ABSTRACT

We have monitored the $R$ and $I$ magnitudes of the black hole candidate system A0620 – 00 (V616 Mon) in the years 1991–1995 at the Wise Observatory. Combining our data with some additional measurements, we analyse a sparsely covered 7-yr light curve of the star. We find that the average $R$-band magnitude varies on a time-scale of a few hundred days, with a peak-to-peak amplitude of 0.3 mag.

The two maxima in the well-known double hump binary cycle, as well as one of the minima between them, vary by a few per cent relative to one another, in a seemingly random way. One maximum is, on average, higher by 0.05 mag than the other. The depth of the second minimum varies with significantly higher amplitude, in clear correlation with the long-term variability of the mean magnitude of the system. It is shallower than the other minimum at times of maximum light. It deepens when the system brightness declines, and it becomes the deeper of the two minima at times of minimum system light.

According to the commonly acceptable phasing of the binary cycle, the systematically varying minimum corresponds to the inferior conjunction of the red dwarf. We cannot suggest any simple geometrical model for explaining the regularities that we find in the long-term photometric behaviour of the V616 Mon binary system.

Key words: binaries: close – stars: individual: A0620 – 00 – X-rays: stars.

1 INTRODUCTION

The X-ray nova A0620 – 00 was discovered on 1975 August 3 (Elvis et al. 1975) during a routine monitoring of the Milky Way with the Ariel V Sky Survey Experiment (SSE). The optical counterpart of the X-ray source was identified as the star V616 Mon at the 1950 coordinates: RA = 6°20′11″.2, Dec. = −0°19′10″ (Boley et al. 1976). A previous outburst of the source was discovered on Harvard photographic plates taken in 1917 (Eachus, Wright & Liller 1976).

Spectroscopic as well as photometric measurements show that the star is a compact binary with a period $P_B = 7.75234 h$ (McClintock & Remillard 1986). The secondary component is a K5–K7 red dwarf (Oke 1977). From the radial velocity curve of the secondary, a mass function $f(M) = 3.18 \pm 0.16 M_\odot$ can be derived (McClintock & Remillard 1986). If the mass ratio does not exceed $q = M_1/M_2 = 10.6$ and an upper limit of 0.8 $M_\odot$ is placed on the mass of the companion star, a lower limit of $M_1 = 4.16 M_\odot$ can be determined for the mass of the compact object (Haswell et al. 1993). As this value is above the theoretical upper limit for the mass of a neutron star, this star is considered a black hole candidate (BHC).

A0620 – 00 is the first X-ray nova that was identified as a BHC, and it is considered a prototype of the small but growing class of similar Galactic objects. As the oldest member in the class of BHC/ X-ray novae and the optically brightest in its quiescent state, it is also probably the most thoroughly studied system of its kind, particularly in optical photometry. The photometric binary cycle of the system has a clear double hump structure (McClintock & Remillard 1986), which is commonly believed to be the result of the ellipsoidal effect. The Roche lobe filling secondary is distorted into an ellipsoidal shape by the strong gravitational pull of its companion, the black hole. As its spin rate is tidally locked with the orbital revolution, it reveals its extended dimension to an observer on Earth twice during each orbital cycle, at the two phases of maximum light in the photometric cycle. Minima in the photometric binary light curve (LC) are observed when one of the narrow ends of the ellipsoid is pointing at the observer. McClintock & Remillard (1986) determined the epoch of minimum light in the binary LC at JD 244 5477.827. From radial velocity measurements they have also established that this is the phase of inferior conjunction of the compact object, i.e. when the black hole is in front of the secondary with respect to the observer.

There are scattered reports in the literature on variations in the average magnitude of A0620 – 00 (McClintock & Remillard 1986;
Haswell et al. (1993) and Bartolini et al. (1990) report about variations in the structure of the binary LC. In particular, the relative height between the two maxima in the double humped LC seems to be different in different epochs, as does the relative depth of the two minima.

The mass function of A0620 – 00, derived from the radial velocity curve, establishes a lower limit to the mass of the compact star. However, in order to better constrain the possible mass value of the black hole candidate, one must have an estimate for the inclination angle \( i \) of the system. This may be achieved by analysing the LC of the system (Haswell 1995; Charles 1995). Thus, a detailed study of the optical photometric behaviour of A0620 – 00 seems to be an important avenue for better understanding this prototype BHC. This was our motivation for initiating, at the Wise Observatory (WO), a program of long-term monitoring of the photometric behaviour of this star. Here we report the results of this 5-year programme. We analyse our own data, as well as some additional relevant data, obtained by other observers, as described in the next section.

