Evidence for evolving accretion disk structure in 4U1957+115

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ABSTRACT

We present results of the first multicolour photometric study of 4U 1957+115, one of the optically less studied low mass X-ray binaries (LMXB). Our quasi-simultaneous UBVRI observations reveal that the light curve pulse shape over the 9.33 hr period discovered by (Thorstensen 1987) has changed substantially since his earlier V band studies. The light curve now shows clear asymmetry and an amplitude more than double of that seen by (Thorstensen 1987). The light curve also shows colour dependence that seems to rule out the X-ray heating model as an origin for photometric variability. We believe that the changes observed in the light curve shape are indicative of evolving accretion disk structure. We discuss implications of this on the origin of optical emission in 4U1957+115 and disk accreting binaries in general.

Key words: Stars: Individual: 4U1957+115 - Stars: binaries - Accretion: disks

1 INTRODUCTION

Low mass X-ray binaries (LMXB’s) are semi-detached compact interacting binaries, where a late type secondary star loses matter via Roche lobe overflow. This matter forms an accretion disk around a compact primary, which is either a neutron star or a black hole. The optical emission from LMXB’s originates in both the accretion disk itself and the X-ray heated secondary star. The accretion disk typically dominates the emission all the way from the optical through UV to the X-rays. Unlike in cataclysmic variables, the optical emission from accretion disks in LMXB’s is mainly due to reprocessing of the X-rays in the disk and not viscous heating. In many cases the optical light curve is roughly sinusoidal. This can be attributed to the X-ray heated secondary. In these systems, the source is generally bluest during the flux maximum. This is due to the fact that the X-ray heated face of the secondary is much hotter than the other side of the companion star. This is the case in systems like X1254-69, Sco X-1, GX339-4, GX9+9 and X1735-444 (van Paradijs 1991). In some other systems, like accretion disk corona (ADC) sources X1822-371 and AC211, the origin of the optical light curves has generally been explained differently (Hellier & Mason 1989). The favoured view has been that the optical emission from the accretion disk is the main source of optical radiation, and that it is modulated in relatively high inclination systems by the vertically extended outer rim of the disk (see for instance Mason & Cordova 1983, Hellier & Mason 1989).

4U1957+115, as the name suggests, was first detected by the Uhuru mission (Giacconi et al. 1974) and its optical counterpart was later identified by (Margon, Thorstensen & Bowyer 1978). The source also appears in the early list of black hole candidates (White & Mason 1985), as it shows an ultrasoft X-ray spectrum. However, as of now, there is no firm evidence on the nature of the compact object. The source has been noted to vary in the optical (Motch et al. 1985), but there has not been any further optical photometry published, since (Thorstensen 1987) discovered a 9.33 hrs modulation in his V band observations. This period, if of orbital origin, implies that if the secondary fills its Roche lobe and belongs to the main sequence, it should have a mass of $0.11*P_{orb} = 1.0 M_\odot$. There is, however, no firm sign of the secondary in the optical spectra (Shahbaz et al. 1996).

In this paper we report first multicolour observations of 4U1957+115 and present an approach for fitting the optical light curve and thus extract some information on the 3D shape of the disk. Section 2 gives details of our observations as well as data reductions performed. In section 3 we give a description of our model and present the results of the model fitting. Finally, in section 4, we discuss the implications of our modelling both in relation to 4U1957+115 and LMXB’s in general.
2 OBSERVATIONS

4U1957+115 was observed on Nordic Optical Telescope (NOT), Observatorio de Roque de los Muchachos, La Palma on 9-10th of August, 1996. NOT is a 2.56m Cassegrain telescope and at the time of our observations, it was fitted with a 2kx2k thinned Loral-Lesser CCD detector. The observations were carried out as a continuous sequence automatically cycling U,B,V,R,I filters during the two consecutive nights. Our data only cover one 9.33 hour period, and the resulting folded light curves thus have no phase overlap.

The data were debiased and flatfielded in usual manner, after which digital aperture photometry was performed, this was done using the DAOPHOT routines available for IDL. The delta magnitudes were measured against a comparison star in the same field of view (star 6 in Dossey et al. (1977)). These delta magnitudes where then converted to absolute magnitudes by observations of a relatively blue standard star number 108 551 from (Landolt 1983).

