The distance of the cataclysmic variable KR Aurigae

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Abstract. We estimated the distance to the cataclysmic variable KR Aur using the photometric measurements of the minimum brightness in $BVRI$ bands and different empirical dependences between P_{orb}, masses, absolute magnitudes and color-indices of the components of the system. We used also 2MASS measurement of the K-magnitude, obtained close to the faintest state. The evaluation of the distance is more than 900 *pc*, on average - 1200 *pc*. We obtained the absolute magnitude M_v of about 3.0–3.5 in the high state. The derived parameters of KR Aur were compared with such of the similar VY Scl type variables.

Key words: cataclysmic variables, anti-dwarf novae; individual: KR Aur

Разстоянието до катаклизмичната променлива KR Aurigae

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Използвайки оценки в минимума на блясъка във филтри $BVRI$ и различни емпирични зависимости между орбиталния период, масите, абсолютните звездни величини и цветните индекси на компонентите на системата, ние оценихме разстоянието до катаклизмичната променлива KR Aur. Използвахме и оценка от каталога 2MASS на звездната величина в K филтър, получена в състояние, близко до минималното. Минималната стойност на оценката за разстоянието до променливата е около 900 *пс*, а средната - около 1200 *пс*. Оценена е и абсолютната звездна величина M_v на около 3.0–3.5 *mag* във високо състояние. Получените параметри на KR Aur са сравнени с подобни на други променливи от типа VY Scl.

Introduction

The cataclysmic variables are close semidetached binary systems consisting of a white and a red dwarf. The material passes through the inner Lagrangian point and forms an accretion disk around the white dwarf. This disk contributes the main part of the system luminosity.

There are several types of cataclysmic variables – novae, dwarf novae, recurrent novae and nova-likes. The nova-like systems have relatively stable disks with high mass accretion rate. VY Scl (or anti-dwarf novae) are a subclass of nova-likes. These systems usually remain in high states, but occasionally mass transfer decreases or stops completely and the luminosity falls up to 5 - 6 magnitudes. The periods of the above mentioned stars are between 3 and 4 hours, while their average absolute magnitude is $M_v = 4.1$ mag. KR Aur is a typical representative of this subclass with an orbital period of $P_{orb} = 3.907$ hours (Shafter[1983]). The system consists of a white dwarf with a mass $M_{wd} = 0.7M_{\odot}$ and a red dwarf with a mass $M_{rd} = 0.48M_{\odot}$ according to Shafter [1983], and respectively 0.59 and 0.35 $M_{\odot}$ according to Ritter and

Kolb [1998]. The distance to the system is estimated to be $D = 180$ pc (Patterson [1984], using the $M_v - E.W.(H_\beta)$ relation) and respectively $D = 230$ pc(Popova and Vitrichenko [1978], using the proper motion of the object).

Usually KR Aur has a magnitude of about 13.5. Between 1994 and 2001 KR Aur was in a low state, dropping as low as 19 mag in V band. In March 2008 a new decrease of the system brightness began and a few months later KR Aur reached the weak state again. That minimum continues until now.

It is impossible to estimate the contribution of the various system components to the brightness while the star is in a high state because the two dwarf stars are not visible at all. We can assume that the disc disappears completely while KR Aur is in minimum and only the red and the white dwarf contributions to the star brightness remain. We calculated the masses, the radii and the absolute magnitudes of the system components using empirical dependencies for CVs and normal color indices for normal stars. Then we used our measurements in the $BVRI$ bands in a low state, together with the above mentioned absolute magnitudes to calculate the distance to KR Aur.

Estimating distances in astronomy is an important problem. Parallaxes were measured only for several cataclysmic stars but none of them belongs to the group of VY Scl stars. In a number of astronomical works the distances to those stars have been recently corrected.

1 The estimates of the distance to KR Aur

1.1 Determination of the mass, radius and absolute magnitude of the secondary star using empirical relationships

There are several empirical relations between the mass or the radius of the red dwarf (secondary star in the system) and the orbital period (P_{orb}) of CVs. We assume the red dwarf has the properties of a normal Main Sequence star. In the case of KR Aur, spectral lines from the red companion have never been observed so we have no indication of its spectral type. We used the following expressions:

$$M(2) = 0.065 \times P_{orb}(h)^{5/4}(Warner[2003]) \tag{1}$$

$$R(2) = 0.094 \times P_{orb}(h)^{13/12}, for 1.3 \leq P_{orb}(h) \leq 9 \tag{2}$$

$$R(2) = M(2)^{0.88}(Patterson[1984]) \tag{3}$$

$$R(2) = 0.955 \times M(2)^{0.917}(Lacy[1977]) \tag{4}$$

$$R(2) = M(2)^{0.867}(Warner[2003]) \tag{5}$$

$$R(2) = 0.2361 \times P_{orb}(h)^{2/3} \times M(2)^{1/3}(Knigge[2006]) \tag{6}$$

