The quiescent light curve and orbital period of GRO J0422+32*

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Abstract

CCD photometry of the black hole candidate GRO J0422+32 in quiescence, obtained at Haute-Provence from 1994 November to 1995 February, reveals a double-wave modulation at a period close to the value we found during outbursts and also close to one of the possible periods derived by Filippenko, Matheson and Ho (1995) from spectroscopic observations with the W. M. Keck 10-m telescope. A period of 0.212140 ± 0.000003 d (5.09136 ± 0.00007 h) fits all our photometric data from 1993 January to 1995 February and yields a minimum in our light curves at the inferior conjunction of the M star, as determined from the radial velocity data of Filippenko et al. (1995) The quiescent R_C-band light curve exhibits a changing asymmetry of shape and a variable amplitude. On two consecutive nights the source was found constant to within ± 0.05 mag, suggesting an upper limit on the ellipsoidal effect in this band.

Key Words: accretion : accretion disks — binaries : close — stars : individual (GRO J0422+32) — X-rays : stars

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1. INTRODUCTION

The remarkable X-ray transient GRO J0422+32, discovered on 1992 August 5 with the BATSE detectors on board the *Compton Observatory*, was extensively observed during its repeated outbursts, both in X-rays (Sunyaev et al. 1993, Pietsch et al. 1993, Harmon et al. 1994, Vikhlinin et al. 1995, van Dijk et al. 1995) and at UV/optical/IR wavelengths (Castro-Tirado et

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al. 1993, van Paradijs et al. 1994, Shrader et al. 1994, Chevalier and Ilovaisky 1995 –hereinafter referred to as Paper I–, Bonnet-Bidaud and Mouchet 1995, Kato et al. 1995, Callanan et al. 1995, Casares et al. 1995, Garcia et al. 1995).

After the last minor optical outburst in January 1994, the optical brightness of the source declined slowly from V=20.7 in March 1994 to V~22 during the Autumn of 1994 (Zhao et al. 1994, Chevalier & Ilovaisky 1994). We showed in Paper I that a periodic modulation was present through the secondary optical outbursts and decays with a period of 0.21213 d and an amplitude which varied from 0 to 0.2 mag on a time scale of a few cycles. This modulation was also observed at times by Kato et al., (1995) and Callanan et al. (1995) and in the spectra obtained by Casares et al. (1995) in December 1993. From the color evolution of the source, when its brightness decreased from V ~ 13.5 to V ~ 20.7, we derived a probable spectral type M0 for the secondary, in agreement with spectroscopic data obtained by Callanan et al. (1995) and Bonnet-Bidaud and Mouchet (1995) during the low state between the last minor outbursts.

When the source was at last in a quiescent state, Orosz and Bailyn (1995) obtained CCD photometry on 1994 October 27 and 28 through a wide-band filter including Johnson I. They also obtained a series of spectra on 1994 November 5-7. Their photometric data were consistent with a double-wave light curve at a period of 0.2107 ± 0.0012 d. Their spectra indicated an M0V spectral type for the secondary and a semi-amplitude of 350 ± 50 km/s for its radial velocity. Filippenko, Matheson and Ho (1995) observed the source with the W. M. Keck 10-m telescope on 1994 November 8, 9 and 1995 January 26, 27. They confirmed an early M (M0V or M2V) spectral type for the secondary and measured its radial velocity. A least-squares fit of their measurements to a cosine curve yielded 5 possible narrow intervals of periods, the two deepest χ^2 minima being centered on 0.21159 d and 0.21216 d. We present in this paper the results of CCD photometry obtained at Haute-Provence between the end of October 1994 and the beginning of February 1995 and show that an orbital period of 0.212140 d, very close to that we proposed in Paper I, is compatible with both the radial velocities of Filippenko et al. (1995) and all our photometric data.

2. OBSERVATIONS

The CCD images used for this study were all taken at the f/6 Newton focus of the 1.2-m Haute-Provence telescope with the same equipment (CCD camera, chip and Cousins V, R, I filter set) as described in Paper I. Data were obtained during 15 nights between 1994 October 31 and 1995 February 3 mainly in the R_C band although a few frames were also taken through I_C and V filters. The exposure times in the R_C band ranged from 20 to 45 minutes depending on atmospheric conditions. All the frames were measured using the PSF-fitting routine NSTAR of

DAOPHOT II (Stetson 1987) as implemented within MIDAS 93 Nov. The internal uncertainty on each measurement varied between 0.03 and 0.12 mag according to the quality of the night, the exposure time and the brightness of the source.

3. RESULTS

3.1. Magnitude evolution and color of GRO J0422+32 in quiescence.

During our observations, the R_C magnitude of the source varied between 20.74 and 21.24 with an average of 21.04. Figure 1a presents the evolution of the nightly mean $\langle R_C \rangle$ as a function of time during our observations, the runs shorter than 3 hours (1994 November 14 and 26, December 3) having been excluded. The time origin is HJD = 2448840.0, the same as in Paper I and corresponds to the start of the first outburst of the source on 5 August 1992. If we except the data obtained on days 852 (1994 December 6), 910 and 911 (1995 February 1 and 2) when the source was brighter, the average brightness $\langle R_C \rangle$ appears to decrease by 0.1 mag from October 31 to February 3. A similar plot (Fig. 1b) for a nearby field star (~ 30" NW) of comparable magnitude and color does not show any trend. Although marginally significant, this result could indicate that GRO J0422+32 had still not reached its lowest level of quiescence by October 1994.

