New Photometric and Polarimetric Observations of the Massive Interacting Binary KX And

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Abstract—New UBVRI photometry and polarimetry of the interacting binary KX And are presented. The shape of its light curve in the 1992–1994 season provides evidence for a shift of the time of minimum light from the phase of main elongation, which can be determined from spectroscopic observations. This previously unobserved effect suggests that the orbital position of the cloud of gas that obscures the hot component can change in longitude. The binary exhibits a variable (with orbital phase) linear polarization. The variable polarization is dominated by the first harmonic of the orbital period. This polarization is shown to arise from the scattering of light in the upper layers of the optically thick shell around the hot component with a thickening at its front edge. An analysis of the polarimetric data has yielded estimates of the orbital inclination, i = 50°, and the spatial orientation of the orbit, Ω = 100° ± 30°.

INTRODUCTION

KX And (HD 218393, BD+49°4045, G8 II + B?) is a well-known interacting binary which was repeatedly studied in the past. A comprehensive review and analysis of the results that were obtained for this star from 1920 through 1990 can be found in Stefl et al. (1990). While refraining from a repeated discussion of all of its observed properties, we highlight those that characterize KX And as an interacting binary at the stage of intense mass transfer.

1. The star exhibits a peculiar emission spectrum. The Balmer Hα and Hβ lines are always observed in emission and show a two-component structure with a significantly blueshifted absorption component. The higher terms of the Balmer series are seen in absorption, but the profiles of most lines are deformed by emission and vary with orbital phase.

2. There are numerous absorption lines of ionized metals (shell lines)—FeII, MgII, AIII, etc.—in the binary’s spectrum. These lines are formed in a dense gaseous shell around the hot star. The intensities and radial velocities of these lines vary with a period of ~39 days.

3. The HeI λ4471, 5875, and 6678 Å lines are always seen in absorption and are blueshifted relative to the metal lines by ~100 km s⁻¹; their radial velocities vary with the same period (39 days). The shape of the He I-line profile is also highly variable.

4. The binary exhibits a long-term nonperiodic variability of emission-line profiles.

The light variations in the binary with orbital phase was discovered by Harmanec et al. (1980). The variability amplitude is at its maximum in U (~0°6) and decreases appreciably longward. The minimum light coincides in phase with the maximum of the radial velocities of metal lines and with the maximum of their intensity.

The pattern of photometric variability, together with the spectroscopic observations, suggest that the hot star is eclipsed by a gas flow that is projected onto its disk at elongation; the light curve shows no clear traces of an eclipse of one component by the other in conjunctions. Until very recently the only reliably determined orbital parameter for KX And has been the orbital period, 38°919. Before 1995, no photospheric line among the great variety of spectral lines could be identified and studied. The different groups of lines that are observed in the binary’s spectrum behave differently. The most reliable radial-velocity curve for the shell lines of metals shows a prominent secondary maximum near phase 0.45, which is responsible for its asymmetry and, accordingly, for the high formal value of the orbital eccentricity (e = 0.5). The radial-velocity curve for the HeI λ4471 Å line has a similar shape, but its γ velocity is blueshifted by 100 km s⁻¹.

Floquet et al. (1995) detected lines of the cool component in the spectrum of KX And and studied their radial-velocity variations. However, since their observations covered only a small interval, they failed to construct the complete orbital radial-velocity curve.

During the 1992–1994 season, we undertook a program of simultaneous photometric, polarimetric, and high-dispersion spectroscopic observations of KX And at the Crimean Astrophysical Observatory.

An analysis of the spectroscopic data allowed us to study in detail the radial-velocity variations of the cool component’s lines that we detected independently of Floquet et al. (1995) and to construct a new orbit for the binary from these lines. The orbit turned out to be cir-
different regions of the shell. We will submit the spectroscopic observations for publication in a separate paper. In this paper, we analyze the photometry and polarimetry.

