SIMULATION OF COLOR VARIATIONS IN GRAVITATIONALLY LENSED QUASAR Q2237+0305 (THE EINSTEIN CROSS)

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ABSTRACT. A mechanism of colorized phenomena in gravitationally lensed quasar Q2237+0305 due to microlensing is analysed in computer simulation. A two-component quasar spatial structure model consisting of a hot central source surrounded by an extended outer structure with a more low-temperature radiation was proposed. The model was shown to provide relationship between variations of the $(V-I)$ color indices and R magnitudes, which is consistent to the observed one presented in our recent publication.

Key words: gravitational lensing: quasars: individual: Q2237+0305.

1. Introduction

The study of microlensing events is known to provide a unique possibility for the quasar spatial structure to be resolved with the unprecedented angular resolution. A regular and highly accurate photometric monitoring of variability is the basis for solving this problem. The programs of such monitoring for Q2237+0305 were undertaken repeatedly, (Corrigan et al. 1991, Ostensen et al. 1996, Alcalde et al. 2002), with the most well-sampled and accurate monitoring data in the V filter obtained by OGLE (Optical Gravitational Lensing Experiment) program, (Wozniak et al. 2000, Udalski et al. 2006). Also, monitoring of the Einstein Cross Q2237+0305 in the V, R and I filters is being carried out with the Maidanak 1.5-m telescope since 1997 (Vakulik et al. 1997, Dudinov et al. 2000, Vakulik et al. 2004, Vakulik et al. 2006).

The importance of multicolor photometry for this object was demonstrated in the first observations of Q2237+0305 by Yee (1988) where the difference in color indices of the components was explained by differential extinction. However, a suspicion arose a bit later (Corrigan et al. 1991, Rix et al. 1992), that the color indices of the components might have changed since the first three-color observations by Yee (1988). As far back as 1986, Kayser, Refsdal & Stabell suggested that colorized phenomena in gravitationally lensed quasars can be expected in microlensing of a source with a radial temperature gradient. This was later confirmed in simulations by Wambsganss & Paczyński (1991). Recently, Vakulik et al. (2004) have shown that a significant correlation between the brightness changes and color changes of the Q2237+0305 components exists, which should be attributed to microlensing events rather than to the variable extinction in the lensing galaxy.

In the present work, we proceed from the assumption that the effective sizes of the quasar emitting regions may be wavelength-dependent, and consider a photometric model of the Q2237 quasar, consisting of a compact central source at some brightness pedestal, as used in our recent work (Vakulik et al. 2006). In the present study, we use the same model to simulate the observed variations of colors in Q2237 reported in the work by Vakulik et al. (2004). Our simulations permitted to obtain the estimates of the compact central part dimension and the energy contributions of the extended outer structure at the spectral intervals corresponding to the V, R and I bands.

2. Simulation of microlensed light curves

Using a method of the inverse ray tracing, (Schneider et al. 1992), it is possible to calculate the distribution of magnification rate $M(y_1, y_2)$ for a small (quasi-point) source for all possible locations (y_1, y_2) – the so-called magnification map. In microlensing of a finite-size source, which is situated at the point (y_1', y_2') of the magnification map and is characterized by a surface brightness distribution $B(y_1, y_2)$, the magnification rate is determined by the formula:

$$\mu(y_1', y_2') = \frac{\int\int B(y_1, y_2) M(y_1 - y_1', y_2 - y_2') dy_1 dy_2}{\int\int B(y_1, y_2) dy_1 dy_2}, \tag{1}$$

where the integrals are calculated within a region where the surface brightness $B(y_1, y_2)$ is non-zero.

The inner compact feature of our two-component source model describes the central part of the accretion disc and is characterized by a surface brightness distribution $B_1(y_1, y_2)$. The other, outer feature is associated with larger structural elements – a shell, a torus, Elvis's biconics (Elvis 2000), – which are of a substantially lower surface brightness $B_2(y_1, y_2)$. For such a two-component source, situated at a point (y_1', y_2'), the values of the magnification rate μ_{12} can be calculated from expression:

$$\mu_{12}(y_1', y_2') = \frac{\mu_1(y_1', y_2') + \varepsilon \mu_2(y_1', y_2')}{1 + \varepsilon}. \tag{2}$$

The magnification rates μ_1 and μ_2 are calculated according to (1) for the surface brightness distributions B_1 and B_2, while ε is determined as a ratio of the integral luminosities of these structures.

