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Infrared spectroscopy of V616 Monaceras (=A0620–00): the accretion disc contamination

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Abstract. We have obtained for the first time K-band infrared spectra of the soft X-ray transient V616 Mon (=A0620–00). We determine the 2-σ upper limit to the fraction of light arising from the accretion disc to be 27 percent. The effect this has on the binary inclination, determined from modelling the infrared ellipsoidal variations is to increase it by less than 7 degrees and decrease the mass of the black hole by less than 3.6 $M_{\odot}$.

Key words: stars: binaries: general – stars: fundamental parameters – stars: individual: V616 Mon (A0620–00) – X-rays: stars

1. Introduction

The soft X-ray transients (SXTs), sometimes referred to as "X-ray novae", are low-mass X-ray binary systems in which a late-type star loses material via an accretion disc to a neutron star or black hole. They undergo brief outbursts, typically lasting a few months with a recurrence time of the order of decades (see Tanaka & Shibazaki 1996 and van Paradijs & McClintock 1995 for reviews of their X-ray and optical properties).

The X-ray transient V616 Mon (=A0620–00) was discovered in 1975 (Elvis et al., 1975). When the system faded into quiescence the binary nature of the system was established; the orbital period was determined to be 7.75 h and the secondary star was found to be a K dwarf (Oke 1977; McClintock et al. 1983). McClintock & Remillard (1986) then went on to measure the orbital radial velocity curve of the secondary star, thereby obtaining a firm *minimum* mass for the compact object (i.e. the mass function) of 3.08 $M_{\odot}$. This result immediately placed V616 Mon amongst the best black hole candidates (see van Paradijs & McClintock 1995).

High resolution optical spectroscopy can provide further constraints on the system masses, as a measurement of the rotational broadening of the secondary star absorption features leads directly to the *ratio* of the component masses (Marsh et al. 1994 hereafter MRW). But the binary inclination, can only be determined by exploiting the ellipsoidal modulation of the secondary star, i.e. the variations caused by observing the differing aspects of the gravitationally distorted star as it orbits the compact object (see Shahbaz et al. 1993 and references within). In V616 Mon these variations have been observed at both optical (McClintock & Remillard 1986; Haswell et al. 1993) and infrared (IR) wavelengths (Shahbaz et al. 1994; hereafter SNC).

SNC determined the binary inclination for V616 Mon by modelling the IR ellipsoidal modulation of the secondary star. They obtained $i \sim 37°$, which when combined with the value for the binary mass function and mass ratio resulted in a most probable mass for the compact object of ~10 $M_{\odot}$(5.1–17.1$M_{\odot}$; 90 percent confidence).

There are several complications in such a determination of the binary inclination; inevitably the optical light from the mass donor is diluted by the flux from the quiescent accretion disc. Also, the ellipsoidal light curve may be distorted by other variable contributions to the observed flux; such as the bright spot, star spots and variable disc emission including the superhump phenomenon. Underestimating the diluting flux leads to an underestimate in the binary inclination. At optical wavelengths it is clear that the accretion disc contributes a significant amount of flux to the optical light curves, which makes any interpretation of these light curves somewhat dubious. This can be seen from the scatter and asymmetric maxima observed in the optical light curves of V616 Mon by McClintock & Remillard (1986). The veiling by the continuum emission from the accretion disc has been measured by MRW. They find that 94 percent or more of the optical flux close to Hα comes from the secondary star, a fraction which rises with increasing wavelength, while the veiling ratio falls. Therefore one would expect the veiling by the accretion disc to be very small or even negligible in the K band.