The resulting U,B,V,R,I light curves are plotted in Figure 1. As the data is not simultaneous in each filter, but we cycled the UBVRI filters throughout the observations, we used 4th order Fourier fits to characterize the data and to measure the colour indices (Figure 2.). As a consistency check we also measured the B magnitude difference between star 6 and another star of similar brightness about 20" NW of star 6. We found no systematic effects and the scatter in that data was 0.01 mag (1σ). This is in very good agreement with the errors we get for 4U 1957+115. We should stress though, that as our absolute magnitude calibration was only done using a single standard star, this error level is valid only for the differential magnitudes, not for the zero point calibration.

The only previously published photometric datasets, that we are aware of are those of (Motch et al. 1985) and (Thorstensen 1987). (Motch et al. 1985) report a 3.5 hours V band observation, which suggests variability at timescales of ∼ 1 hour with an amplitude of ∼ 0.1 mag. Later dataset by (Thorstensen 1987) shows very ‘clean’ sinusoidal modulation with the period of 9.33 hours and a peak to peak amplitude of 0.232 ± 0.008 mag. This was explained to be due to the X-ray heated surface of the secondary, which is otherwise assumed to be of almost solar type star in terms of mass and radius. Such variability is a common explanation for optical light curves in LMXB’s.

Our multicolour data, however, does not support such hypothesis. It is clear from our light curves folded on the 9.33 hours period, that the pulse shape is not sinusoidal. Furthermore, the amplitude of modulation is roughly about twice that seen by (Thorstensen 1987). We have estimated variation amplitudes from our 4th order Fourier fits. These fits are shown, together with our data in Figure 1. The resulting full UBVRI amplitudes, as a function of wavelength, are plotted in Figure 3. In addition to these, we have added a point, which shows the V band amplitude estimate by (Thorstensen 1987).

Characterising signatures of X-ray heating model include almost sinusoidal pulse shape and colour dependence over the orbital period. Typically, the source is bluest at flux maximum, when the X-ray heated surface of the secondary is facing towards the observer. Unfortunately the data published by (Thorstensen 1987) only includes V band. Therefore, they could only base the X-ray heating argument on the sinusoidal pulse shape. It is quite clear, however, from our multicolour light curve (Figure 1. and Figure 2.) that the source is at its bluest near the phase of minimum brightness, which totally contradicts the X-ray heating hypothesis. The colour dependence is only clearly evident in U-B, while other colours do not show very significant variations over the orbital phase (Figure 2.).

In order to produce light curves, which turn bluer when the source gets fainter, one needs to obscure some of the ‘redder’ light from the source. One way to explain this, is to have a grazing eclipse, where part of the disk outer rim, close to the L1 point gets eclipsed by the secondary. This has lead us to experiment with disk rim models in order to explain our results.
3 MODELLING

One way to explain light curves of disk-accreting systems is to assume that the bulk of modulation is due to the varying viewing aspect of the three dimensional disk. This has especially been applied to the accretion disk corona (ADC) sources, where (Hellier & Mason 1989) have managed to fit the optical and X-ray light curves of X1822-37 simultaneously by varying the disk rim height over the azimuth. Also, more recently, (Meyer-Hofmeister et al.1997) have reproduced light curves of supersoft sources by the same approach. Their models have implied H/R as high as 0.5. Observational evidence for extended vertical structure can also be found in AC211 and X1916-05 (Callanan 1993), (Grindlay et al. 1988).

However, there is serious objection to the disk rim models on the theory side. Even to produce H/R ratios of the order of 0.1, outer rim of the disk temperatures of the order of $10^5$ K are required. This is not feasible within our current understanding of accretion disks in accreting binaries. Alternatively, since the discovery of the 35 d period in Her X-1 (Tananbaum et al.1972) several authors have proposed thin tilted and/or warped disks to explain observable long term periodicities in X-ray binaries (see for instance (Maloney and Begelman 1997) for summary of tilted/warped disk models).

In our attempt to model the light curves of 4U1957+115 we have roughly followed the disk outer rim fitting idea of (Hellier & Mason 1989), but with some modifications. Our code proceeds as follows.