The scattering of light serves as the formation mechanism for linear polarization in binary systems with gaseous shells, while its (polarization) variability is produced by orbital motion. The orbital inclination $i$ and the spatial orientation of the orbit $\Omega$ can be determined from polarimetric observations of such a binary. By now the corresponding techniques have been well developed and are described in several papers (Brown et al. 1978; Milgrom 1979; Karitskaya and Bochkarev 1983; etc.).

In addition, the geometric properties of a gaseous shell and the distribution of circumstellar matter in a system can be inferred from an analysis of polarization variability. Therefore, polarimetry must serve as a good additional means of studying interacting binaries such as KX And.

**PHOTOMETRY AND POLARIMETRY OF KX And IN CRIMEA**

We carried out the photometric $UBVRI$ and polarimetric observations of KX And during the season of 1992–1994 using the 1.25-m telescope of the Crimean Astrophysical Observatory. Twelve to sixteen polarization measurements were made on a single night, which were then used to calculate the means. We also measured the star’s magnitude on each night, if weather conditions permitted. The comparison star was BD+49°4059; the same star was used by Harmanec et al. (1980). We obtained all our observational data on 76 nights with a good coverage of the orbital period. The error in the nightly mean polarization was $\sim 0.04$–$0.05$ in $U$ and no greater than $0.03\%$ in $BVRI$. The error in the magnitude estimate of the binary was within $0^\prime.01$–$0^\prime.02$. In our calculations of the phase, we used the new

![Graph](image)

*Fig. 1. The orbital light curve of KX And in $UBVRI$.*

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$B$</th>
<th>$V$</th>
<th>$R$</th>
<th>$I$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_0$</td>
<td>$-0.153 \pm 0.008$</td>
<td>$-0.153 \pm 0.006$</td>
<td>$-0.133 \pm 0.006$</td>
<td>$-0.112 \pm 0.006$</td>
</tr>
<tr>
<td>$q_1$</td>
<td>$0.090 \pm 0.012$</td>
<td>$0.066 \pm 0.010$</td>
<td>$0.044 \pm 0.009$</td>
<td>$0.023 \pm 0.009$</td>
</tr>
<tr>
<td>$q_2$</td>
<td>$-0.090 \pm 0.010$</td>
<td>$-0.077 \pm 0.008$</td>
<td>$-0.028 \pm 0.008$</td>
<td>$-0.006 \pm 0.007$</td>
</tr>
<tr>
<td>$q_3$</td>
<td>$-0.007 \pm 0.011$</td>
<td>$-0.013 \pm 0.009$</td>
<td>$-0.008 \pm 0.008$</td>
<td>$-0.003 \pm 0.008$</td>
</tr>
<tr>
<td>$q_4$</td>
<td>$0.010 \pm 0.011$</td>
<td>$0.006 \pm 0.008$</td>
<td>$-0.007 \pm 0.008$</td>
<td>$-0.015 \pm 0.008$</td>
</tr>
<tr>
<td>$u_0$</td>
<td>$0.773 \pm 0.009$</td>
<td>$0.784 \pm 0.009$</td>
<td>$0.712 \pm 0.008$</td>
<td>$0.642 \pm 0.006$</td>
</tr>
<tr>
<td>$u_1$</td>
<td>$-0.044 \pm 0.014$</td>
<td>$-0.040 \pm 0.014$</td>
<td>$-0.031 \pm 0.012$</td>
<td>$-0.019 \pm 0.010$</td>
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<tr>
<td>$u_2$</td>
<td>$-0.069 \pm 0.012$</td>
<td>$-0.052 \pm 0.011$</td>
<td>$-0.051 \pm 0.010$</td>
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<td>$u_3$</td>
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<tr>
<td>$u_4$</td>
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<td>$0.016 \pm 0.012$</td>
<td>$0.016 \pm 0.011$</td>
<td>$0.015 \pm 0.009$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>840</td>
<td>450</td>
<td>150</td>
<td>100</td>
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</tbody>
</table>
Fig. 2. Variations in the Stokes parameters of linear polarization in KX And with orbital phase. The Fourier fits are indicated in the figure by the solid lines.

