Mon. Not. R. Astron. Soc. **289,** L17–L20 (1997)

UBVRI photometry of the pulsations in V2116 Ophiuchi ≡ GX 1+4

F. Jablonski★ and M. G. Pereira★

Astrophysics Division, Instituto Nacional de Pesquisas Espaciais, PO Box 515, 12201-970 São José dos Campos, Brazil

Accepted 1997 June 15. Received 1997 June 2; in original form 1997 April 24

ABSTRACT

The colours of pulsed and non-pulsed light in V2116 Oph have been measured with the *UBVRI* photometer of the Laboratório Nacional de Astrofísica, in Brazil. The symbiotic binary was in an optical bright state with $V \sim 17$. If the blue component in the spectrum of V2116 Oph follows the prescription for a standard optically thick accretion disc spectrum, its contribution to the light of the system at 6600 Å is ~20 times the contribution of the red giant, with $E(B-V) = 2.1 \pm 0.1$ mag and a distance of 8.3 kpc. The pulsed component is estimated to have $M_V \sim -1.7$, implying characteristic sizes (for blackbody emission) of 1.4, 4.3 and 9.3 $R_\odot$, for temperatures T_{BB} = 100 000, 20 000 and 10 000 K, respectively.

Key words: accretion, accretion discs – binaries: symbiotic – stars: individual: V2116 Oph – pulsars: individual: GX 1+4 – X-rays: stars.

1 INTRODUCTION

GX 1+4 is a low-mass X-ray binary known for its large luminosity, very hard spectrum, and alternate states of spin-up and spin-down of the neutron star at rates in excess of 1 per cent yr^{-1} (Nagase 1989). The optical counterpart, V2116 Oph, was identified by Glass & Feast (1973) and characterized as a symbiotic star (see Kenyon 1986 for a review on symbiotics) by Davidsen, Malina & Bowyer (1977). The orbital period of the system is unknown so far.

Optical pulsations with ~124-s period were recently discovered in V2116 Oph (Jablonski et al. 1996, 1997).

2 OBSERVATIONS AND DATA REDUCTION

The data presented here consist of a 42-min monitoring with 15-s time resolution starting on 1996 May 27, 04:12 UT, with the FOTRAP *UBVRI* photometer (Jablonski et al. 1994) installed at the 1.6-m telescope of the Laboratório Nacional de Astrofísica (LNA), Brazil. The seeing was better than 1 arcsec during the observations and an 11-arcsec diaphragm was used. V2116 Oph was measured with the Magnitude & Colours mode of FOTRAP before and after the monitoring. In that mode, data were accumulated during an integration time of 320 s, followed by a sky background measurement. Since the sky background measurements bracket the monitoring, a linear interpolation was used to calculate the net counts in the light curve. The data were extinction-corrected and calibrated by observing 11 standards in regions SA 109/113 of Landolt (1992) at both high and low airmasses.

Fig. 1 shows the power spectra of the data in the *UBVRI* bands. The two top panels show power spectra of light curves obtained on the same night with a CCD photometer at the 0.6-m B&C telescope. The starting times for these light curves were 00:55 UT ($CuSO_4$) and 05:02 UT (*R*), and they were 55 and 50 min long, respectively. The integration time was 20 s in both cases, with no dead time between integrations.

As one can see in the second and third panels (starting from the bottom), no pulsed signal is detected in the *U* and *B* bands of FOTRAP. This is consistent with the count rate observed with the $CuSO_4$ filter + CCD if we take into account the lower quantum efficiency of the photomultiplier and the time-multiplexing scheme for the measurements with FOTRAP. The instrument has a high-speed filter wheel (1200 rpm) that produces quasi-simultaneous measurements in six bands with a duty cycle of ≈12 per cent per band (Jablonski et al. 1994).