Photometry of the source in a somewhat bright state on 1994 December 3 yielded the following Cousins magnitudes: V = 21.96 ± 0.2, R_C = 20.99 ± 0.1, I_C = 19.91 ± 0.1. In a diagram of I_C versus $V–I_C$, which reproduces the magnitude/color evolution of GRO J0422+32 during its outbursts, as plotted in Fig. 4 of Paper I, the point obtained in quiescence agrees well with the path followed in this diagram during the 1994 January-March decline.

The average color index during our observations in quiescence is $\langle R_C–I_C \rangle$ = 1.14 (internal dispersion of ± 0.06). The large exposure times and uncertainties and the small number of measurements through the I_C filter do not allow us to detect a significant variation of the color in function of the brightness (or phase). Assuming a reddening E(B–V) in the range 0.2-0.4 as previously suggested (see Paper I and other references cited above) yields $(R_C–I_C)_o$ = 0.92 ± 0.2, a value intermediate between the color indices of M0V and M2V stars (Bessell 1990). This implies that during quiescence the light from the M star dominates the system in these bands and that other contributions, such as a (bluer) residual disk or a heating effect, should be minor.

3.2. Variability and time analysis

3.2.1. Night to night variations

Night to night variations of the average magnitude $<R_C>$ have already been mentioned and are plotted in Fig. 1. At least 3 times, on 1994 December 6, 1995 February 1 and 2, the source brightened for a few hours at a level 0.1 to 0.2 mag above the slowly decreasing trend of the other nights.

3.2.2. The 5.1-hour modulation

The duration of our nightly runs ranged from 2 to 9 hours, eight of them (1994 November 11, 28, 29 and 30, December 1 and 6, 1995 February 1 and 2) being longer than 5 hours. Inspection of the data obtained each night reveals a changing behaviour of the source, reminiscent of what we observed during its successive outbursts and decays in 1993, especially the occurrence of nights during which the R_C magnitude of the source remained almost constant. This was observed on the nights of 1995 January 21, 31 and February 3, although with a large uncertainty due to the poor quality of these nights, but was also observed on the 1994 November 30 with a better S/N ratio.

In contrast, a modulation with an amplitude of 0.1 to 0.3 mag peak to peak and a time scale between 2 and 3 hours was observed during several nights and we selected the corresponding data set (63 measurements) for time analysis. We did not normalize the data relative to the nightly average in order to eventually detect periodicities longer than a few hours. As in Paper I we used the Analysis of Variance (AoV) method (Schwarzenberg-Czerny 1989), based on phase binning, which does not make any prior assumption concerning the shape of the light curve. Our coarse data sampling forced us to use a small number of bins (6 or 3 according to the frequency range) and we took a frequency step of 0.001 c/d.

Figure 2a shows the variance statistic Θ_{AoV} as a function of trial frequency computed for GRO J0422+32 and Fig. 2b shows the same periodogram computed for the same check-star mentioned in paragraph 3.1 (Fig. 1b). The strongest peak in Fig. 2a is seen at a frequency of 9.424 c/d with 1-day aliases at 8.424 and 10.424 c/d. It corresponds to a simple-wave modulation at a period of 0.1061 d. A smaller peak at 4.712 c/d corresponds to a double-wave modulation at a period of 0.2122 d. Maxima are also seen at frequencies of 1 c/d and 2 c/d, which are probably associated with the night to night variations in brightness. Figure 2b does not show any signal at the above frequencies and illustrates the noise level in the periodogram for a star of similar brightness.

The peak of Fig. 2a around 4.71 c/d is plotted in Fig. 3 as a function of period in the small interval 0.2105 - 0.2135 d (step curve). A scaled (Θ_{AoV} divided by ten) representation of our "high state" periodogram for 1993 January, February and December (Fig. 6 top of Paper I) is overplotted as a dotted line. The thin vertical lines in Fig. 3 indicate the periods corresponding to the four deepest χ^2 minima in the fits to the radial velocities of the secondary star computed by Filippenko et al. 1995 (their Figure 3), 0.21102, 0.21159, 0.21216 and 0.21273 d. Each one of these four periods has previously been proposed to fit photometric or spectroscopic data. Filippenko et al. chose 0.21159 d (but the minimum corresponding to 0.21216 was almost as deep), Orosz and Bailyn (1995) proposed 0.2107± 0.0012 d for their light curve in quiescence, Casares et al.1995 found a modulation at 0.2127 ± 0.0013 d in the radial velocities and equivalent widths of the emission lines during the December 1993 mini-outburst and the peak frequency of our "high state" periodogram was 4.7139 ± 0.0005 c/d (Paper I), corresponding to a period of 0.212139 ± 0.000023 d.

Figure 3 clearly shows that only <u>one</u> of the periods compatible with the radial velocities measured by Filippenko et al., 0.21216 d, is consistent with our photometry in quiescence and is very close to the period fitting our "high state" data. It is therefore highly probable that the optical flux of GRO J0422+32 was already modulated at the orbital period in 1993 January, February and December.