Haswell et al. (1993) attempted to deduce the binary inclination from modelling their optical multi-colour light curves with a combination of an ellipsoidal variation and a grazing eclipse, assuming a large circular disk. The inclination derived from the grazing eclipse constraint is in serious disagreement with that determined from the ellipsoidal variations in the IR light curves (SNC). However, it is known that in low-mass X-ray binaries and cataclysmic variables the outer, cool regions of the accretion disc can be a strong source of IR radiation (e.g. Beall et al. 1984; Berriman et al. 1985). Consequently, this introduces doubts on the SNC assumption that the observed IR flux has very little contamination by the accretion disc. This would then imply that any interpretation of the ellipsoidal variations of the

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Table 1. Journal of observations

Object	Date	UTC (hrs)	Airmass (mags)	Exposure time (secs)	Comments
V616 Mon	13/11/1997	11:34	1.18	1280	ϕ=0.31
V616 Mon	13/11/1997	12:53	1.10	5120	ϕ=0.48
V616 Mon	13/11/1997	14:56	1.23	5120	ϕ=0.74
HD42606	13/11/1997	10:50	1.29	160	K3V
BS5706	29/6/1995	06:23	1.12	96	K0V
61 Cyg A	30/6/1997	15:49	1.16	96	K5V
61 Cyg B	30/6/1997	15:46	1.16	96	K7V

secondary star in the IR might be misleading. Nevertheless, for the SXT V404 Cyg we have already shown directly that the IR accretion disc contamination is small; it only affects the implied mass of the black hole by at most 2 $M_\odot$(Shahbaz et al., 1996).

We therefore decided to obtain through IR spectroscopy a direct measurement of any contamination of the IR flux by the accretion disc in V616 Mon. From this we can determine the effect it has on the interpretation of the ellipsoidal variation of the secondary star, and hence on the component masses.

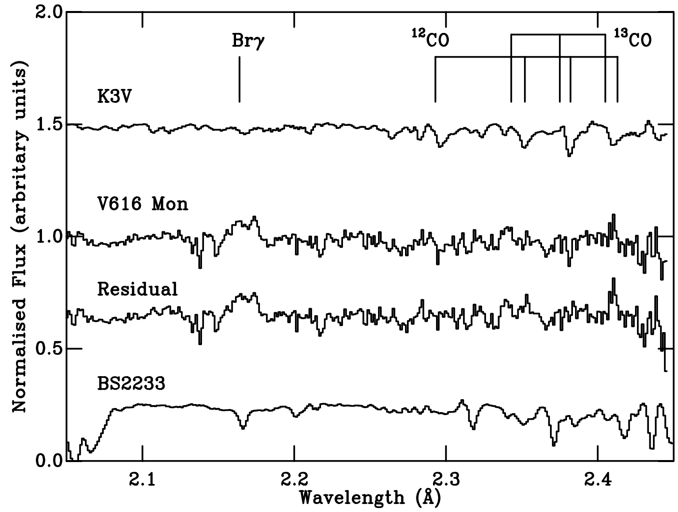

Fig. 1. This figure shows the spectrum of V616 Mon and that of the template K3V star. The ^{12}CO bandheads can clearly be seen. Also shown is the residual spectrum after optimally subtracting the template star from the V616 Mon spectrum. The lower-most spectrum is of an F6V star (BS2233) which indicates the location of telluric absorption features. All spectra have been normalised by dividing by a spline fit to the continuum. The stars indicate bad pixels.

2. Observations and data reduction

We obtained K-band (2.0–2.5 μ) spectra of V616 Mon using the Cooled Grating Spectrometer (CGS4) on the United Kingdom 3.8-m Infrared Telescope on Mauna Kea, during the night of 1997 November 13. The 40 l/mm grating was used with the 300 mm camera and the 256$\times$256 pixel InSb array. The bright star BS2233 was also observed through-out the night in order to remove telluric atmospheric features. A journal of observations is presented in Table 1.

In order to minimise the effects of bad pixels, the standard procedure of oversampling was used. The spectra were sampled over two pixels by mechanically shifting the array in 0.5 pixel steps in the dispersion direction, giving a full width half maximum resolution of 47 Å ($\sim$610 km s^{-1}at 2.31 μ). We employed the non-destructive readout mode of the detector in order to reduce the readout noise. The slit width was 1.2 arcseconds which corresponds to 2 pixels on the detector. In order to compensate for the fluctuating atmospheric emission lines we took relatively short exposures and nodded the telescope primary so that the object spectrum switched between two different spatial positions on the detector. Throughout the observing run the slit orientation was north to south in the spatial direction.