Table 1 summarizes the properties of the pulsation in different bands. The periods were obtained from a Lomb periodogram (Press et al. 1992) and the amplitudes from a least-squares fit of a sinusoid of constant period through the data points. Table 2 presents the magnitude and colours of V2116 Oph. The DC component is the weighted average of the two measurements before and after the monitoring. The magnitude and colours of the pulsation are calculated exactly as in the case of the DC component, with the particularity that the inputs are the *peak-to-peak amplitudes* of the pulsation in each band.

3 A MODEL FOR THE COLOURS OF V2116 OPHIUCHI

The spectroscopic determinations of spectral type for the giant in V2116 Oph are M6 (Davidsen et al. 1977), M5 (Shahbaz et al. 1996), and M5 (Chakrabarty & Roche 1997). The colours in Table 2 are bluer than the expected for an M5–6 giant heavily reddened by interstellar extinction. The reason for this is the presence of an additional source of light in the system, probably an accretion disc. Jablonski et al. (1997) show that, besides coherent optical pulsations, V2116 Oph also displays strong flickering, as do cataclysmic

★E-mail: chico@das.inpe.br (FJ); marildo@das.inpe.br (MGP)

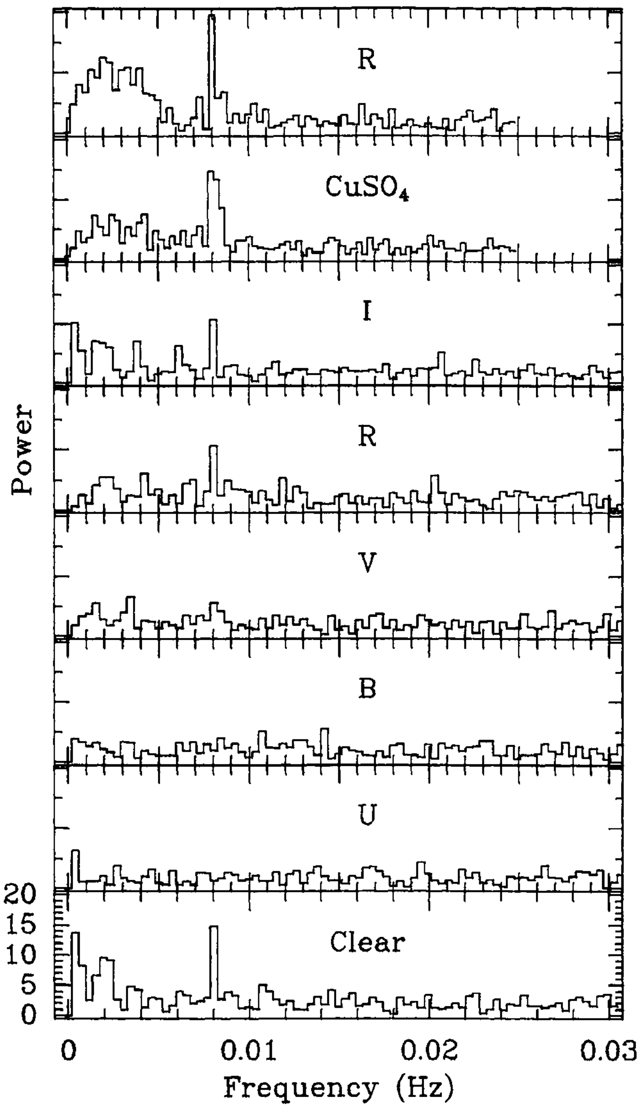

Figure 1. The power spectra of V2116 Oph on 1996 May 27, based on photoelectric photometry (six lower panels) obtained with FOTRAP at the 1.6-m telescope of LNA. The two topmost curves are the power spectra of CCD light curves obtained on the same night with a 0.6-m telescope. All spectra have the same vertical scale.

variables. Flickering is an omnipresent characteristic of binaries with accretion discs.

