin (1999) within the error bars, despite the fact that the results in 1999 were found from much less observational data.

5 POSSIBLE CAUSES OF SLOW APSIDAL MOTION IN AS CAM

Influence of the third companion on the apsidal motion rate in general was studied by Khaliullin et al. (1991); Khodykin & Vedeneyev (1997); Khodykin et al. (2004). The low apsidal motion rate in DI Her and in AS Cam probably could be explained by perturbations caused by the third body. This idea was improved by Borkovits et al. (2007), who conducted theoretical investigations of configurations of the central binary's orbit and the third companion's orbit using AS Cam as an example. Borkovits et al. (2007) considered four variants of the mutual disposition of both orbits, in which the angle between them equaled $0.8°$, $20°$, $60°$ and $90°$. The results were shown in figures 6–9 by Borkovits et al. (2007) for fast (on a time scale of about ≤ 100 years) and slow (on a time scale of about 3000 years) evolution of orbital parameters.

It is possible to compare the values of parameters obtained in the past (since 1981 for our data) with those from modern (2017) observations on a short time scale. A large amount of light curves corresponding to primary and secondary minima was accumulated. We took light curves with precision better than 1% within the light curve minima in our data, as well as the light curve published by Hilditch (1972). This approach allowed us to compute orbital elements, e.g. (Kozyreva & Zakharov 2001). We used our light curves of AS Cam obtained in 1981, 1992, 1993, 1994, 1995, 1996, 2002 and 2017, and light curves obtained by Hilditch (1972) in 1967 and 1968. The dataset covered 50 years of observations and allowed us to trace the change of eccentricity and inclination of the central binary's orbit (see Table 2), and to compare the observed changes with the theory of Borkovits et al. (2007). The eccentricity change is $\approx 0.03 \pm 0.01$ during 50 years of observations, and the inclination change during the same period of time is $\approx 1 \pm 0.5°$. Our value of the eccentricity change is higher than its theoretical value for mutual inclination of the orbits $i' = 0$ and $i' = 20°$. It is almost the same as the theoretical value calculated for $i' = 60°$, see Borkovits et al. (2007), fig. 2. Their paper contains only four values of mutual inclination of the orbits, therefore it is possible that i' is less than $60°$. For the case of $i' = 60°$ Borkovits et al. (2007) showed that the dependence of the difference between primary and secondary minima is more complicated than a simple difference between two sinusoidal functions shifted relative to each other by $180°$. The dependence between times of minima is complicated and has non-uniform character, so the apsidal motion rate can change in different periods of time, see figure 3 by Borkovits et al. (2007). Such periods with different apsidal motion rates can have durations of up to several centuries, and now we can see that AS Cam exhibits the pattern of slow apsidal motion.

There is another explanation of the slow apsidal motion rate, which is spin-orbit misalignment (Albrecht et al. 2009, 2011). Pavlovski et al. (2011) obtained spec-

Table 3 Values of the Parameters in Equation (3)

Parameter	Value
$\frac{a_3 \sin i_3}{c}$	$4.5 \pm 0.3\,\mathrm{min}$
e_3	0.42 ± 0.05
P_3	$805.9 \pm 1.5\,\mathrm{d}$
ω_3	$69 \pm 2\,°$

tral lines of AS Cam and found that the lines are narrow in comparison with the expected line width when synchronous rotation of the stars is assumed. They concluded that the axial and orbital rotations are not aligned. Shakura (1985) found that the apsidal line can undergo retrograde motion if the rotation axes of the stars are not aligned to the orbital axis, with the largest effect being when the axes are perpendicular. If the stars were rotating at three times the synchronous rate around axes that lie almost in the orbital plane, and if one takes into account the projected rotational velocities, the stars' rotational axes should be tilted by $82°$ and $87°$ with respect to the orbital axis (Pavlovski et al. 2011). If the orbit of that body is highly inclined with respect to the orbit of the inner two stars, then the Lidov-Kozai mechanism (Lidov 1962; Kozai 1962) may be invoked to explain the spin-orbit misalignment.

Probably, both mechanisms (the influence of the third body and the spin-orbit misalignment) that can lead to deceleration of the apsidal motion rate are plausible in the AS Cam binary system.

6 CONCLUSIONS

During the 50 year time interval, the orbit of the close binary star AS Cam changed its eccentricity by ≈ 0.03. This fact indicates that the system possesses a third body in a highly inclined orbit with respect to the central binary's orbit. Such configuration can induce the precession of rotational axes of the stars in the binary, and trigger their spin-orbit misalignment. Both mechanisms can slow down the apsidal motion rate compared to a system without a third companion, if the rotational axes are aligned with the orbital axis.

The unresolved question is how the third body with a mass comparable to the masses of the stars in the central binary does not show itself either in spectra of the stars or in photometric elements obtained as a solution for the light curves. This body could be a degenerate star or a very close binary system like YY Gem consisting of low luminosity main-sequence stars.

References

Albrecht, S., Reffert, S., Snellen, I. A. G., & Winn, J. N. 2009, Nature, 461, 373

Albrecht, S., Winn, J. N., Carter, J. A., Snellen, I. A. G., & de Mooij, E. J. W. 2011, ApJ, 726, 68

Borkovits, T., Forgács-Dajka, E., & Regály, Z. 2007, A&A, 473, 191

Claret, A. 1997, A&A, 327, 11

Claret, A. 1998, A&A, 330, 533

Claret, A., Torres, G., & Wolf, M. 2010, A&A, 515, A4

Hilditch, R. W. 1969, The Observatory, 89, 143

Hilditch, R. W. 1972, PASP, 84, 519

Khaliullin, K. F., & Kozyreva, V. S. 1983, Ap&SS, 94, 115

Khaliullina, A. I., & Khaliullin, K. F. 1984, Soviet Ast., 28, 228

Khaliullin, K. F., Khodykin, S. A., & Zakharov, A. I. 1991, ApJ, 375, 314

Khodykin, S. A., & Vedeneyev, V. G. 1997, ApJ, 475, 798

Khodykin, S. A., Zakharov, A. I., & Andersen, W. L. 2004, ApJ, 615, 506

Kozai, Y. 1962, AJ, 67, 591

Kozyreva, V. S., & Khaliullin, K. F. 1999, Astronomy Reports, 43, 679

Kozyreva, V., & Zakharov, A. 2001, Astronomy Letters, 27, 712

Lidov, M. L. 1962, Planet. Space Sci., 9, 719

Maloney, F. P., Guinan, E. F., & Mukherjee, J. 1991, AJ, 102, 256

Martynov, D. I., & Khaliullin, K. F. 1980, Ap&SS, 71, 147

Moffat, J. W. 1989, Phys. Rev. D, 39, 474

Pavlovski, K., Southworth, J., & Kolbas, V. 2011, ApJ, 734, L29

Samus N. N., Kazarovets E. V., Durlevich O. V., Kireeva N. N., Pastukhova E. N., 2017, Astronomy Reports, 61, 80

Shakura, N. I. 1985, Soviet Astronomy Letters, 11, 224

Strohmeier, W., & Bauernfeind, H. 1968, Bamberg Veroeffentlichungen der Remeis-Sternwarte, 7, 72

Wolf, M., Sarounova, L., & Diethelm, R. 1996, A&AS, 116, 463

Zakharov, A. I., Khaliullin, K. F., & Khodykin, S. A. 1988, Astronomicheskij Tsirkulyar, 1529, 13