The characteristic time-scale of the observed Q2237 microlensing brightness fluctuations is known to be almost a year. We regard that such a scale is due to microlensing of the compact inner quasar structure. Since the expected spatial scale of the outer structure may be more than an order of magnitude larger as compared to the inner part, (Elvis 2000, Schild & Vakulik 2003), the expected time scale of its microlensing brightness variations will exceed ten years. In addition, because of the large dimensions of the outer structure, the amplitudes of microlensing magnification must be noticeably less, as compared to microlensing of the compact structure. Thus we suggest as well, that on time-scales of about 4 years, the magnification rate $\mu_2(y_1, y_2)$ is almost invariable and does not differ noticeably from the average magnification rate of the j-th component μ_j resulting from microlensing, that is, $\mu_2(y_1, y_2) \approx \langle \mu_2(y_1, y_2) \rangle \approx \mu_j$ in expression (2).

It is clear that, at the short time intervals, microlensing of the extended structure reveals itself in reducing, by a factor of $1/(1 + \varepsilon)$, the amplitudes of brightness variations resulted from microlensing of the compact structure. Therefore, in analysing the light curves at the time interval of 4 years, we did not seek estimation the effective size of the outer structure, and the value of ε was its only characteristics. The inner compact structure, which imitates a central part of the accretion disc, was modeled by a disc with the Gaussian brightness profile, and its effective size r/r_E at the half-intensity level was the sought-for parameter, (r_E is the Einstein radius of a microlens).

3. Results of simulation

Since multicolor observations of Q2237+0305 have been carried out only episodically, there was no possibility to analyse a behavior of color variations of the components in time. Therefore, in the present work, we focused at simulation of statistical relations between the color indices and magnitudes, which have been recently discovered and analysed in (Vakulik et al. 2004). And it was only for the C component, for which, in addition to the detailed V light curve (Woźnyak et al. 2000), the brightness estimates near the 1999 microlensing brightness peak were also available in R and I, that an attempt to simulate the light curves had been undertaken.

From the magnification map for the C component, using the method of a random search, we found the light curves which fitted qualitatively to its light curve obtained by the OGLE collaboration in the V filter during 1997-2000 (Woźnyak et al. 2000). Varying the source model parameters – the effective size of the central compact feature r and the relative intensity of the outer extended structure ε, – we reached the best fit of the simulated light curve to the observed one. For the same source trajectory, the source model parameters r and ε were estimated similarly for the R and I light curves by fitting the simulated light curves to those obtained from observations at the Maidanak Observatory (Vakulik et al. 2004). For one of successful trials, the parameters estimates were obtained to be $r = 0.36 r_E$, $0.53 r_E$, $0.71 r_E$, and ε= 3.3, 5.0, 6.2 for the V, R and I filters, respectively. Since our observations in the R and I filters were not regular enough, the obtained differences between the central source size estimates in different filters can not be regarded as significant. However, the relative energy contribution of the extended outer structure definitely tends to increase towards the longer wavelengths. This may be explained as due to the more low-temperature radiation from the extended structure. This result is an expected one, since in our model, radiation from the central source is associated with a high-temperature emission of the inner edge of the accretion disc, while the outer structure most probably re-emits the hard short-wave radiation of the accretion disc.

For the source model described above, a statistical analysis of variations of colors and brightness was carried out as well. To analyse the effects of differences of both the central source dimensions and energy contributions from the outer structure on variations of colors, we simulated microlensing events for three sets of the source parameters r and ε. In one case, the values of the source parameters obtained in fitting of the simulated light curve to that observed in filter V for image C were accepted. In the second case, the central compact source size was regarded to be the same for all