2 OBSERVATIONS

2.1 Photometry at the Wise Observatory

Photometric observations of A0620 – 00 (V616 Mon) were performed at WO from 1991 January to 1995 November. A journal of the observations is presented in Table 1. Runs 1 to 17 were performed with the observatory 320 × 520 RCA CCD camera. From Run 18 onwards, we used the newer Tektronix 1024 × 1024 CCD camera. A detailed description of the WO optics and measuring instruments is given by Kaspi et al. (1995). Most of our observations (Runs 1–5, 8–21) were made through a Cousins R-band filter, and some with an I filter (Runs 1–7). The typical integration time was 6 to 8 min.

All of our frames were subjected to the usual data reduction procedure of bias subtraction and division by flat-field frames, taken each night in the corresponding filters. Using the program DAOPHOT (Stetson 1987) we then performed aperture photometry, deriving from each frame instrumental magnitudes of A0620 – 00, as well as of a few reference stars in its neighbourhood. We then used the Wise Observatory program DAOSTAT (Netzer et al. 1996) to calculate the magnitude of the object, relative to some mean magnitude of a group of 10 reference stars that proved to be non-variable during the course of our observations. The observational error in the value of the relative magnitudes is \( \pm 0.02 \) mag, while the error in the absolute value is around 0.1 mag.

2.2 Additional observations

In this work we also analyse, in addition to our own data, a few photometric results obtained by L. Solmi with the CCD camera attached to the 1.52-m telescope of the Bologna University at Loiano, Bologna (Solmi 1989). We were able to combine L. Solmi’s \( R \) data with our own, by finding one standard star that was used as a reference star in both sets of observations. Based on the measurements of this star, we introduced a shift of \( -0.0962 \) mag. into Solmi’s values and thus obtained a consistent 7-yr \( R \) LC of A0620 – 00. This LC is analysed in Sections 3 and 4.

3 ANALYSIS

3.1 Long-term variations

Fig. 1 shows our 7-yr \( R \)-band light curve of V616 Mon, with individual measurements shown as dots. Squares denote mean values.
magnitudes of 11 subgroups of observations. Each subgroup consists of close consecutive measurements that together cover a complete cycle of the binary periodicity. The time interval spanned by the observations in each group is detailed in Table 2, the largest being 41 d. The mean value displayed is the free term in a three-harmonics Fourier expansion of the corresponding observed magnitudes around the binary period $P_B$.

A power spectrum analysis (Scargle 1982) was performed over the entire $R$-band data set. In its high-frequency end, the power spectrum is dominated by a very high peak corresponding to the periodicity 0.161 508 0 d. Twice this value should be the photometric binary period of the system $P_B = 0.323 016 0d = 7.752 38h$.

Epoch of phase 0, i.e. of minimum M2 (see Section 3.2), is at JD 245 0000.025. In the long-period end of the power spectrum there is a high peak at the frequency corresponding to a period of 255 d. The power spectrum of just the 11 mean magnitude values also has its highest peak at the same frequency.

The peaks around the 255-d periodicity in both power spectra, that of the entire data set and that of the 11 point LC, are statistically not significant. There is, however, hardly any doubt that the mean brightness of the star varies with an amplitude of $\sim 0.3$ mag on a time-scale of hundreds of days. The change in the general brightness of the star is also mentioned by McClintock & Remillard (1986) and by Haswell (1992).

### 3.2 The structure of the binary light curve

For each one of the 11 groups of data points discussed in the previous section, we calculated a mean binary LC by least-squares fitting to the data the first three harmonics of the Fourier expansion around the known binary period. All 11 light curves show the double hump structure with variations in the amplitudes of the extrema from one LC to another. Three examples are shown in Fig. 2(a)–(c). The typical, smooth LC of A0620 – 00, as shown in Fig. 2(d), is characterized by two minima – M2 and M1 around phases 0.0 and 0.5, and two maxima – X1 and X2 near phases 0.25 and 0.75. Phase 0 here and in all other binary LCs shown in this work is at JD 244 5477.827, as in McClintock & Remillard 1986.