3.3. The light curve in quiescence

The shape of our folded quiescent light curve does not change if the period lies within the narrow interval 0.21213 - 0.21216 d allowed by both the spectroscopic data of Filippenko et al. and our 1993 photometry. We adopt as phase ϕ = 0.0 the time origin T_0 corresponding to an inferior conjunction of the M star, which precedes the time of maximum velocity by 0.25 cycle. For each value of the period we find the value of T_0 by fitting a cosine curve to the radial velocities of Filippenko et al. (their Table 1). When P changes from 0.21213 to 0.21216, T_0 varies from HJD 2449661.424 to 2449661.419, but these small changes of T_0 and P have no influence on the phase of the minima and maxima in our folded ligth curve (obtained at the same epoch as the data of Filippenko et al.). Figure 4a shows this folded light curve for P = 0.21214 d and T_0 = HJD 2449661.422 (the nights during which the source did not appear to vary have been excluded). For comparison, folded data for the check star are plotted in Fig. 4b, illustrating the noise level achieved for a star of comparable brightness.

One of the minima, the deepest in the light curve of Fig. 4a, falls as expected near phase zero (M star inferior conjunction) and the maxima appear near quadratures (phases 0.2 and 0.7). The data dispersion between phases 0.6 and 0.8 in Fig. 4a is larger than uncertainties and corresponds to real changes in the amplitude and shape of the light curve.

These changes are detailed in Fig. 5 a, b, c where nightly data sets corresponding to similar light curves have been plotted together. Figure 5a shows the light curves of 1994 November 11 and

28 and December 1. In Fig. 5b, which groups the data obtained on the 29 and 30 November, the amplitude is reduced to within ± 0.05 mag and the source could be considered as constant (see Fig. 5b). Figure 5c shows the light curves of 1994 December 3 and 6 superposed to those of 1995 February 1 and 2.

4. OUTBURST AND QUIESCENCE : THE ORBITAL PERIOD

To refine the orbital period within the above range, we assume that the light curves obtained during outbursts are in phase with the light curve in quiescence, as observed for GS 2000+25 (Chevalier and Ilovaisky 1993). Then each of the light curves of January, February and December 1993 should exhibit a minimum near the inferior conjunction of the M star. This condition is satisfied for a period P = 0.212140 ± 0.000003 d and a time origin T_0 = HJD 2448991.060 ± 0.001. The folded light curves for our data of 1993 January, February and December are plotted in Fig. 6 a, b and c respectively. Nights where the modulation was very small or absent have not been plotted. The three sets of light curves show a minimum at phase 0. For P = 0.212135 d, all the minima are found at phase 0.9 and for P = 0.212145 d, all the minima are found at phase 0.1. This determines a conservative allowed period interval.

A preliminary analysis of our 1994 November and December data, which did not include 1995 February 1 and 2, yielded a period of 0.212265 d (Chevalier and Ilovaisky 1994) and gave a slightly better fit to our data in quiescence. This period gave also an acceptable fit to our 1993 data, corresponding to the secondary maximum (to the right of the highest peak in Fig. 3) of our 1993 periodogram. However, this value of the period is now excluded since it is incompatible with the radial velocity data of Filippenko et al.

5. CONCLUSION

The period 0.212140 ± 0.000003 d fits both the M star radial velocities measured by Filippenko et al. in 1994 November and 1995 January and all our photometric data , including the data in quiescence between November 1994 and February 1995 as well as the data during the optical outbursts in January, February and December 1993. Our folded light curves show a minimum at the phase corresponding to the M star inferior conjunction. The R_C light curve in quiescence is double-waved as expected, but exhibits changing asymmetries of shape, the highest maximum being either near phase 0.25 or near phase 0.75, and changing amplitude, the semi-amplitude varying from 0-0.05 mag to 0.2 mag.

What is the M star contribution to these changes? The color index $\langle R_C - I_C \rangle$ = 1.14 in quiescence indicates that the light from the system is dominated by the M star in the R_C and I_C

bands, although we cannot exclude a disk contribution. Part of the large variations observed near phase 0.7 could arise from the impact area of a gas stream on a residual disk. If the small amplitude (0.05 mag or less) observed on 1994 November 29 and 30 (Fig. 5b) sets an upper limit to the ellipsoidal effect in the R_C band, is there another stellar origin for the larger amplitude modulation ?

Our data suggest that a progressive distortion in the light curve may be present when data are obtained on several consecutive nights (see Fig. 5). This encourages to search for a distortion wave like the one we detected in GS 2000+25 in quiescence (Chevalier and Ilovaisky 1993), which might be due to active regions on the secondary. Note that Filippenko et al. mention that the Ca II near-infrared triplet lines in GRO J0422+32 might actually be in emission, which is one of the spectroscopic signatures of stellar active regions. Note also that while the narrow absorption lines present in the spectrum of GRO J0422+32 are best matched by an M0V star, the depths of the broad undulations mainly due to TiO correspond to an M2V star (Filippenko et al. 1995, Garcia et al. 1995). A similar behavior is often observed on the active late-type components in RS CVn or BY Dra systems where it indicates the presence of cool starspots. Excess absorption in the TiO bands, which are nearly independent of surface gravity, depends upon the temperature difference between the photosphere and the spotted regions and upon the fractional area covered (Huenemoerder & Ramsey 1987).