We assume an optically thick disk that has constant surface brightness and which is surrounded by vertically extended outer rim. This rim emits both on its inner and outer surface. The inner surface has the same emissivity as the disk surface, but the ratio of the rim outer surface emissivity to that of the inner surface emissivty is a free parameter (as in (Hellier & Mason 1989)). As there is significantly different colour information only in the U-B index, we use U and B light curves only. These are fitted simultaneously. In order to be able to reproduce the colour information, we must fix temperatures for the inner and outer rim. This enables us to compute relative differences in the emissivity ratios for U and B bands. In our model we use 15000K and 7500K for inner and outer rim respectively. This implies that the U band emissivity ratio is roughly 1.5 times the B band ratio, for any fitted value. This values is, however, not very strongly dependent on chosen temperatures. Following (Hellier & Mason 1989) the possible emission from the X-ray heated face of the secondary is treated as an extra sinusoidal component in the fit. The amplitude (or relative flux fraction) of this component is a free parameter in the fit, whilst the phasing is fixed so that the maximum flux always occurs at the time when the X-ray heated face of the secondary faces the observer (phase 0.5). The free system parameters in the fit are:

- The ratio of outer/inner rim emissivity, $\nu$
- Inclination of the system, $i$
- Mass ratio $q$, defined as $q = M_2/M_1$ , where $M_1$ is the mass of the compact object
- Disk outer radius, $D_{rad}$
- Time of eclipse, $\phi_0$. (One should note that for 4U1957+115 there is no ephemeris available, thus we do not...
know the phasing of the data and this has to be treated as a free parameter as well)

- Amplitude of the sinusoidal (X-ray heating) component, $a$

In addition to these system parameters we do a regularised inversion of the disk rim height over the azimuthal direction. To do this, we have defined a grid of 36 points spaced by 10 degrees along the azimuthal direction at the outer edge of the disk. The vertical height of the disk rim at these points is a free parameter at each of these locations. However, we do employ a Tikhonov regularisation functional (Tikhonov 1963; Potter, Hakala & Cropper 1998) instead of entropy functional in order to find the smoothest possible disk rim that can fit our data.

The actual fitting procedure is carried out by a genetic algorithm (GA) (see for instance Charbonneau 1995; Hakala 1995; Potter, Hakala & Cropper 1998) for applications of genetic algorithms to astronomical problems). The merit function to minimise takes the following form.

$$F(\nu, i, q, D_{\text{rad}}, \phi_0, a, p_j) = \chi^2 + \lambda \sum_j (p_j - p_{j-1})^2 + (p_j - p_{j+1})^2$$

where $\nu$ is the outer rim/inner rim emmissivity ratio, $i$ is the system inclination, $q$ is the mass ratio, $D_{\text{rad}}$ is the disk outer radius, $\phi_0$ is the zero phase offset, $a$ is the sinusoidal component amplitude and $p_j$ are the rim heights. $\chi^2$ is the fit Chi-square value, $\lambda$ is the Lagrangian multiplier and the latter sum is the Tikhonov regularisation term.

Ideally our modelling would come out with best value for all the free parameters, but given the number of free parameters and the nonlinear nature of the optimisation problem it is not immediately clear whether the solutions obtained are unique. Thus, it is vital to test the uniqueness by performing a sample of independent fits. This can be done very easily with the genetic optimisation method, which intrinsically always starts with a set of random solutions to the problem. Thus, running the fitting procedure with different seeds for the random number generator will produce a set of independent solutions that can be studied for uniqueness. In Figure 4. we have plotted the histograms of system parameters obtained from 300 independent fits performed this way. Furthermore, we have plotted the resulting 300 outer rim profiles in Figure 5.

It is clear from Figure 4. that some of the system parameters are much better constrained by our modelling than others. Especially, the phase of the eclipse (i.e. when the compact star is furthest from the observer) is very well constrained. On the other hand, system inclination, mass ratio $q$ and the inner rim/outer rim emissivity ratio are not that tightly constrained. The same applies to the outer disk radius as well. More importantly, however, the disk rim shape...
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Figure 5. The different rim profiles obtained from our 300 different fits. The scatter in the plot includes both the effects of the noise in our data and the possible non-uniqueness in the solutions. The azimuth is measured starting from the L1 point and increasing towards the opposite direction to the disk rotation. The orbital phases at which a particular rim element is between the compact object and the observer are indicated.

is rather well constrained. This is probably not very surprising, since the bulk of the light curve shape is mostly influenced by the 3D shape of the disk.