To understand better the relative importance of the main sources of light in this system, we have modelled its spectrum as a sum of two components,

$$C(\lambda) = S(\lambda) + D(\lambda), \tag{1}$$

where $S(\lambda)$ is the stellar spectrum and $D(\lambda)$ is the disc spectrum, the latter following either a blackbody $[D(\lambda) \propto B(\lambda, T_{\rm BB})]$, or a power-law $[D(\lambda) \propto \lambda^{\alpha}]$ spectral distribution. The relative contribution of $D(\lambda)$ is measured at a reference wavelength λ_0 by a parameter

$$\Delta(\lambda_0) = -2.5 \log \left[\frac{D(\lambda_0)}{S(\lambda_0)}\right]. \tag{2}$$

The combined spectrum $C(\lambda)$ can be reddened and submitted to synthetic photometry for a comparison with the observed values. We have adopted the *UBVRI* passbands for the synthetic photometry from Bessell (1990) and the reddening law for the interstellar

Table 1. Periods and amplitudes in V2116 Oph.

Passband	Period (s)	Peak-to-peak amplitude (%)
Clear	124.5 ± 0.5	2.5 ± 0.4
U	—	—
B	—	—
V	124.1 ± 0.1	5.3 ± 1.6
R	124.6 ± 0.6	3.3 ± 0.6
I	124.1 ± 0.6	2.2 ± 0.4

Table 2. Magnitude and colours of V2116 Oph.

Colour	DC component	Pulsed component
V	16.93 ± 0.05	19.37 ± 0.17
U–B	+0.08 ± 0.30	...
B–V	+1.67 ± 0.13	< +2.2
V–R	+1.83 ± 0.05	+1.33 ± 0.18
R–I	+1.40 ± 0.02	+0.92 ± 0.13

medium from Seaton (1979). For the late-type spectrum $S(\lambda)$, we have chosen objects #164, #165 and #166 from Gunn & Striker (1983). These are unreddened giants with spectral types M5, M5 and M6, respectively. The colour indices indicate that object #165 could be classified as M5.5. All zero-points in the synthetic photometry are set by using the Vega spectrum (Dreiling & Bell 1980).

Experiments with the `FITSPEC` task in the `STSDAS.SYNPHOT` package of `IRAF` show that we obtain poor results if we try to fit only the DC colours with equation (1). This is a consequence of the small number of constraints in the problem. However, if we force the pulsation colours to be simultaneously fitted, better results are obtained. A key assumption that we have introduced at this point is to identify the pulsed spectrum with $D(\lambda)$.

We have built a figure-of-merit to compare a trial $C(\lambda)$ with the observations:

$$\chi^2 = \frac{1}{(7-p)} \left[\sum_{i=2}^{i=5} \left(\frac{m_{{\rm o},i} - m_{{\rm c},i}}{\sigma_i} \right)^2_{\rm DC} + \sum_{i=3}^{i=5} \left(\frac{m_{{\rm o},i} - m_{{\rm c},i}}{\sigma_i} \right)^2_{\rm puls} \right],$$

where $m_{{\rm o},i}$, $m_{{\rm c},i}$, and σ_i correspond to the observed magnitudes, the synthetic magnitudes and the observed errors for passband i. The indices $i = 2, ..., 5$ correspond to the bands $B, ..., I$. Notice that for the DC component the sum runs from B to I while for the pulsed component it goes from V to I. The number of fitted parameters is p and the choices for minimization are $T_{\rm BB}$ (or α), $E(B-V)$ and Δ. We have used the `AMOEBA` algorithm of Press et al. (1992) to explore the minima in the χ^2 hypersurface.

A few comments should be made at this point.

(i) The U colour in symbiotic stars is strongly affected by emission in the Balmer continuum (Kenyon 1986). This emission cannot be easily incorporated into our calculations, and, since we did not detect pulsations in this filter anyway, we keep this band out of the analysis.

(ii) The R magnitude is strongly affected by Hα emission. Fortunately, we have a spectrum of V2116 Oph obtained on 1995 June 5 with the object only 0.2 mag fainter than on the night of the observations discussed here. The equivalent width of Hα in that spectrum is ~700 Å. Synthetic photometry on a M6 III spectrum

Table 3. Late-type giant + disc compositions.