The long-term observation of light curve changes will require large telescopes (and, preferably, multi-site observing runs) in order to obtain a better S/N ratio with shorter exposure times. A study of the infrared light curves of soft X-ray transients would also be useful to investigate their long-term stability since distortion waves of up to 0.1 mag amplitude in the J, H, K and L bands have been observed in the IR light curves of close binaries including active K or M components (see for example Zeilik et al. 1990). Ellipsoidal and maculation effects may be difficult to separate when the inclination is not accurately known.

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FIGURES

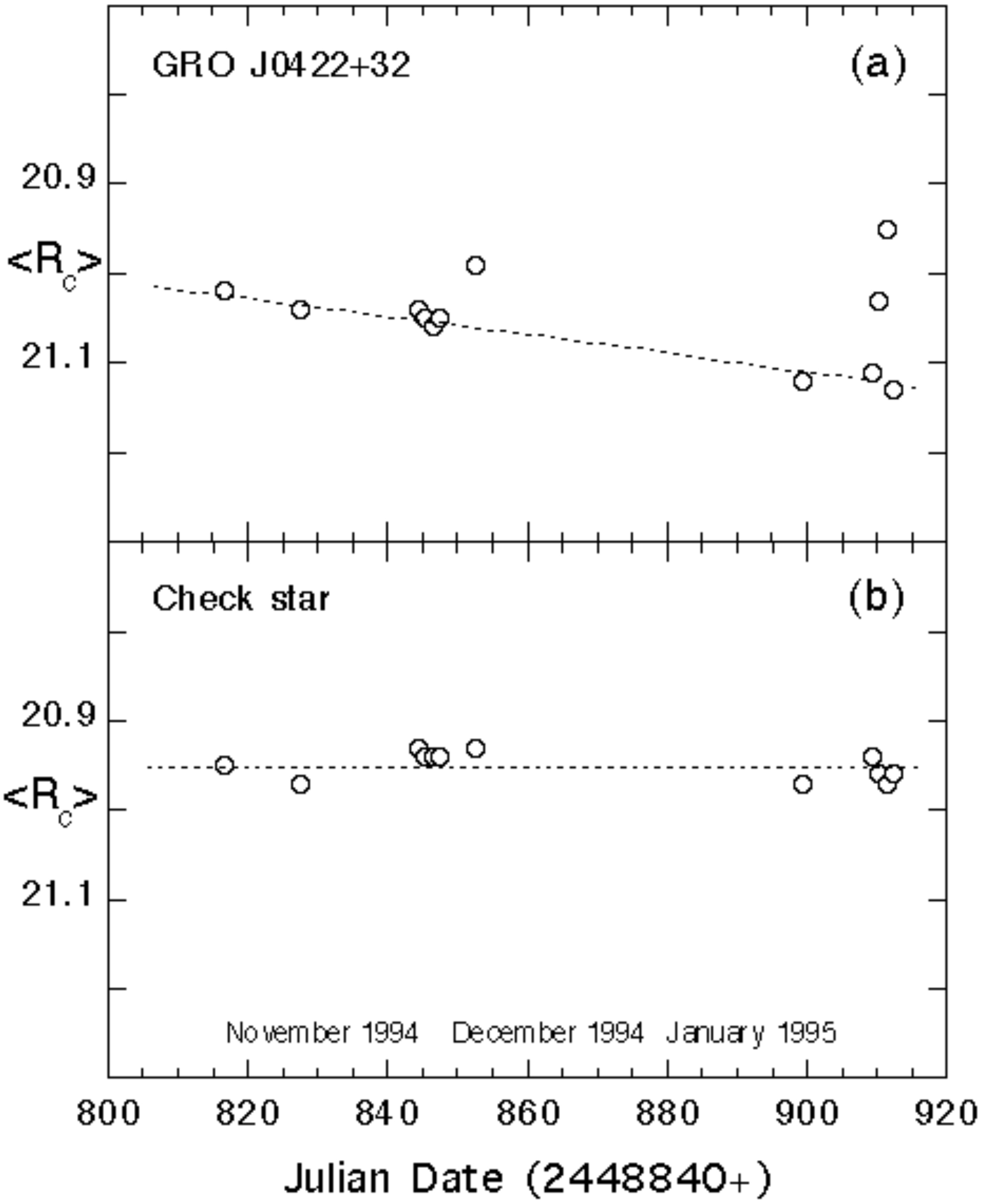

Figure 1. Evolution of the nightly average <R_C> magnitude from 1994 November to 1995 February. Time is given as days since the start of the first X-ray outburst (5 August 1992 = JD 2448840). Panel **a** (top) shows the data for GRO 0422+32 with the possible long-term trend illustrated by a dotted line, while panel **b** (bottom) shows the data for a nearby check star (approximately 30" NW of the variable), which illustrates the long-term stability obtained with the 1.2-m CCD camera for this R_C ~ 21 star.