The CGS4 data reduction system performs the initial reduction of the 2D images. These steps include the application of the bad pixel mask, bias and dark subtraction, flat field division, interlacing integrations taken at different detector positions, and co-adding and subtracting the nodded images (see Daly & Beard 1994). Extraction of the 1D spectra, wavelength calibration, and removal of the telluric atmospheric features was then performed using IRAF. A more detailed description of the data reduction procedure is provided in Shahbaz et al. (1996).

First the individual spectra of V616 Mon were averaged using the variance in the spectrum as the weight. This resulted in a final summed spectrum which had a signal-to-noise ratio of $\sim$ 30. We then cross correlated all the summed V616 Mon spectrum with the template star spectrum in order to determine the velocity shift. Given the poor resolution of the data this was not done on the individual spectra of V616 Mon before they were averaged. We applied the appropriate velocity shift and then binned all the spectra onto a uniform velocity scale. Fig. 1 shows the summed spectrum of V616 Mon and the K3V template star spectrum, normalised and shifted for clarity. The V616 Mon spectrum shows the CaI triplet and ^{12}CO bands in absorption and doubled-peaked Brγ in emission.

The peak separation of the Brγ emission line arising from the accretion disc is 1204$\pm$156 km s^{-1}. Note that this is comparable with the peak-to-peak separation in the Hα and Hβ emission lines (MRW). The equivalent width (EW) of Brγ in the K3V star spectrum is -1.6$\pm$0.3 Å whereas in the residual spectrum [i.e. the spectrum of the accretion disc; see Fig. 1 and Sect. 3] it is 14.6$\pm$1.3 Å. The ^{12}CO bands are the strongest features and will be used in the next section to determine the fraction of light arising from the secondary star.

3. The accretion disc contamination

We first binned the V616 Mon and template star spectra onto a logarithmic wavelength scale using a $\sin x/x$ interpolation scheme to minimize data smoothing (Stover et al. 1980). We then optimally subtracted the template star from the V616 Mon spectra using the standard procedure (see MRW) as follows. Taking the accretion disc contribution as a flat continuum, we fit the V616 Mon spectra with this plus a variable fraction of the template star. The fraction of light from the template star, (f), is adjusted to minimise the residual scatter between the spectra. The scatter is measured by carrying out the subtraction and then computing the χ^2 between the residual spectrum and a smoothed version of the residual spectrum. This is done to remove any large-scale structure. The χ^2 for different fractions of the template star is computed and fitted with a parabola, and the fraction at the minimum value of χ^2 is taken to be the best fit. The above analysis was performed only on the 2.292 μ ^{12}CO(2,0) bandhead in the summed spectrum of V616 Mon. Other bandheads were not used because of poor atmospheric subtraction and bad pixels. Fig. 1 shows the summed spectra of V616 Mon along with the template K3V star. The residual light spectrum (i.e. the accretion disc light) is also shown.

In addition to using HD42606 (K3V) we also used template stars of other spectral types [HD42606 (K0V), HD42606 (K5V) and HD42606 (K7V)] in order to determine the sensitivity of f to the assumed spectral type. We find that for the summed spectra of V616 Mon, the minimum value for χ^2_ν (1.01, a good fit) is obtained using the K3V secondary star, which contributes 75±17 percent of the flux in the IR (the disc fraction is 25 per cent). We also fitted the region used in the V616 Mon spectrum for the optimal subtraction with a constant and obtained a much worse fit with a χ^2_ν of 2.7 thereby showing that the absorption feature is real as the 99.9 per cent level.

The large uncertainties we obtain for the accretion disc light suggest that our result is consistent with the secondary star contributing all the light to the observed flux. In order to determine a lower limit to the fraction of light from the secondary, we simulated a spectrum in which *all* the light arises from the secondary star. This was done using the K3V template star and adding noise to the data such that the signal-to-noise was the same as the V616 Mon spectrum. We then performed the optimal subtraction and determined the 2-σ per cent lower limit to the fraction of light arising from the secondary to be 73 per cent. This value is comparable with the fraction of light arising from the secondary star deduced from our spectrum of V616 Mon, suggesting V616 Mon most probably contains a companion star which contributes all the light in the IR.