For each of the 11 LCs established from our observed data, we determined the magnitude of the star at X1, M1, X2, and M2, by considering the four extremum points in the fitted smooth curve. The mean magnitude value $M$ was determined for each LC by the free term in the Fourier expansion of the fitted curve.

| Data Group | JD 244 0000+ | Time Span (days) | No. of Points |
|------------|-------------|-----------------|---------------|
| 1          | 8230        | 1               | 20            |
| 2          | 7567 - 7577 | 11              | 38            |
| 3          | 8265 - 8305 | 41              | 29            |
| 4          | 9298 - 9302 | 5               | 89            |
| 5          | 9314 - 9337 | 24              | 138           |
| 6          | 9361 - 9362 | 2               | 131           |
| 7          | 9372 - 9373 | 2               | 98            |
| 8          | 9399 - 9421 | 29              | 89            |
| 9          | 9693 - 9697 | 5               | 179           |
| 10         | 9723 - 9758 | 36              | 111           |
| 11         | 10041       | 1               | 31            |

| Figure 2. (a–c) Light curves of A0620 – 00 at different times. The smooth line represents a three-harmonics least-squares fit of the known orbital period. (d) Scheme of a typical light curve of the star. X1, M1, X2, M2 denote the four extremum points of the LC. M denotes the mean magnitude of the star at that time.

| Figure 3. (a) Magnitude differences X1–X2 (° symbol) and M1–M2 (diamonds) versus mean magnitude (M) for the 11 groups of R data. The dotted line represents a least-squares linear fit to the X1–X2 points and the solid line represents a least-squares linear fit to the M1–M2 points. (b) Magnitude differences X1–M1 (triangles) and X2–M2 (x symbol) versus mean magnitude (M) for the 11 groups of R data. The solid line represents a least-squares linear fit to the X1–M1 points and the dotted line represents a least-squares linear fit to the X2–M2 points.

As is evident from Fig. 2, the structure of the binary LC and the mean magnitude of the star vary from one data group to another. To isolate the structural effect, we consider magnitude differences between extremum points in a given binary LC. Fig. 3(a) is a plot of the magnitude difference X1–X2 (° symbol) and of M1–M2 (diamond symbol) versus the system mean magnitude M. Fig. 3(b) is a plot of the magnitude difference X1–M1 (triangle symbol) and of X2–M2 (x symbol) versus the mean magnitude M. The dotted line represents a least-squares linear fit to the X1–X2 points and the solid line represents a least-squares linear fit to the X2–M2 points.

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symbol) and of $X_2\!-\!M_2$ (X symbol) versus the system mean magnitude $M$. The solid and dotted straight lines are the linear regression lines of the corresponding sets of points.

The error bars in the figures were determined by the bootstrap method (Efron & Tibshirani 1993). For each LC we calculated all the differences $d_i$ between observed magnitudes and the corresponding values on the smooth curve. We then added to each magnitude on the fitted curve one number, drawn randomly from the ensemble of the $d_i$ values (with repetitions). We thus created a new pseudo-observed binary LC, to which we fitted by the least-squares method a smooth LC of three Fourier harmonics. For this LC we found, as before, the magnitude value of the four extremum points. Repeating the procedure 1000 times we obtained 1000 values of magnitudes for each extremum point. The error bars are the half width at 0.04 of the maximum in the histogram of the corresponding parameter.

### 3.3 Photometric correlation

In Fig. 3(a) one can see that, although the $X_1\!-\!X_2$ magnitude difference (× symbol) varies by up to 0.1 mag, there is no dependence of this variation on $M$. The mean value of this parameter is around 0.05 mag. On the other hand, the $M_1\!-\!M_2$ parameter (diamond symbol) appears to be correlated with the system mean magnitude $M$. This is also borne out by statistical tests. The dotted straight line in Fig. 3(a) is a regression line fitted to the $X_1\!-\!X_2$ points by the least-squares method. The slope of this line is 0.043. By the bootstrap method (Efron & Tibshirani 1993), on a pseudo-sample of 1000, we find a 60 per cent confidence interval around this value of ±0.06. Thus the slope of this line is consistent with being zero. On the other hand, the slope of the solid, regression line of the $M_1\!-\!M_2$ parameter values is 0.381. With the bootstrap method, we find that the probability that the slope is 0 or negative is not larger than 0.2 per cent, i.e. the slope is significantly different from 0.