We show a typical fit to the U and B data and in Figure 6. Our model is capable of producing all the main features in the light curve, including the difference in the depth of the minimum, which causes the source to turn blue in the minimum. In Figure 7, we have plotted separately the different components of our U band model, shown in Figure 6. The light curve is dominated by a roughly sinusoidal component arising from the variable obscuration of the disk and inner rim surface by the rim itself. In addition, the outer rim provides the means for producing the blue minimum, as it shows a wide eclipse by the secondary. The sinusoidal, X-ray heating, component is found to contribute only of the order of 10% of the total flux in maximum.

4 RESULTS

As a result of our fits, we can set some limits on the systems parameters of 4U 1957+115. However, we must emphasize that although our data is of high S/N, these fits are based on a single light curve and thus should be noted with caution.

We find that the system inclination is likely to be 70-75 degrees. This is in agreement with the fact that no clear optical or X-ray eclipses have been detected. Furthermore, this can explain the ‘blue minimum’ as a result of partial eclipse of the accretion disk. We can also give a lower limit for the mass ratio \( q \), of the order of 0.4-0.5. Our fits tended towards very high values of \( q \), and this can be seen as a very skewed distribution in Figure 4. In our fits we used a hard upper limit of 0.7 for \( q \). This was thought to be justified as the compact object (as a black hole or neutron star) has a minimum mass of 1.4-1.5 \( M_\odot \) and the Roche lobe

Figure 6. The simultaneous disk model fits to our U band (top) and B band light curves. A couple points clearly deviating from the general trend in the light curve were assigned artificially large errors to eliminate their contribution to the fit.

Figure 7. The different emission components that effect the fit. From top to bottom: The U band fit to the data, contribution from the disk surface and inner rim, contribution from the outer rim and the contribution from the X-ray heating component.
filling secondary should have a maximum mass of 1.0 M⊙.

The fact that many q values were pegged at the hard upper limit implies that the primary might have an unusually low mass for a neutron star and certainly does not support the early suggestions that the system might contain a black hole. The disk outer radius was also truncated to 0.5 to easily fit within the Roche lobe of the primary. We get 0.4-0.5 for disk outer radius. The emissivity ratio of inner/outter rim (2-3.5) roughly agrees with the values obtained by (Hellier & Mason 1989). Also, as expected, the fit is able to constrain the location of zero phase very accurately. Finally, we find that the X-ray heating component provides ~10% of the optical (U,B) flux at maximum. For error estimates on these parameter values we refer the reader to Figure 4 and Figure 5, which show the distributions of resulting parameters from our fits.

It is interesting to note that if we take the H/R ratio in the direction of the L1 point to be ~0.3 (Figure 5) and take the most probable value of 0.7 for the mass-ratio, we find using the standard formula by (Eggleton, 1983) that the secondary is almost completely in the X-ray shadow due to the disk rim (R2/a ~ 0.35). This further suggests that at the time of our observations the X-ray heating of the secondary was not significant. As noted earlier we get 10% modulation due to X-ray heating from our fits, while Thorstensen (1987) report an amplitude of ~25%. Clearly something has changed in the way the system accretes between these two epochs. The overall brightness has however remained roughly the same. Thorstensen (1987) gives a mean brightness of V=18.8. This is consistent with the phases of maximum brightness in our light curves. It is thus feasible that the light curves we observed could be produced by ‘extra’ vertical structure imposed on a ‘clean’ disk seen by Thorstensen (1987). What has caused this change in the appearance of the accretion disk is unclear. One possibility might be that there has been a change in the amount of accreting matter leaving the L1-point. This is supported by the

5 CONCLUSIONS

Our UBVI photometry of 4U1957+115 supports the 9.33 hours period found by (Thorstensen 1987). We observe, however, significant changes in the light curve parameters when compared to those measured by (Thorstensen 1983). First of all, the amplitude of modulation is ~0.5-0.6 mag compared to ~0.23 mag observed by Thorstensen (1987). Secondly, we find that the light curve is no longer sinusoidal, but displays clear asymmetry. We also find, that the source is at its bluest in the phase of minimum brightness. Our model fits yield some estimates for the system parameters and suggest significant geometrical thickness for the non-axisymmetric disk. Further observations are strongly encouraged to monitor the changes in the light curve of 4U 1957+115 and other LMXB’s, which are likely to show similar behaviour.

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