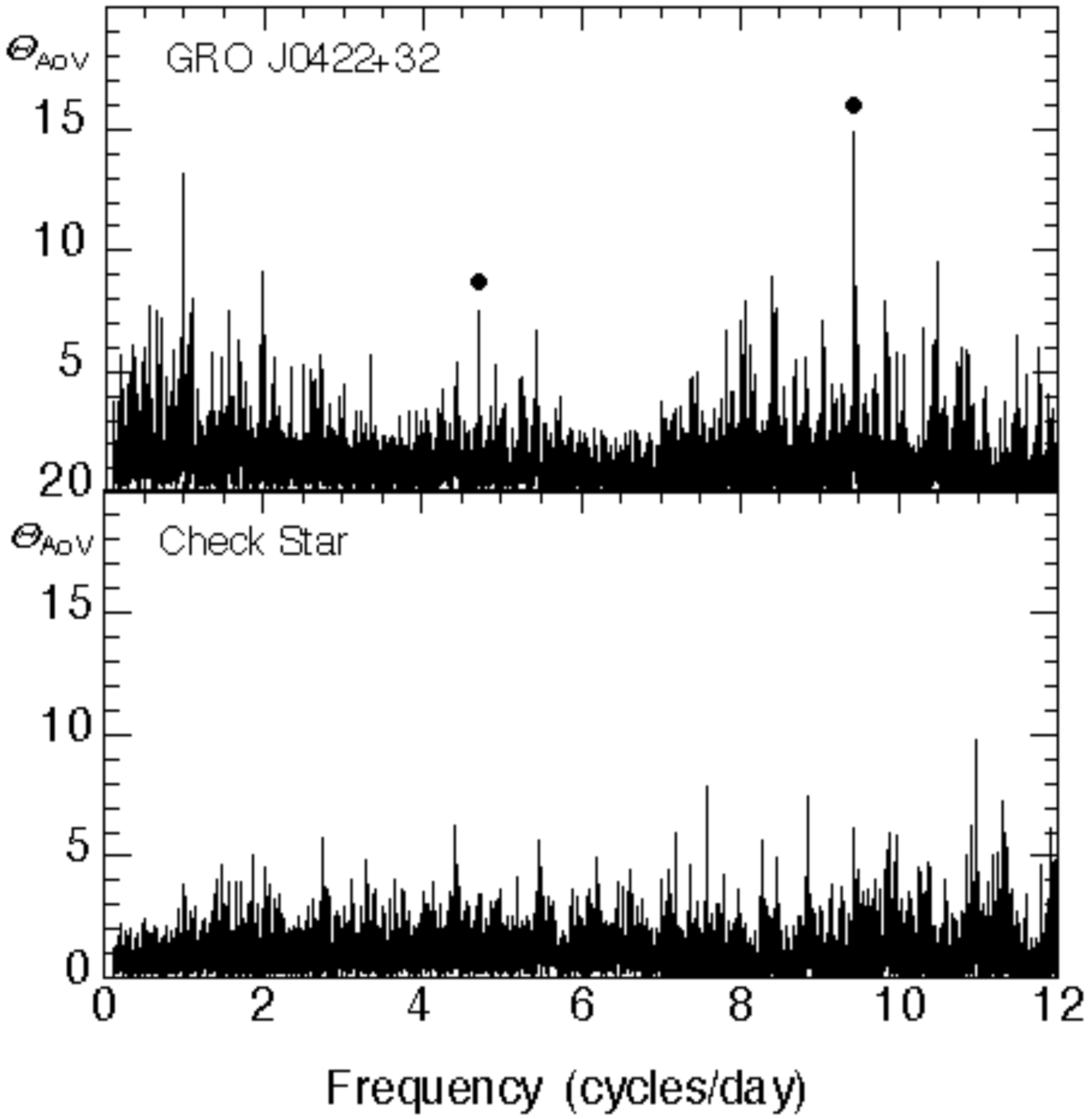

Figure 2. Analysis-of-Variance periodograms computed using our data obtained between 1994 November and 1995 February. Panel **a** (top) shows the results for GRO J0422+32 while panel **b** (bottom) shows the results for the check star (see Fig. 1). The main peak in panel **a** is found at the frequency 9.424 c/d corresponding to a period of 0.1061 d (with 1-day alias sidelobes). A smaller peak is detected at half this frequency (0.2122 d). The periodogram for the check star illustrates the noise level for a 21 mag object.