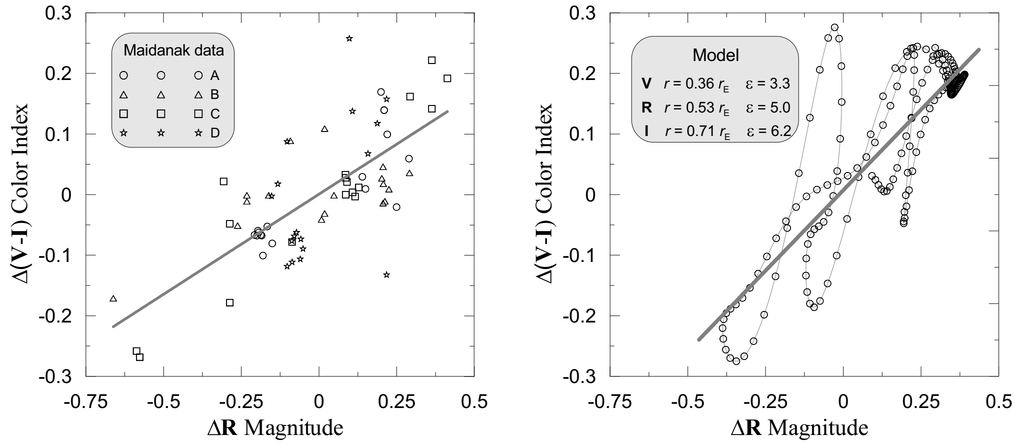

Figure 1: – (a)(left panel): variations of the color indices $\Delta(V-I)$ vs variations of brightness ΔR, built from the observations of 1997-2000 at the Maidanak Observatory; (b)(right panel): a similar dependence built from the simulated light curves for the two-component source model with the compact feature dimensions r/r_E and with the time-dependent relative energy contribution of the extended structure ε.

Table 1: The maximal variations of color indices and R magnitudes, as well as regression line slopes a and correlation indices k for dependencies $(V-I)$ vs R as was obtained from the Maidanak data (the first line), and calculated for various parameters of the two-component source model in simulations (the last three lines).

	V	R	I	$\Delta(V-R)$	$\Delta(R-I)$	$\Delta(V-I)$	ΔR	$(V-I)$ vs R	
								a	k
Observational data				0.32 ± 0.09	0.31 ± 0.09	0.49 ± 0.14	0.71 ± 0.27	0.31 ± 0.08	0.75 ± 0.08
r/r_E	0.36	0.53	0.71	0.41 ± 0.09	0.20 ± 0.05	0.55 ± 0.13	0.78 ± 0.23	0.53 ± 0.06	0.86 ± 0.03
ε	3.3	5.0	6.2						
r/r_E	0.53	0.53	0.53	0.23 ± 0.07	0.11 ± 0.03	0.33 ± 0.10	0.77 ± 0.22	0.44 ± 0.03	0.99 ± 0.00
ε	3.3	5.0	6.2						
r/r_E	0.36	0.53	0.71	0.87 ± 0.16	0.52 ± 0.11	1.20 ± 0.26	2.87 ± 0.87	0.08 ± 0.21	0.28 ± 0.15
ε	0	0	0						

filters, and only energy contribution of the outer structure was varied. In the third case, the outer structure was absent, and the values $r = 0.36r_E$, $0.53r_E$, $0.71r_E$ were adopted for the V, R and I filters, respectively. Since statistical characteristics of microlensed light curves have been shown to depend on the effective size of the source rather than on the brightness distribution over the source (Mortonson et al. 2005), we used the effective source radii in our analysis.

For each of these cases, 10 trajectories of the source were randomly selected at the magnification maps and the light curves were calculated corresponding to observations in filters VRI. The estimates of variations of color indices and magnitudes were obtained from these data, correlation coefficients and regression line slopes were determined, and a comparison with the corresponding data of observations presented in (Vakulik at al. 2004) was made. The results are presented in Table 1. For the source model with the parameters obtained in fitting the image C light curves, a regression line slope for the $(V-I)$ color – R magnitude dependence is $a = 0.53$, and a correlation index is $k = 0.86$ (Fig. 1b). It is a bit larger values than those obtained by (Vakulik et al. 2004) from the data of observations, ($a = 0.31$, $k = 0.75$, Fig. 1a). However, taking into account the random errors inherent in the photometry data, which decrease both a correlation index and a regression line slope, we regard the modeled and observed color-magnitude dependencies to be consistent.

In the second case, when the effective size of the inner compact source component is not wavelength-dependent, the regression line slope decreases ($k = 0.4$), and becomes closer to the value obtained from observations (Vakulik et al. 2004), but extremely high correlation index of $k = 0.99$ is observed. This is a consequence of virtually unambiguous relationship between the color and brightness variations in this case: in microlensing of such a source, the increase of brightness always is accompanied by the shift of the color indices towards the bluer ones.

Finally, noticeable color variations can be obtained in the third case, when the effective source size is substantially wavelength-dependent, much more dependent than the classical blackbody-radiating accretion disc. However, since there is no unique dependence between the color and brightness variations in this case, the color-brightness correlation index is low ($k = 0.28$), and consequently, the regression line slope is low too ($a = 0.08$), that is much less than those obtained for the data of observations.