The slope of the solid regression line in Fig. 3(a) is admittedly very much dependent on the value of one single point. When we remove from the data the diamond point at the extreme right end of the figure, the slope of the regression line of the remaining 10 points is no longer significantly different from 0. We do believe, however, that the correlation presented in the solid line in Fig. 3(a) is nevertheless significant. The position of that crucial point in the plane of the graph is well established, as evident from the very small error bar around it. Secondly, we made a further check by dividing all the observed measurements into 12 subgroups rather than into 11 groups as described in Section 3.2. We plotted the 12 $M_1\!-\!M_2$ values versus $M$ as in Fig. 3(a), and computed the corresponding regression line. Its slope is similar to that of the solid line in Fig. 3(a), and it does not depend critically on any single point among the 12 in that plot. As a third test for the significance of the slope of the solid line in Fig. 3(a) we performed a second, different bootstrap analysis, by randomly reshuffling the 11 $M_1\!-\!M_2$ values among the 11 mean magnitude ($M$) values. We computed the regression lines of the 1000 different distributions of 11 ($M, M_1\!-\!M_2$) points so obtained. In only 18 cases out of the 1000, the slope was found to be equal to or larger than the value in the real, observed data.

In Fig. 3(b) we plot two other magnitude differences among the four extremum points of the binary LC. The triangle symbol denotes the $X_1\!-\!M_1$ difference and the X symbol represents the $X_2\!-\!M_2$ difference. Here we see again that one parameter is independent of $M$, while the other one is correlated with it. The slope of the dotted straight line in Fig. 3(b), the regression line of the $X_2\!-\!M_2$ parameter values, is 0.066. With a 60 per cent confidence

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**Table 3.** The five groups of data points.

| Mean magnitude | No. of data points |
|---------------|-------------------|
| 17.00         | 268               |
| 17.09         | 142               |
| 17.21         | 118               |
| 17.27         | 445               |
| 17.33         | 20                |

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**Figure 4.** The five light curves of data regrouped according to the mean magnitude $M$. The magnitude of maximum $X_1$ in all LCs is set to 0. Minimum $M_1$ (at phase $\approx 0.5$) varies with a considerably larger amplitude than the other two extremum points $X_2$ and $M_2$.

**Figure 5.** Magnitude differences (upper panel: $X_1\!-\!X_2$ and $M_1\!-\!M_2$, lower panel: $X_1\!-\!M_1$ and $X_2\!-\!M_2$) versus mean magnitude for the five subsets of $R$ data, grouped by magnitude.
interval of ±0.07, it is consistent with being 0. The mean value of the X2–M2 magnitude difference is −0.15. On the other hand, the slope of the solid regression line of the X1–M1 parameter is −0.272. With the bootstrap, we find that the probability that the slope of the true line of regression is 0 or positive is smaller than 5 per cent. Here again we also performed the other two checks described in the previous paragraph. They too show that the slope of the solid regression line in Fig. 3(b) is significantly different from 0. In order to further check this correlation with a better signal-to-noise ratio, we regrouped all our single-night light curves into five new subgroups. These are defined according to the mean magnitude value of each LC rather than by the time of observations. Table 3 presents the central magnitude of each of the five bins that we have defined on the magnitude axis, as well as the number of observed points in each bin. For each bin we fitted by least-squares the first three harmonics of a Fourier series, expanded around the fundamental periodicity $P_B$ of the binary cycle. As before, the free term in this expansion was taken as the mean magnitude of the system, and the four extremum points X1, M1, X2 and M2 were determined. In Fig. 4 we draw all the five fitted LCs together, and we assign the magnitude value 0 to all X1 maxima. One can clearly see that the resulting variation in the magnitude value of minimum M1 is significantly larger than the variations in the magnitude value of the other two extremum points, X2 and M2. The systematic difference between the heights of the 2 maximum points is also apparent in this presentation. Figure 5(a) is a plot of the magnitude difference X1–M1 and X2–M2 of the LCs shown in Fig. 4, as functions of M, the mean magnitude of the system. The straight lines are linear regression lines of the corresponding observed points. As in Fig. 3(a), we see here that X1–X2 is independent of M, while M1–M2 is very much correlated with it. Fig. 5(b) is the corresponding plot for the magnitude differences X1–M1 and X2–M2. Again we see, as in Fig. 3(b), that X2–M2 is independent of M while X1–M1 is clearly correlated with it. Combining the results presented in Figs 3(a) and (b), or in Figs 5(a) and (b), we can arrive at the following conclusion: among the four extremum points X1, X2 and M2 and M1, the systematic difference between the heights of the 2 maximum points is also apparent in this presentation. In LMC X-4, the minimum in the binary LC that varies with the larger amplitude is the one at binary phase 0.5, which according to HvP corresponds to inferior conjunction of the X-ray source in the system (HvP figs 9 and 10). This is the binary phase at which the illuminated hemisphere of the secondary star is facing the observer. This is, therefore, the phase at which variations in the X-ray illumination, due to disc precession, are mostly reflected in the optical radiation. In V616 Mon the situation is different. Comparing phases of the photometric data with spectroscopic radial velocity measurements, McClintock & Remillard (1986) determined that the maximum that we denote X2 is the phase of maximum radial velocity of the red dwarf in the binary system. The varying minimum M1 is accordingly at the phase of inferior conjunction of the red dwarf. At this phase the red dwarf is located between the observer and the compact object, with its non-illuminated hemisphere in the direction of the observer. This is the phase when variations in the illumination of the secondary are hardly affecting the binary optical LC. It therefore seems to us that if no discrepancy is found in the commonly adopted relative phasing of the LC and the radial velocity curve, a simple geometrical model, based on ellipsoidal and reflection effects, cannot account for the photometric long-term behaviour of A0620 − 00. Needless to say, further photometric monitoring of the system and/or publication of additional LCs that are no doubt still in the possession of a few observers of this star, are crucial for a proper understanding of this prototype BHC.