Star	T_{BB}/α	$E(B-V)$	$\Delta(R)$	χ^2
GS164	$\alpha = \underline{-2.33}$	2.23	−2.94	7.62
GS165	$\alpha = \underline{-2.33}$	2.20	−2.98	6.56
GS166	$\alpha = \underline{-2.33}$	2.11	−3.28	3.50
GS164	$\alpha = -2.66$	$\underline{2.3}$	−2.97	7.62
GS165	$\alpha = -2.65$	$\underline{2.3}$	−3.02	6.56
GS166	$\alpha = -2.68$	$\underline{2.3}$	−3.36	3.50
GS164	$\alpha = -0.37$	$\underline{1.63}$	−2.70	7.62
GS165	$\alpha = -0.44$	$\underline{1.63}$	−2.75	6.56
GS166	$\alpha = -0.74$	$\underline{1.63}$	−3.06	3.50
GS164	$T = 10320$	$\underline{2.3}$	-3.00	10.9
GS165	$T = 10850$	$\underline{2.3}$	-3.06	9.3
GS166	$T = 13570$	$\underline{2.3}$	-3.39	4.7
GS164	$T = 4720$	$\underline{1.63}$	-2.78	16.4
GS165	$T = 4810$	$\underline{1.63}$	-2.83	14.7
GS166	$T = 5180$	$\underline{1.63}$	-3.13	8.9

from Gunn & Striker (1983) with and without a superimposed 'Gaussian Hα' of FWHM = 36.6 Å and EW = 700 Å shows that the R magnitude becomes 0.26 mag brighter due to the presence of the line, and the V magnitude is correspondingly affected by 0.11 mag. We apply these corrections to the V and R values of Table 2 to compare calculated magnitudes with the observations.

(iii) The V and R pulsed magnitudes are corrected exactly in the same proportion as done for the DC component.

(iv) We have measured $R = 17.72$ on two occasions on which the system had completely lost its flickering characteristics (Jablonski et al. 1997). This means that the disc contribution was a minimum, and we were observing only the M giant. A correction due to Hα contamination in this measurement may be needed, but we assume it to be zero, since Sood et al. (1996) observed very low levels of Hα emission when the system was in a similar faint state.

4 RESULTS

Table 3 summarizes the results of our calculations. An underlined value means no minimization for that particular parameter. The first three lines show the results for $E(B-V)$ and $\Delta(R)$ assuming the disc spectrum given by the standard theory for optically thick discs, $D(\lambda) \propto \lambda^{-2.33}$ (Frank, King & Raine 1985). The uncertainty in the spectral type of the M giant produces an uncertainty in $E(B-V)$ of about ± 0.1 mag. The following groups of lines show the minimization of α and $\Delta(R)$, assuming fixed values of $E(B-V)$, as given by the most recent determinations, namely 2.3 (Shahbaz et al. 1996), and 1.63 (Chakrabarty & Roche 1997). We see that our simple model produces closer agreement with the result of Shahbaz et al. (1996). The last two groups of values show what happens if we model $D(\lambda)$ as a single-temperature blackbody.

5 CONCLUSIONS

The data in Table 2 show that the spectrum of the pulsed light in V2116 Oph is substantially bluer than the DC component. We have explored the consequences of identifying this blue component with the spectrum of an accretion disc in the system.

If we assume that the disc spectrum follows the canonical $F_\lambda \propto \lambda^{-2.33}$ for optically thick discs, we obtain $E(B-V) \sim 2.1$, roughly consistent with the determination by Shahbaz et al. (1996), namely $E(B-V) = 2.3$. The parameter $\Delta(R)$ defined in equation (2) indicates that the accretion disc is $\sim$20 times intrinsically brighter than the red giant at 6600 Å! This explains why flickering and pulsations are easily observed up to the I band in this system (Jablonski et al. 1997).

We have also explored the behaviour of the parameters α and $\Delta(R)$ when we fix $E(B-V)$ at the values available in the literature, namely 2.3 (Shahbaz et al. 1996) and 1.63 (Chakrabarty & Roche 1997). The results follow the expected trends: less steep spectra and lower blackbody temperatures are obtained with the smaller values of $E(B-V)$.