ephemeris that was determined from the Crimean spectroscopic observations,

\[ T_{\text{max RV}} = \text{JD}2423220.25 + 38.919E. \]  

(1)

LIGHT VARIATIONS IN KX And

The light curve of KX And, which we obtained at the Crimean Astrophysical Observatory, is shown in Fig. 1. The new photometric data are in good agreement with the previously published UBV observations. The variability amplitude is at its maximum in U and decreases longward. This tendency is also observed in R and I. The star is clearly seen to become redder, as it dims. The new data are closely consistent with the previous conclusions regarding the cause of light variations in the binary. Before falling on the accretion disk, the matter that is lost by the cool component forms an enclosing arm around the B star and, being projected onto its disk, produces the observed dimming.
According to Harmanec et al. (1980), however, the time of minimum light coincided closely with the time of maximum of the radial velocities (phase 0.0). As can be seen from Fig. 1, the time of eclipse is delayed in phase from zero by \(-0.07\)–\(-0.08\), as implied by the new data. This suggests that the eclipsing cloud can change its orbital position in longitude. In turn, this circumstance may serve as an indication of precession of the accretion disk.

**POLARIZATION VARIATIONS IN KX And**

The first trial polarization observations of KX And were performed by Huang et al. (1989). They detected night-to-night variations in the polarization of the binary. However, because of the small amount of observational data, the authors could not analyze this variability and reach any conclusions about its cause.

Our new polarization observations of KX And are shown in Fig. 2 as a plot of the normalized Stokes \(q\) and \(u\) parameters against the orbital phase. The variability amplitude is at a maximum at short wavelengths and decreases longward. It reaches 0.5-0.4\% in \(B\) and \(V\), respectively. Erratic polarization fluctuation are noticeable in \(U\). In accordance with the method of analyzing polarization in binary systems, the observed variability of the normalized Stokes parameters is commonly represented as a Fourier expansion (Brown et al. 1978). The orbital phase is used as the argument of this expansion. The expansion itself includes the terms up to the second harmonic inclusive,

\[
q = q_0 + q_1 \cos \lambda + q_2 \sin \lambda + q_3 \cos 2\lambda + q_4 \sin 2\lambda, \\
u = u_0 + u_1 \cos \lambda + u_2 \sin \lambda + u_3 \cos 2\lambda + u_4 \sin 2\lambda, \quad \lambda = 2\pi \varphi, \quad \varphi = \text{phase.}
\]

The Fourier fits are indicated in Fig. 2 by the solid lines. The numerical values of the Fourier coefficients are given in Table 1. We clearly see from this table and from Fig. 2 that the polarization variability of KX And is dominated by the first harmonic.

This situation appears very unusual. Most of the binaries with variable polarization are dominated by the second harmonic. According to Brown et al. (1978), the dominance of the first harmonic of the orbital period in the polarization variability of KX And should be interpreted as being a result of a great asymmetry of the shell relative to the orbital plane. However, apart from purely geometric factors, which give rise to the first harmonic in the classical method, there can also be additional factors that produce the effect of an apparent symmetry breaking.

Eclipses, light reflection from the surface of one of the components, and effects related to a considerable optical depth of the shell are among these additional factors. In eclipsing systems, as the bright star dims, a steep increase in the polarization due to the contrast that results from an increase in the contribution of scattered polarized light can be observed at minimum light. However, KX And is a noneclipsing star, and it is difficult to assume that a slight shielding of the hot component, which causes the system to dim by a mere 0.78 in \(V\), will be accompanied by a substantial change in the proportion of polarized and nonpolarized light. In addition, the maximum of polarization in this case must coincide in phase with the time of the eclipse itself, which is not observed.

The appearance of the first harmonic can be attributed to the violation of the corotation condition for the shell, if the orbit has a considerable eccentricity. However, the true orbit of KX And is circular. With the same definiteness, we can exclude from our analysis the contribution of the reflection to the observed polarization of KX And.