Table 2. Optimal Subtraction of the Companion Star

Star	Sp. Type	χ^2 (DOF=13)	f
BS5706	K0V	23.7	35 ± 12
HD42606	K3V	13.2	75 ± 17
61 Cyg A	K5V	31.7	13 ± 13
61 Cug B	K7V	32.6	5 ± 12

4. Discussion

4.1. Variability of the optical light curves

The quiescent optical light curves of V616 Mon show a double-humped ellipsoidal modulation due to the changing projected area of the Roche-lobe filling mass donor star. Maxima occur at quadrature, corresponding to maximum projected area, and are hence expected to be symmetric. Minima occur at orbital conjunctions; in general they have differing depths due to limb- and gravity-darkening. The light from the secondary star is diluted by the flux from the accretion disc. Also the ellipsoidal light curve may be distorted by other variable contributions to the total light; the bright spot associated with the impact of the mass transfer stream on the edge of the disc (McClintock & Remillard 1990); star spots on the secondary; and variable disc emission, including the superhump phenomenon (Warner 1995).

Recently Leibowitz et al. (1998) have collated the optical light curves of V616 Mon obtained over the last 7 years. They find that the depth of the maxima and minima of the light curves vary with time. They observe a long term photometric behaviour of a few hundred days with a peak to peak amplitude of 0.3 mag. They suggest that the minimum in the light curve corresponding to when the red dwarf lies between the observer and the compact object (orbital phase 0.0) changes depth with time. Since in the standard precessing disc model one does not expect this minimum to change depth significantly (as at this phase the secondary star is least affected by X-ray illumination) they conclude that they cannot explain the variations in terms of a simple geometrical precessing accretion disc model (Heemskerk & van Paradijs 1989).

However, it should be noted that the main thrust of their conclusion lies in the interpretation of the varying component in the light curves. In the precessing disc model the depth of either minimum can vary with time, depending on the tilt of the accretion disc (Heemskerk and van Paradijs 1989). Also they have assumed that the maximum in the light curve (orbital phase 0.75) with respect to which the minima is measured remains constant. This is probably not the case as the observed optical light near this orbital phase is contaminated by the bright spot. Optical spectroscopy of V616 Mon shows the presence of a bright spot (MRW). Bright spots have been seen in the optical light curves of cataclysmic variables with similar mass ratios such as Z Cha and OY Car (Wood et al. 1986, 1989) where it is observed between orbital phase 0.6 and 1.1. Variations in the optical flux emitted by the bright spot as the result of clumpy mass transfer from the secondary star could easily give rise to variability in the optical flux observed at this orbital phase.

In the IR the effects of the variability discussed above are much less (SNC). The IR light curve of V616 Mon shows equal maxima; this is what is expected if the IR variations are due solely to the ellipsoidal modulation of the secondary star.

4.2. The Brackett-γ emission line

Various authors have pointed out that the double-peaked emission line profiles can be interpreted as arising from an accretion disk viewed at high inclination. However, it should be noted that a double-peaked emission line profile can also arise from a system with an inclination as low as 15° (see the models of Horne & Marsh 1986). Assuming that the double-peaked lines arise entirely from the disk, we can estimate the binary inclination of V616 Mon by measuring the separation of the Brγ emission-line peaks.

The Keplerian velocity of the outer edge of the disk (v_d) is given by $v_d = (GM_1/R_d)^{0.5}$. Combining this with Kepler's third law, Paczynski's (1971) formula for the Roche lobe radius, and using the fact that the accretion disk fills 50 per cent of the compact object's Roche-lobe (MRW), gives $v_d = 998(M_1/P_{hr})^{1/3}\,\mathrm{km\,s^{-1}}$, where M_1 is the mass of the black hole (in solar masses), and P_{hr} is the orbital period (in hours). The separation of the Brγ emission-line peaks measured from the summed spectrum of V616 Mon is 1204 km s^{-1}, implying a projected velocity of the outer edge of the accretion disk of $v_d \sin i \sim 602$ km s^{-1}. Using the above formula with P_{hr}=7.75 hrs (MRW) and $M_1 \sim 10M_\odot$ (SNC) gives a $i \sim 34°$, which agrees well with that obtained by SNC.