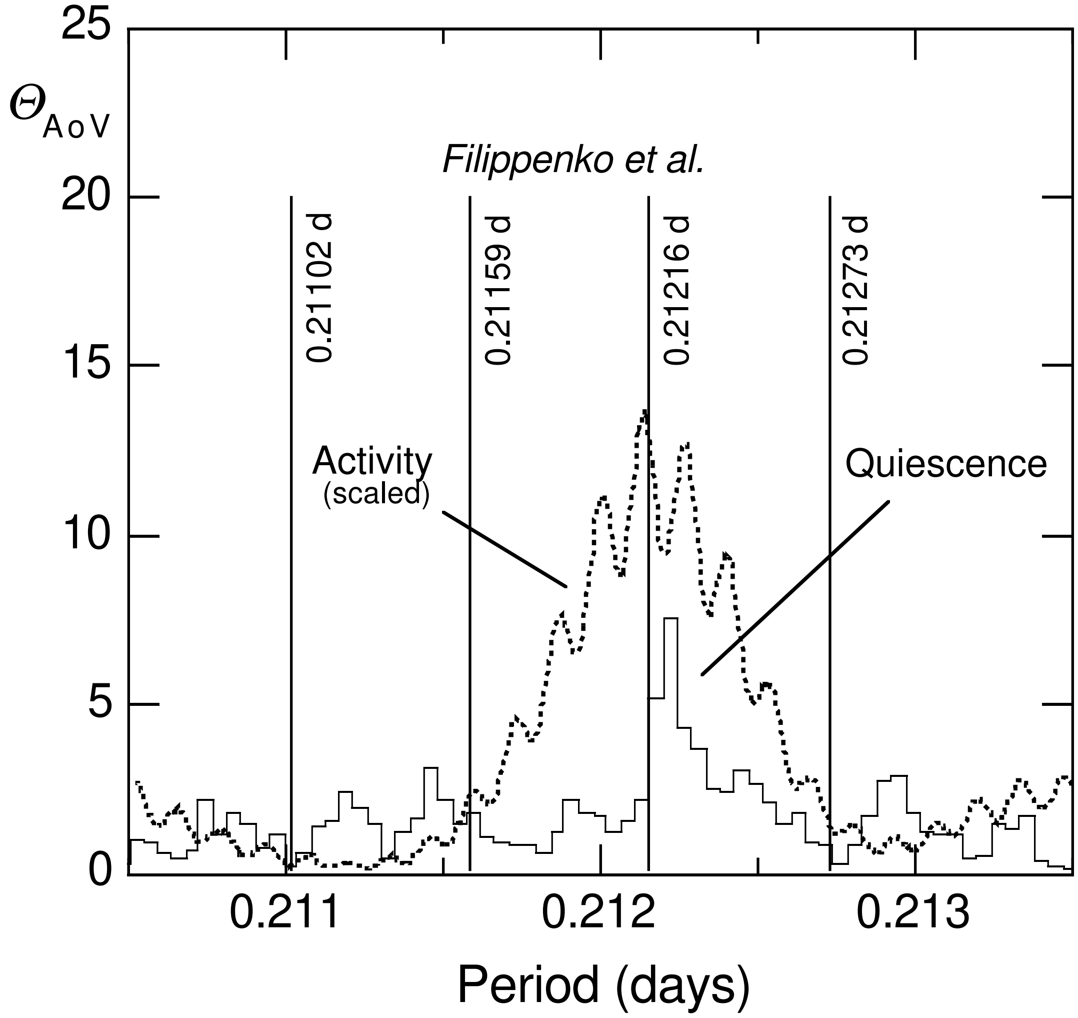

Figure 3. The periodogram of Fig. 2a is plotted here in detail for the small period interval 0.2105 - 0.2135 d (step curve). The scaled (divided by 10) periodogram we gave in Paper I, based on data obtained in 1993 January, February and December, is plotted as a dotted curve. The four thin vertical bars show the possible periods derived by Filippenko et al. from their spectroscopic observations of 1994 November and 1995 January.