The most plausible explanation for the dominance of the first harmonic in the polarization variability of KX And is a considerable optical depth of the shell around the hot component. In this case, the light is scattered in the surface layers, whereas the inner layers, which lie “on the other side” of the orbital plane, do not contribute to the scattered polarized light because of the

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**Fig. 3.** A scheme that illustrates the formation of a large-amplitude second harmonic in the variable polarization of KX And. The wavy line indicates the path of photons of the incident and scattered light at various times of the orbital motion toward the observer: (a) at elongations (\(\varphi = 0.0\) and 0.5) and (b) in conjunctions (\(\varphi = 0.75\) and 0.25).
strong absorption. As a result, the effect of asymmetry appears in the observed polarization. At the same time, the shell itself is symmetric relative to the orbital plane.

Interestingly, a similar formation mechanism for the first harmonic of considerable amplitude was proposed by Kemp and Barbour (1983) to interpret the variable polarization in the X-ray binary X Per (see Fig. 9 in their paper). Although this interpretation raises serious doubts in the case of X Per itself (primarily because of the incorrect orbital period of 580 days on which the analysis of Kemp and Barbour was based), this mechanism for KX And is fairly justifiable.

There is much evidence for a considerable optical depth of the shell around the hot component. In addition to photometry, this conclusion is also supported by the fact that the amplitude of the polarization variations in KX And changes appreciably with wavelength. The high degree of opacity of this disk is one of the reasons why there are no photospheric lines of the hot component in the observed spectrum of the binary.

PECULIAR GEOMETRY OF THE SHELL AROUND KX AND

The presumed scheme for the formation of variable polarization in KX And is shown in Fig. 3. It has much in common with the scheme that was proposed by Kemp and Barbour (1983), except for the difference in the position of the light source. The cloud of gas that forms a thickening at the front edge of the accretion disk around the hot component is responsible for the break of symmetry and for the dominance of the first harmonic in the observed polarization variability. This cloud lies in front of the B star in the direction perpendicular to the line of the centers. The effect of asymmetry, which is attributable to the large optical depth of the shell, arises and manifests itself at elongations (φ = 0.0, 0.5) and in conjunctions (φ = 0.25, 0.75). In the first case (Fig. 3a), the contribution to the intrinsic polarization of its negative component (i.e., the component with the vector parallel to the orbital plane) is greatest at phase 0.5. At the opposite phase (φ = 0.0), this component gives virtually no contribution to the observed polarization. The effect of large optical depth also produces "angular splitting" (according to the terminology of Kemp) between the components of the intrinsic polarization which arise during the scattering in conjunctions (Fig. 3b). Since the polarization vectors in opposite conjunctions cease to be parallel, their projections onto the axis of the standard coordinate system have different magnitudes. A similar effect was used by Kemp et al. (1981) to interpret the variable polarization in Algol.

While analyzing the polarization variability of KX And, we could not help but notice the large scatter of points about the fit. The amplitude of this scatter in B, V, R, and I is ~0.2%. These fluctuations in U are so large that the periodicity itself is distinguished with great uncertainty. The fluctuations appear to be caused by real nonstationary processes in the shell. This oscillating component, indubitably, hampers the reliable identification of the small-amplitude second harmonic in the observed variability.

DETERMINING THE ORBITAL INCLINATION AND THE ORIENTATION OF THE ORBIT

Since the optically thin integrals that describe the scattering of light by the shell, as applied to the outer layers of the disk around the hot component, must hold (Brown et al. 1978), we can use the classical method of determining i and Ω for KX And. In this case, it seems appropriate to use the so-called geometric method. For such an analysis, it is better to use observations only in two photometric bands, B and V. The periodicity in these bands has the greatest amplitude and is identified most reliably.