In cataclysmic variables there is observational evidence that the accretion disc contamination in the K-band is significant. The eclipse light curves of the dwarf nova OY Car, for example show that during quiescence the accretion disc can contribute about 30 percent of the flux at 2.2 μ (Sherrington et al. 1982). IR spectra of cataclysmic variables also show emission lines arising from the optically thin gas in the accretion disc (Ramseyer et al. 1993; Dhillon & Marsh 1995), such as HeI (2.0587 μ) and Brγ (2.1655 μ). In contrast, the X-ray transients V404 Cyg (Shahbaz et al. 1996) and V616 Mon show only Brγ in emission. It should also be noted that the mass accretion rate during quiescence in the X-ray transients is a factor of 10 lower than that in dwarf novae.

One expects the EW of the emission lines arising from the accretion disc to decrease as the orbital period of the binary increases. This is simply because larger systems will have larger, cooler accretion discs. If one looks at the Hα EW in the SXTs, then one can find some evidence for this type of correlation; for Nova Per 1992 the Hα EW is 205 Å, whereas for the larger systems such as Nova Mus 1991 and V404 Cyg it is 50 Å and 40 Å rrespectively. Also note that in all the SXTs the disc contamination near Hα is in the range 6–16 percent, i.e. it is small despite the large Hα EW. In V404 Cyg the Br-γ EW of the accretion disc is 2.7 Å. One expects the Br-γ EW of the accretion disc in the much shorter system V616 Mon to be higher; this is what is observed (see Sect. 2).

4.3. *The effect on the mass of the black hole*

SNC obtained an IR light curve of V616 Mon which showed a double humped feature characteristic of the ellipsoidal variations of the secondary star. They modelled these variations assuming all the IR flux was arising from the secondary star, and determined the most probable mass of the compact object to be 10 M$_\odot$. Justification for this assumption comes from the analysis of the IR light curve of the transient Cen X–4 (Shahbaz et al. 1993). The mass of the compact object in Cen X–4 is consistent with that of a canonical neutron star; which the compact object must be because of the type I X-ray bursts observed during outburst (Matsuoka et al. 1980). This provides indirect evidence that the contribution of the accretion disc to the observed IR flux is very small, at least from Cen X–4. This may also be the case for V616 Mon; an upper limit to the accretion disc contribution to the IR flux being 27 percent (Sect. 3).

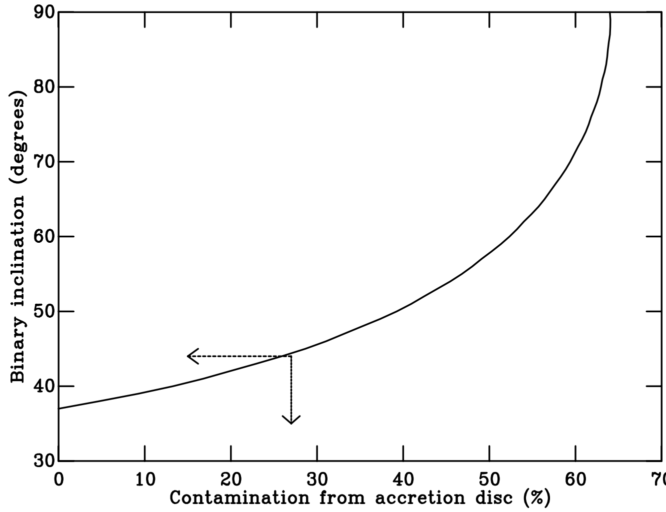

Fig. 2. The effect of the accretion disc contamination on the value for the binary inclination, derived by modelling the K-band ellipsoidal variations of the secondary star (SNC). The 2-σ upper limits to the accretion disc contamination and inclination are shown. binary inclination respectively.

The effects of any accretion disc contamination to the observed IR flux will be to dilute the actual ellipsoidal modulation, making the observed modulation smaller than the *true* value. Since the amplitude of the ellipsoidal modulation is correlated with the binary inclination (large amplitudes imply a high binary inclination), this means that modelling a contaminated light curve will underestimate i.