Table 3 indicates that the best composite spectrum is obtained with a red giant of spectral type M6. Using the photometric relations for the Cousins VRI system of Thé et al. (1990) according to which $M_R = -1.75$ for a M6 III star – together with the standard relations $A_V = 3.1E(B-V)$, $A_R = 0.748A_V$ – we obtain $D = 8.3$ kpc for $E(B-V) = 2.1$ and $m_R = 17.72$ at minimum light.

Using the distance and reddening derived above, the absolute magnitudes of the DC and pulsed components turn out to be $M_V(\mathrm{DC}) \sim -4.2$ and $M_V(\mathrm{puls}) \sim -1.7$. These values set limits on the size of the emitting regions, if we suppose blackbody emission. For $T = 100\,000$ K, the spherical radius of the emitting region would be 4.4 and 1.4 $R_\odot$, for the DC and pulsed components, respectively. For $T = 20\,000$ K the dimensions are 13.2 and 4.3 $R_\odot$. For $T = 10\,000$ K the dimensions are 29 and 9.3 $R_\odot$. Temperatures lower than 7500 K produce dimensions that exceed the estimated size of the Roche lobe for the neutron star. Likely regions to produce the optical pulsations would be the atmosphere of the M giant or any non-axisymmetric structure in the accretion disc. The stream of gas between the late-type star and the disc can be ruled out since its projected area is very small.

The most important improvements to refine the parameters determined with the technique outlined here include better quality measurements of the pulsation amplitude, especially in the B band (since this is crucial to put constraints on the reddening), and extension of the measurements to the near-infrared (to constrain better the shape of the pulsed spectrum and to verify if the M giant is variable).

ACKNOWLEDGMENTS

We would like to thank the referee, Dr Ian Glass, for his helpful suggestions. FJ acknowledges partial support from CNPq under Proc. # 52.2787/95-9. This paper was based on observations collected at CNPq/Laboratório Nacional de Astrofísica, Brazil.

REFERENCES

Bessell M. S., 1990, PASP, 102, 1181
Chakrabarty D., Roche P., 1997, ApJ, in press
Davidsen A., Malina R., Bowyer S., 1977, ApJ, 211, 866
Dreiling L. A., Bell R. A., 1980, ApJ, 241,736
Frank J., King A. R., Raine D. J., 1985, Accretion Power in Astrophysics. Cambridge Univ. Press, Cambridge, p. 85
Glass I. S., Feast M. W., 1973, Nature Phys. Sci., 245, 39
Gunn J. E., Striker L. L., 1983, ApJS, 52, 121
Jablonski F., Baptista R., Barroso J., Jr, Gneiding C., Rodrigues F., Campos R. P., 1994, PASP, 106, 1172
Jablonski F., Pereira M. G., Braga J., Gneiding C. D., 1996, IAU Circ. 6489
Jablonski F., Pereira M. G., Braga J., Gneiding C. D., 1997, ApJ, 482, L171

Kenyon S. J., 1986, The Symbiotic Stars. Cambridge Univ. Press, Cambridge
Landolt A. U., 1992, AJ, 104, 340
Nagase F., 1989, PASJ, 41, 1
Press W. H., Teukolsky S. A., Vetterling W. T., Flannery B. P., 1992, Numerical Recipes FORTRAN, 2nd edn. Cambridge Univ. Press, Cambridge
Seaton M. J., 1979, MNRAS, 187, 73P
Shahbaz T., Smale A. P., Naylor T., Charles P. A., van Paradijs J., Hassal B. J. M., Callanan P., 1996, MNRAS, 282, 1437
Sood R., James S., Lawson W., Manchanda R., Heisler C., 1996, IAU Circ. 6496
Thé P. S., Thomas D., Christensen C. G., Westerlund B. E., 1990, PASP, 102, 565

This paper has been typeset from a TEX/LATEX file prepared by the author.