It was interesting to estimate the linear dimensions of the central compact feature of the source from the results of fitting the VRI light curves for image C. If the effective velocity of the source is accepted to equal $V_e = 5000$ km·s^{-1}, then the estimate of the linear radius in filter R will be $r = 3.3 \cdot 10^{15}$cm, while a typical microlens mass is $\langle m_* \rangle = 1.6 \cdot 10^{-3} h^2 M_\odot$. This is consistent with the estimates obtained by other authors.

It should be noted in conclusion that the solution found in simulation for the image C light curve is not a unique one. Other solutions are possible, which may provide somewhat different values for the source model parameters. Therefore, the analysis presented here should be regarded as a qualitative one, and therefore, we do not indicate the errors for the obtained estimates of the source model parameters. Nevertheless, we have managed to follow the principal peculiarities qualitatively, and to understand possible reasons for color variations emerging in microlensing events of the source with a complicated structure, as is formulated below.

4. Conclusions

To explain possible reasons for color variations observed in the Q2237+0305 gravitationally lensed quasar, microlensing of a source consisting of a compact inner feature and an extended outer structure has been simulated. By fitting the simulated and observed light curves of the C component, the inner feature dimensions have been estimated to be $r = 0.36 r_E$, $0.53 r_E$, and $0.71 r_E$ for filters V, R and I, respectively, with the corresponding estimates for the relative energy contributions from the extended structure of $\varepsilon = 3.3$, 5.0 and 6.2. Simulation and statistical analysis of microlensing of such a source demonstrates a satisfactory consistency of the simulated relationships between the color and brightness variations to those obtained from the data of observations for Q2237+0305.

Also, the cases have been analysed, when the size of the compact feature does not depend on the wavelength, or when the energy contribution from the outer structure is $\varepsilon = 0$, which is equivalent to a particular case of a simple (Gaussian) source with the wavelength-dependent effective size. Noticeable color variations were shown to appear in this case as well, but however, the correlation index for the color-magnitude dependence is low and, as a consequence, the regression line slope is inconsistent to that obtained from observations. Therefore, a suggestion that variations of colors in gravitationally lensed quasars are due to microlensing of the accretion disc, does not seem to be convincing enough. A model consisting of a hot central source surrounded by an extended outer structure with a more low-temperature radiation seems to be preferable.

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References

Alcalde D., Mediavilla E., Moreau O., et al.: 2002, *ApJ*, **572**, 729.
Corrigan R.T., Irwin M.J., Arnaud J.: 1991, *AJ*, **102**, 34.
Dudinov V.N., Vakulik V.G., Zheleznyak A.P. et. al.: 2000, *Kinem. i Fiz. Neb. Tel.*, **16**, 346.
Elvis M.: 2000, *ApJ*, **545**, 63.
Huchra J., Gorenstein M., Kent S., et. al.: 1985, *AJ*, **90**, 691.
Kayser R., Refsdal S., Stabell R.: 1986, *A&A*, **166**, 36.
Mortonson M.J., Schechter P.L., Wambsganss J.: 2005, *ApJ*, **628**, 594.
Ostensen R., Refsdal S., Stabell R., et al.: 1996, *A&A*, **309**, 59.
Racine R.: 1992, *ApJ*, **395**, L65.
Rix, H.-W.; Schneider, D.P.; Bahcall, J.N.: 1992, *AJ*, **104**, 967.
Schild R., Vakulik V.: 2003, *AJ*, **126**, 689.
Schneider P., Ehlers J., Falco E.E.: 1992, *Gravitational Lenses*, Springer-Verlag.
Udalski A., Szymanski M. K., Kubiak, M., et al.: 2006, *Acta Astronomica*, **56**, 293.
Vakulik V.G., Dudinov V.N., Zheleznyak A.P., et al.: 1997, *Astron. Nachr.*, **318**, 73.
Vakulik V.G., Schild R.E, Dudinov V.N., et al.: 2004, *A&A*, **420**, 447.
Vakulik V.G., Schild R.E., Dudinov V.N., et al.: 2006, *A&A*, **447**, 905.
Vakulik V.G., Schild R.E., Smirnov G.V., et al.: 2007, *arXiv:0708.1082*
Wambsganss J., Paczyński B.: 1991, *AJ*, **102**, 864.
Wozniak P.R., Alard C., Udalski A., et al.: 2000, *ApJ*, **529**, 529.
Yee, H.K.C.: 1988, *AJ,* **95**, 1331.