4 DISCUSSION

The BHC system A0620 − 00 (V616 Mon) is found to vary in its optical brightness on a time-scale of hundreds of days. This is in addition to its well-known photometric variation with the binary periodicity of the system. The amplitude of the long-term variation is ~0.3 mag. It is possibly periodic, with a period of $P_B = 255$ d, but this could not be established at any statistically significant level from the data at our disposal. In 11 different $R$-band binary LCs of the system that were observed over 7 yr, we find systematic variations in the structure that are correlated with variations in the mean magnitude of the system. The most apparent variations are in the relative magnitude of the four extremum points that characterize the photometric binary cycle. We find that the relative magnitudes of the three extremum points X1, X2 and M2 do vary among the different LCs. Some of these variations are the result of observational uncertainties in the determination of the respective magnitude values, but some of them seem to be real. The standard deviation of the magnitude of these three extremum points, relative to the mean system magnitude, are 0.0255, 0.0266 and 0.0280 mag, respectively. There is no apparent correlation of this variation with the mean magnitude of the system. The behaviour of minimum M1 is quite different. The standard deviation of its depth, relative to the mean system magnitude, is 0.0314 mag, significantly larger than the other three extremum points. The variations of this minimum are well correlated with the system mean magnitude. The correlation is in the sense that this minimum is deepest when the system is faint, and it becomes shallower as the system brightens. In quantitative terms, as the $R$ magnitude of the system varies by 0.30 mag, the relative depth of the M1 minimum is varying by ~0.12 mag. Variations in the structure of a double hump binary LC, similar to those in V616 Mon reported here, have been observed in the massive X-ray binary LMC X-4 (Heemskerk & van Paradijs 1989, hereafter HvP). In that system, as in ours, there are noticeable variations in the relative height of the two maxima as well as in the relative depth of the two minima, with one minimum showing much larger variations than the other. In LMC X-4, the variations are found to be correlated with the 30-d periodicity of the X-ray on/off cycle of that system. HvP interpreted the observed structural variations on the basis of a precessing disc model. With a combination of a tidal and rotational distorted secondary, X-ray heating of the secondary surface, and a luminous precessing disc, they were able to reproduce rather faithfully the varying structure of the binary optical LC, at all phases of the 30-d periodicity.

It is tempting to suggest a similar model for the temporal behaviour of the optical LC of V616 Mon. There is, however, one fundamental difference that severely harms the analogy between these two cases. In LMC X-4, the minimum in the binary LC that varies with the larger amplitude is the one at binary phase 0.5, which according to HvP corresponds to inferior conjunction of the X-ray source in the system (HvP figs 9 and 10). This is the binary phase at which the illuminated hemisphere of the secondary star is facing the observer. This is, therefore, the phase at which variations in the X-ray illumination, due to disc precession, are mostly reflected in the optical radiation.
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