We calculated the mass of the secondary star as 0.36 $M_\odot$. For the radius of the red dwarf we obtained a value between 0.36 and 0.41 $R_\odot$. From the relation $M_v(2) = 16.7 - 11.1 \times \log P_{orb}(h)$ (Warner [2003]), we obtained secondary's absolute magnitude $M_v(2) = 10.13$.

All these values of the $M(2)$, $R(2)$ and $M_v(2)$ led us to the assumption that the possible spectral type of the red dwarf is between M0 and M4, most likely M2. Following semi-empirical sequence of Knigge[2006], we found that system with period of 3.9 h must have MV3 secondary with mass of 0.30 $M_{\odot}$.

1.2 Absolute and minimum of observed magnitudes of KR Aur

Following Allen [1973], we estimated the possible range of the absolute magnitudes of both components – the white (1) and the red (2) dwarfs (Table1).

Table 1. The range of the absolute magnitudes in B and V for primary and secondary.

$M_v(1) \sim 10.7$ - 12.5	$M_b(1) \sim 10.2$ - 11.8
$M_v(2) \sim 10.0$ - 11.0	$M_b(2) \sim 11.5$ - 12.4

Using data from the previous(Boeva et al. [2006]) and present lowest state, the obtained minimum values of observed magnitudes in B, V, R and I bands of KR Aur were as follows:

Table 2. The minimum of observed magnitudes.

B = 19.02 ± 0.22
V = 19.04 ± 0.05
R = 18.70 ± 0.08
I = 18.16 ± 0.20

1.3 Assessment of the distance using the "standard candle" method

Comparing the estimated absolute magnitude and the observed brightness we can calculate the distance to KR Aur using the well known equation:

$$m - M = 5 \times logD - 5 + A \tag{7}$$

We calculated the interstellar reddening corrections using color excess $E_{B-V} = 0.05$ (Bruch and Engel [1994]) and the law from Zombeck [1990]:

In Table 4 we present the absolute magnitudes of the components, errors, minimum, maximum and average distance to the object. We assumed that the contribution of the white dwarf in R and I band is negligible in the minimum luminosity state of the system and the red dwarf has a normal color-indices for M star ($V - R \sim 1.5 \pm 0.5$; $V - I \sim 2.5 \pm 0.5$).

Table 3. The interstellar reddening corections .

$$A_b = 0.21$$
$$A_v = 0.16$$
$$A_r = 0.13$$
$$A_i = 0.10$$

Table 4. The derived distances to KR Aur from evaluations of the absolute magnitudes of the components in different colours.

Filter	M	Err	D_{min}	D_{max}	D_{av}
B	11.0 (1)	0.8	280	670	430
	12.0 (2)	0.5			
V	11.5 (1)	1.0	410	780	560
	10.5 (2)	0.5			
R	9.0	0.5	630	1070	820
I	8.0	0.5	750	1420	1030

1.4 Estimation of the distance from *K* magnitude (Bailey's method)

A widely used method for determination of distances to CVs is given by Bailey [1981]. Following this method we used the function of the surface brightness of the secondary:

$$S_k = K + 5 - 5 \times logD + 5 \times log(R/R_\odot) \tag{8}$$

For all M–type stars there exists an approximation:

$$S_k = 4.55, for(V - K) > 3.5 \tag{9}$$

From 2MASS data, obtained on January 14th, 1998, the K magnitude of KR Aur was $K = 15.77 \pm 0.19$. At that moment the B and R magnitudes were 16.70 and 17.40 respectively. Our observations in January, 1998 indicated that KR Aur was close to the lowest state. This value for K and the average radius of the red dwarf $0.4 R_\odot$ give a distance between 655 and 780 *pc*, with an average of 715 *pc*.

In minimum light KR Aur showed color index $V - R \sim 0.3$, so V magnitude must be about 17.7 or approximately 1.3 magnitudes above the faintest state. We can suppose the measured K magnitude is not the maximum possible. The absolute minimum for R magnitude of KR Aur is 18.7 and $R - K$ is near 1.6 from 2MASS data. If the color-index $R - K$ remains approximately constant, K_{min} should be about 17.0, giving the distance of 1260 *pc*. Similarly, if use the value of $I_{min} = 18.1$ and a normal color-index for M2V star is $I - K \sim 1.6$, then K_{min} should be about 16.5, which gives a distance of 1000 *pc*.