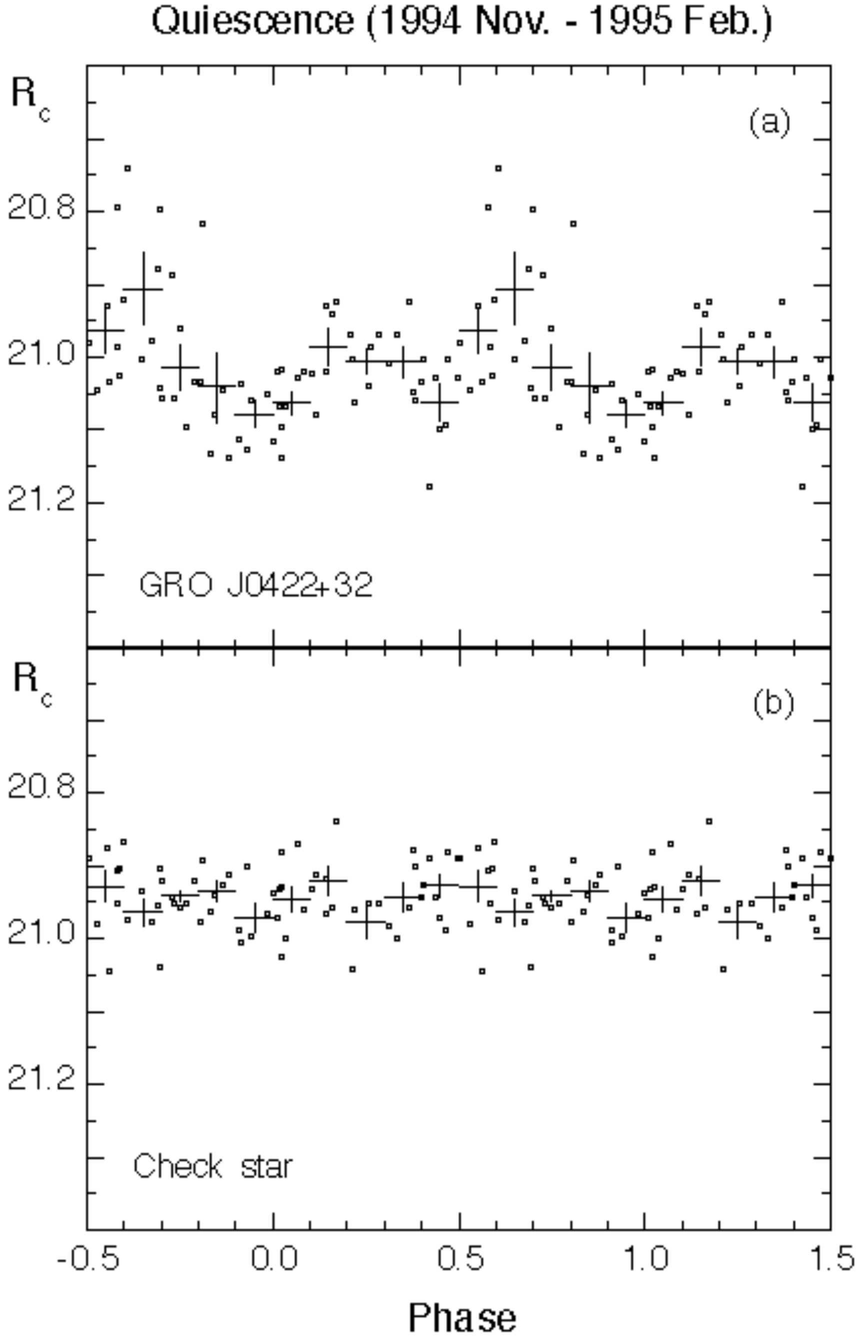

Figure 4. Panel **a** (top) shows the R_C-band folded light curve of GRO J0422+32 in quiescence (1994 November to 1995 February). The phase is computed for a period of P = 0.212140 d and an epoch for $\phi = 0.0$ of T_0 = HJD 2449661.422, which corresponds to an inferior conjunction of the M star. Panel **b** (bottom) shows the data for the check star folded using the same ephemeris. Individual data points are shown as dots while the crosses are the result of averaging the curve into ten bins. Vertical bars represent the errors on the bin means.

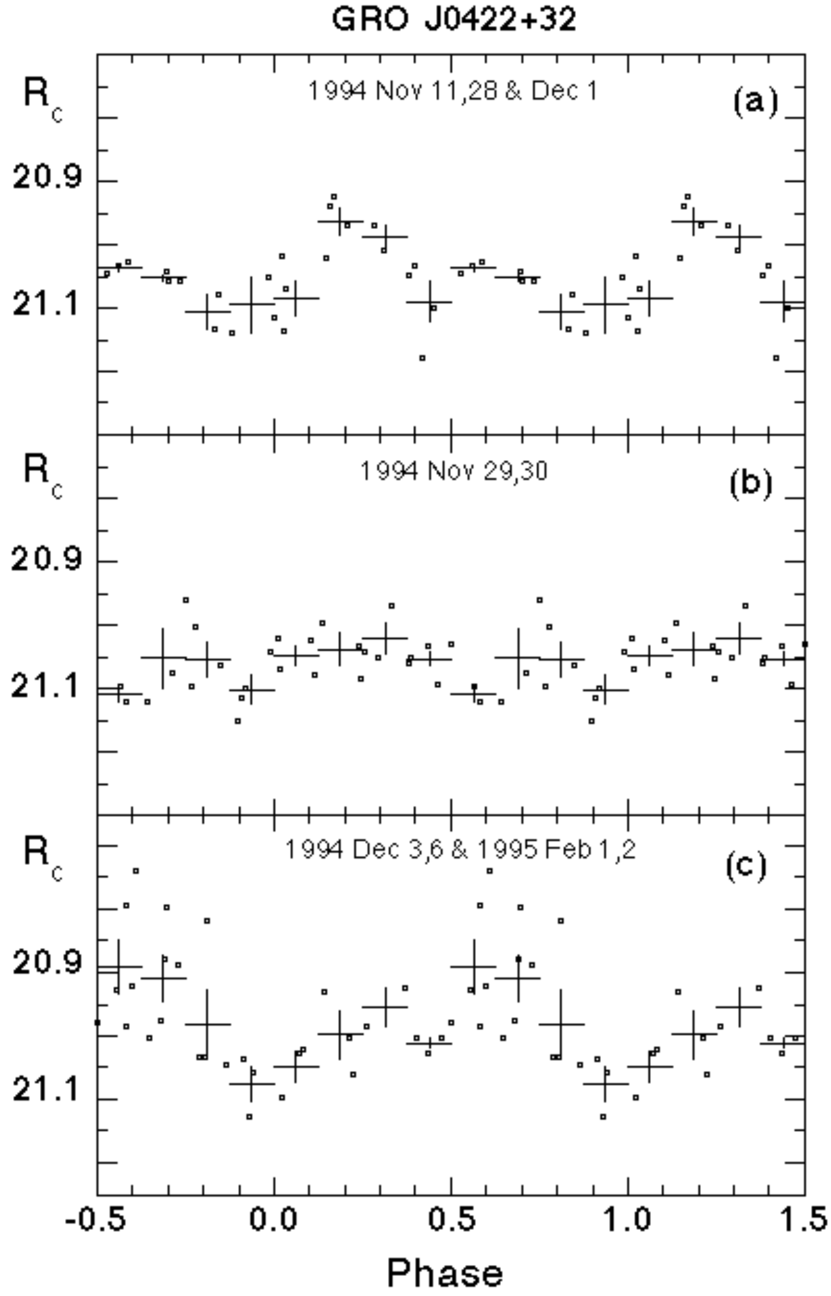

Figure 5. An illustration of the variations in shape and amplitude found in the R_C-band light curve of GRO J0422+32 in quiescence, folded using the ephemeris given in Fig. 4. Panel **a** (top) shows the light curve observed on 1994 November 11 and 28 and on December 1. Panel **b** (middle) shows the light curve obtained on 1994 November 29 and 30. Note the low amplitude modulation on those two nights. Panel **c** (bottom) shows the light curve observed on 1994 December 3 and 6 and 1995 February 1 and 2. Individual data points are shown as dots while the crosses are the result of averaging the curve into eight bins. Vertical bars represent the errors on the bin means.