We have modelled the amplitude of the ellipsoidal variations as a function of i. We used the same parameters as SNC: T$_{eff}$=4000 K, q=14.9 (MRW), a gravity darkening exponent of 0.08 (Lucy 1967), and the limb darkening coefficient from Al-Naimiy (1978). Fig. 2 shows the effect of differing amounts of contamination in the IR light curves on the binary inclination. If we take the 2-σ limit to the disc contamination of 27 percent, we find that i increases by 7 degrees and the mass of the black hole decreases by 3.6 M$_\odot$(2-σ limit). Note that this extreme value for i is still lower than that obtained by Haswell et al. (1993), and the implied mass of the compact object ($\sim$ 6.4 M$_\odot$) still substantially exceeds the canonical maximum mass of a neutron star (3.2 M$_\odot$; Rhoades & Ruffini 1974).

5. Conclusion

We have determined the contamination of the observed IR flux by the accretion disk in V616 Mon. We obtained IR spectra of V616 Mon which when optimally subtracted from the secondary star spectrum (K3V star) allows us to determine the 2-σ upper limit to the accretion disc contribution to be less than 27 percent. We find that this only increases the determination of the binary inclination by less than 7 degrees; the mass of the black hole is decreased by less than 3.6 M$_\odot$.

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References

Al-Naimiy H.M., 1978, Ap&SS 53, 181
Beall J.H., Knight F.K., Smith H.A., et al., 1984, ApJ 284, 745
Berriman G., Szkody P., Capps R.W., 1985, MNRAS 217, 327
Daly P.N., Beard S.M., 1994, CGS4/IRCAM3 V2.0-0 Users' Guide, SUN/27, Starlink Project, DRAL
Dhillon V.S., Marsh T.R., 1995, MNRAS 275, 89
Elvis M., Page C.G., Pounds K.A., Ricketts M.J., Turner M.J.L., 1975, Nat 257, 656
Haswell C.A., Robinson E.L., Horne K., Steining R.F., Abbott T.M.C., 1993, ApJ 411, 802
Heemskerk M.H.M., van Paradijs J., 1989, A&A 223, 154
Horne K., Marsh T.R., 1986, MNRAS 218, 761
Leibowitz E.M., Hemar S., Orio M., 1998, MNRAS 300, 463L
Lucy L.B., 1967, SvA 65, 89
Marsh T.R., Robinson E.L., Wood J.H., 1994, MNRAS 266, 137
Matsuoka M., Inoue H., Koyama K., et al., 1980, ApJ 240, L137
McClintock J.E., Remillard R.A., 1986, ApJ, 308, 110
McClintock J.E., Remillard R.A., 1990, ApJ 350, 386
McClintock J.E., Petro L.D., Remillard R.A., Ricker G.R., 1983, ApJ 266, L27
Oke J.B., 1977, ApJ 217, 181
Paczynski B., 1971, Acta Astron. 21, 417
Ramseyer T.F., Dinerstein H.L., Lester D.F., Provencal J., 1993, AJ 106, 1991
Rhoades C.E., Ruffini R., 1974, Phys. Rev. Lett, 32, 324
Shahbaz T., Naylor T., Charles P.A., 1993, MNRAS 265, 655
Shahbaz T., Naylor T., Charles P.A., 1994, MNRAS 268, 756 (SNC)
Shahbaz T., Bandyopadhyay R., Charles P.A., Naylor T., 1996, MNRAS 282, 977
Sherrington M.R., Jameson R.F., Bailey J., Giles A.B., 1982, MNRAS 200, 861
Stover R.L., Robinson E.L., Nather R.E., Montemayer T.J., 1980, ApJ 240, 597
Tanaka Y., Shibazaki N., 1996, ARA&A 23, 607
van Paradijs J., McClintock J.E., 1995, In: Lewin W.H.G, van Paradijs J., van den Heuvel E.P.J. (eds.) X-ray Binaries. Cambridge University Press, 101
Warner B., 1995, Cataclysmic Variable Stars. Cambridge, Cambridge Unversity Press
Wood J.H., Horne K., Berriman G., et al., 1986, MNRAS 219, 619
Wood J.H., Horne K., Berriman G., Wade R.A., 1989, ApJ 341, 974