A new determination of the surface brightness derived from additionally obtained data from Beuermann[1999], gave us value of $S_k = 4.15 \pm 0.05$.

Then we can estimate the distance from 760 to 960 *pc*, on average - 840 for $K = 15.77$. If we adopt as admissible the value of 17 *mag* for K, we receive $D \sim 1500$ *pc*. The assessments for the absolute K magnitude taken by the orbital period or secondary's mass sequences approximations, were $K = 6.6$ (Beuermann[1999]) and 6.3 (Knigge[2006]). Then we calculated a distance of 1200–1400 *pc*.

1.5 KR Aur compared to other similar VY Scl systems

As a final test for the calculated distance of KR Aur we compared the system with other members of VY Scl subclass with already known distances. These systems have very similar orbital periods and so they must have similar Roche lobes. It means that the red dwarfs radii and masses are close to these of KR Aur. Furthermore, the average masses of primaries are almost equal. There are, however, some differences in the strength of magnetic field of the white dwarfs, which lead to different sizes and temperatures of the accretion disks.

We can assume that the absolute magnitudes of VY Scl systems are almost the same, so again we can apply the "standard candle" method by using the mean apparent magnitudes and the distances of these objects. This is only a rough evaluation of the applicability of the above mentioned methods and it demonstrates that the distance of 1000–1200 *pc* is completely acceptable.

Recently the estimates of the distances to many of VY Scl variables were corrected after applying new methods. The obtained new distances are greater than the previously considered ones. In Table5 we present 4 systems, their average V magnitude, the old and the new data taken from the literature and our assessment of the distance to KR Aur on the supposition that M_v are approximately the same in the normal high state. The new data are taken from: (1)-Hoard et al.[2004]; (2)- Gänsicke et al.[1999]; (3)-Godon et al.[2007]; (4)-Ringwald, Naylor[1998].

Table 5. Distances to VY Scl systems and estimated distance to KR Aur .

CVs	V	D_{old}	D_{new}	D_{KRAur}
MV Lyr	12.5	320	505 (1)	800
TT Ari	10.7	135	285 - 385 (2)	1200
V 794 Aql	14.5	200	690 ± 105 (3)	440
BZ Cam	12.9	500	830 ± 160 (4)	1100

In these calculations we didn't take account of the interstellar reddening of the variables.

2 Discussion

The distance we calculated is several times greater than the commonly accepted one for KR Aur (~ 200 *pc*). The method of K magnitude is the most trustworthy one, but it show only a lowest limit of the distance because the secondary emits only part of this radiation. Even using rough estimates of absolute $BVRI$ magnitudes of the components we obtain a distance of up to several hundred parsecs. These calculations were made assuming the absence of the disk. But the redder is the filter, the larger distance we obtain.

From the estimates of the absolute magnitudes of the primary and the secondary stars we calculated the system's absolute luminosity: $M_b = 10.60$ and $M_v = 10.10$. The distance modulus m - M should be 9.0 (in V), but if we assume the distance as 1000–1200 *pc* we have some excess of approximately 2.0 mag in B, 1.5 mag in V, 0.75 mag in R and about 0.25 mag in I. So we can conclude that there is another component in the system in the low state - a weak accretion disk. This leads to an estimate of the minimum brightness of KR Aur of about 20.5 *mag* and the absolute total V magnitude of KR Aur in the high state $M_v = 3.0 - 3.5$. Then the disk luminosity in the bright state is approximately 6.5-7.0 *mag*. The value of total M_v is a little greater than the usually accepted ones for the nova–likes variables: 4.0 *mag*. It is possible the used above dependences are not fully realized for that class of objects.

In support of the our supposition that the accretion disk of KR Aur commonly remains even in the weak state is the fact that our observations pointed the flickering activity have never ceased completely. We observed brightness variations often up to 1.5 *mag* in the low state. Probably the mass-transfer from the secondary never stops fully. Perhaps KR Aur is one of the brightest and most active members of its class.

Recently two works noticed the difference between the accepted and the real distance for KR Aur: Sion et al.[2009] and Ak et al.[2008]. In the last mentioned article the calculated distance is about 4000 *pc* which seems too large, but the authors have accepted another assessment of the color excess E_{B-V}.

3 Conclusions

We estimated the luminosity of the components and the distance to the cataclysmic variable KR Aur. We received the system is brighter in the high state than other similar variables. We evaluated the range of the distance from 900 to 1500 *pc*, on average - 1200 *pc*.

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