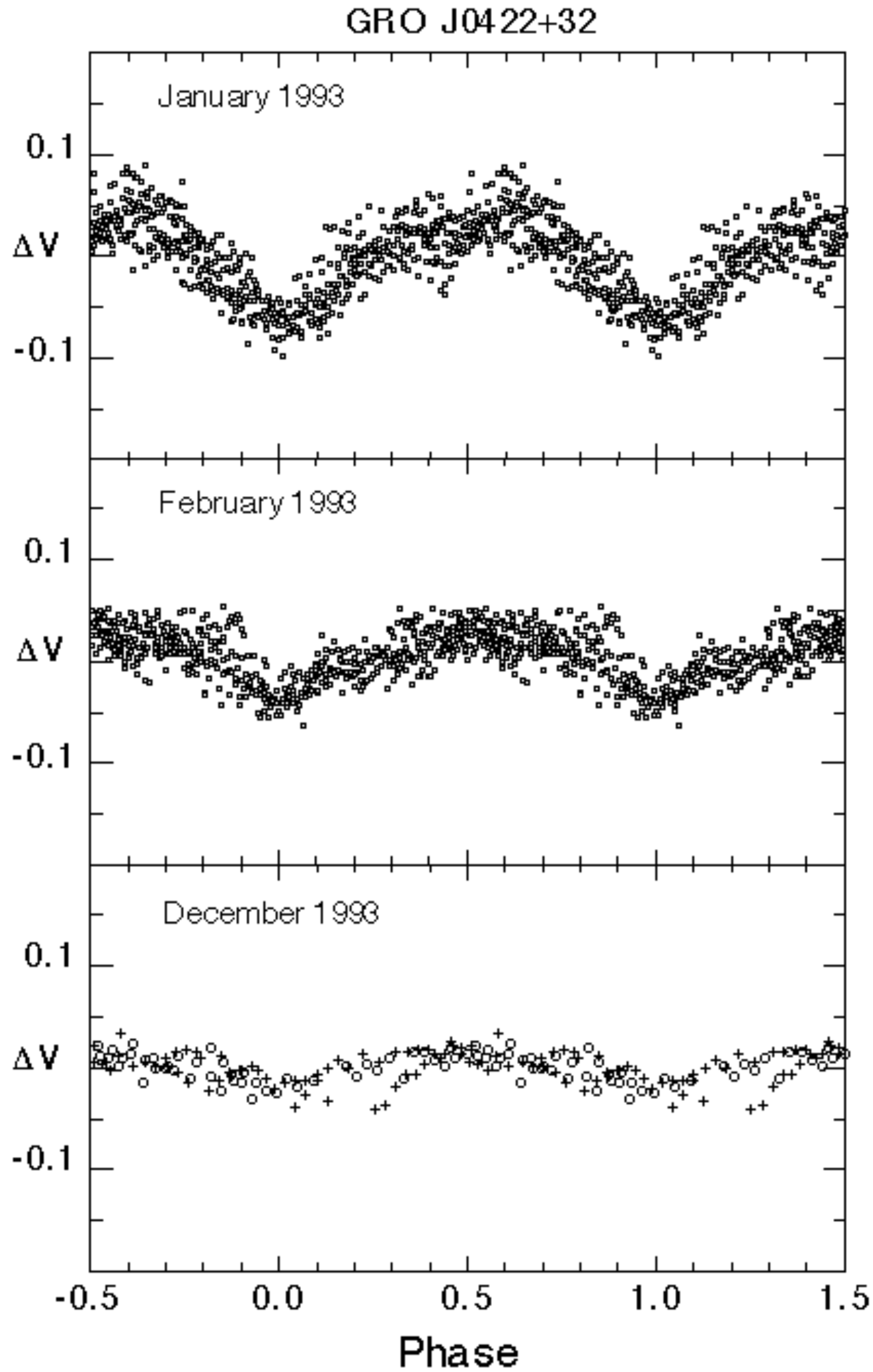

Figure 6. The V-band differential light curves for GRO J0422+32 observed during the secondary outbursts. Data have been folded using the period P = 0.212140 d and an epoch for $\phi = 0.0$ of T_0 = HJD 2448991.060, which corresponds to an inferior conjunction of the M star 3160 cycles earlier than the value used for Figs. 4 and 5. Panel **a** (top) shows the data for 1993 January 3, 4, 14, 15, 18, 19, 22 and 23 (were excluded : January 20, 21). Panel **b** (middle) shows the data for 1993 February 10, 11, 12, 13, 15, 17, 18, 19 and 20 (were excluded : February 14, 16). Panel **c** (bottom) shows the data for 1993 December 17 (crosses) and 21 (circles).