The geometric method is based on the separation of the first and second harmonics by constructing the \((q_+, u_+\) and \((q_-, u_-)\) ellipses in the \((q, u)\) plane:

\[
\begin{align*}
q_+(\lambda) &= 0.5(q(\lambda) + q(\lambda + \pi)), \\
u_+(\lambda) &= 0.5(u(\lambda) + u(\lambda + \pi)), \\
q_-(\lambda) &= 0.5(q(\lambda) - q(\lambda + \pi)), \\
u_-(\lambda) &= 0.5(u(\lambda) - u(\lambda + \pi)).
\end{align*}
\]

(3)

The \((q_+, u_+)\) ellipse contains the terms of the second harmonic and is circuited twice in the period, whereas \((q_-, u_-)\) is the ellipse of the first harmonic and is circuited once in the period.

The coordinates of the center of the ellipse for the second harmonic are given by the relations

\[
\begin{align*}
q_c &= q_c^\prime + \tau_0(1 - 3\gamma_0)\sin^2 i, \\
u_c &= u_c^\prime.
\end{align*}
\]

(4)

Here, \(q_c^\prime\) and \(u_c^\prime\) are the Stokes parameters of the interstellar polarization in the internal coordinate system (i.e., in the coordinate system connected with the binary’s orbit). The semimajor axis of this ellipse is aligned with the \(q^\prime\) axis of the internal \((q, u')\) coordinate system, and its orientation relative to the \(q^\prime\) axis of the standard \((q, u)\) coordinate system gives the value of \(\Omega\). The orbital inclination \(i\) can be determined from the eccentricity of the ellipse using the canonical relation

\[
e_2 = \sin^2 i/(1 + \cos^2 i).
\]

(5)

The center of the ellipse for the first harmonic coincides with the origin of the internal coordinate system, and its semimajor axis is aligned with the \(q^\prime\) axis. The angle \(\Omega\) is thus determined by the orientation of the semimajor axis of the ellipse for the first harmonic relative to the \(q\) axis of the standard coordinate system.
The orbital inclination $i$ is related to the eccentricity of the ellipse by

$$e_1 = \sin i.$$  \hspace{1cm} (6)

Thus, using these two ellipses, we can independently determine $i$ and $\Omega$, thereby ensuring their cross-verification. Although these ellipses are not completely independent, because their eccentricity is determined by the same angle $i$, the condition for mutual orthogonality of their semiaxes can serve as an additional test for the validity of the method in question.

For KX And, however, we cannot make full use of the geometric method. As can be seen from Table 1, the numerical values of $q_3$, $q_4$ and $u_3$, $u_4$ are so small that they are comparable to the errors of their determination. Accordingly, the shape of the ellipse for the second harmonic is determined with great uncertainty, and the value of $i$, which is obtained from its eccentricity, contains a very large error. Nevertheless, the position of the center of this ellipse must be related to the Stokes parameters of the interstellar polarization by relation (4), and the direction of its semimajor axis may yield an estimate of $\Omega$.

In order to estimate the interstellar polarization for KX And, we performed observations of nine stars in a surrounding field of size $\pm 1.5^{\circ}$. The positions of the stars are marked in Fig. 4 by the points, and the directions of their polarization vectors are indicated by the rectilinear segments. The segment length corresponds to the magnitude of measured polarization. We see from this figure that the polarization vectors of the field stars are aligned with a well-defined, predominant direction of $\sim 53^{\circ}$, which suggests that the directions of interstellar magnetic field lines in this region of the sky show a regular pattern. The weighted mean parameters of the interstellar polarization in the five photometric bands that we calculated using our measurements of the field stars are given in Table 2. As can be seen from Table 2, the interstellar polarization determined in this way has the same direction in all photometric bands, reaching its maximum in $V$.

Figure 5 shows the ellipses of the first and second harmonics in the $(q, u)$ coordinate plane. The position that corresponds to the interstellar polarization is also marked in this figure. In order to reproduce the ellipse of the second harmonic, we had to use an enlarged scale. The axes of the internal $(q', u')$ coordinate system, whose positions were determined from the directions of the axes of the ellipse for the first harmonic, are also shown in the figure.

The angle $\Omega$ in $B$ and $V$ turned out to be the same: $\sim 100^{\circ}$. As can be seen from Fig. 5, the condition for mutual orthogonality of the semiaxes of the ellipses for the first and second harmonics is satisfied. According to (3.7), $u'_c = u'_i$. For the $B$ band we have $u'_c = -0.07$ and $u'_i = 0.00$, and for the $V$ band their values are $-0.05$ and $0.10$, respectively.

Of course, in any case, it is difficult to expect these values to match each other. The sample of field stars is, to a large extent, arbitrary, and we cannot be sure that the selected stars are all at the same distance as KX And itself. Nevertheless, the values of $u'_c$ and $u'_i$ are rather similar.

We found the orbital inclination from the ellipse of the first harmonic in $B$ and $V$ to be $52^{\circ}$. The accuracy of determining the orbital inclination by the method in question is governed by the following factors: by the accuracy of observations, by the quality of the fit, and by the true orbital inclination (Aspin et al. 1981; Simonson et al. 1982; Wolinski and Dolan 1994). The observationally determined value of $i$ was shown to be a biased (toward greater values) estimate of the true orbital inclination $i$. The authors of the above papers proposed methods of estimating the confidence interval for $i$ and $\Omega$ that were based on statistical modeling. In this case, the quantity $\gamma$

$$\gamma = \left( A / \sigma_p \right)^2 N / 2,$$  \hspace{1cm} (7)

$$A = (|q_{max} - q_{min}| + |u_{max} - u_{min}|) / 4,$$

where $\sigma_p$ is the mean observational error, and $N$ is the number of points in the phase curve, is used as a parameter that reflects the accuracy of the observations and the quality of their Fourier fit.
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Fig. 5. Ellipses of the first and second harmonics in $B$ and $V$ ($q, u$) and $(q', u')$ are the axes of the standard coordinate system and in the coordinate system connected with the binary’s orbit, respectively. The filled triangle marks the position of the point of interstellar polarization. The ellipse of the second harmonic is shown on an enlarged scale.

We estimated the confidence interval for $i$ and $\Omega$ by using the method of Wolinski and Dolan (1994). In accordance with their diagram, the best estimate of the true orbital inclination $i$ at $i = 52^\circ$ for $\gamma = 300$ is $56^\circ$. However, the lower limit of the confidence interval extends to $0^\circ$! Nevertheless, we can place a reasonable lower limit on $i$ for KX And on the basis of photometric data. Since the hot component in the system is shielded by the outer edge of the shell, the inclination cannot be too small. It would be quite acceptable to assume that $i \geq 45^\circ$. Taking this into account, we can give the following estimate of the orbital inclination for KX And:

$$45^\circ < i < 56^\circ.$$  (8)

If we set $i = 45^\circ$ as a lower limit, then the limits of the $1\sigma$ confidence interval for $\Omega$ are

$$70^\circ < \Omega < 130^\circ.$$  (9)

The best estimate for the orientation of the orbit is an unbiased value of $\Omega = 100^\circ$.

CONCLUSION

Thus, our analysis of the photometric and polarimetric observations, which we obtained at the Crimean Astrophysical Observatory, led us to the following conclusions.

(1) The observations provide further evidence for the previously made assumption that the hot component is surrounded by an optically thick disk with a noticeable thickening at its front edge in the direction perpendicular to the orbital plane. The scattering of light in the surface layer of this disk is responsible for the dominance of the first harmonic in the observed polarization variability of KX And.

(2) Our new photometric data suggest that this thickening can change its orbital position in longitude with time.

(3) Our analysis of the polarimetric data yielded estimates of the system’s orbital inclination, $45^\circ < i < 56^\circ$, and the orientation of the orbit, $70^\circ < \Omega < 130^\circ$.

REFERENCES


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