

The soft X-ray transient GS2000 + 25 – I. An 8.3-hr modulation during outburst

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Accepted 1990 November 21. Received 1990 October 16; in original form 1990 July 12

SUMMARY

Optical spectroscopy of the X-ray transient, GS2000 + 25, during its 1988 outburst shows that this system is similar to A0620 – 00, but at a greater distance (> 2 kpc). We present photometry from La Palma and Russia that reveal a ~ 0.1 -mag modulation at a period of 8.33 hr which we associated with the orbital period. We propose that the modulation, which is in the form of a ‘hump’ in the light curve, is analogous to the mechanism of an eccentric, precessing accretion disc used by Whitehurst (1988) to account for superhumps in SU UMa systems. If confirmed, this would strengthen the relationship between the outburst behaviour of low mass X-ray binaries and cataclysmic variables.

1 INTRODUCTION

This work is the first of two papers concerning optical observations of the soft X-ray transient, GS2000 + 25, in outburst and quiescence. GS2000 + 25 was a very bright X-ray transient (Nova Vul 1988) which reached a maximum of 12 times the strength of the Crab Nebula in the 1–6 keV band. The corresponding visible maximum was only $V=16.4$. The X-ray light curves and e-folding times of GS2000 + 25 and A0620 – 00, the brightest X-ray source yet recorded, are almost identical (Tsunemi *et al.* 1989). Both sources also had a soft X-ray spectrum and similar optical spectra (Boley *et al.* 1976; Wagner, Henden & Bertram 1988; Charles *et al.* 1988) and exhibited variable radio emission (Hjellming *et al.* 1988). A0620 – 00 has a period of 7.75 hr and is a strong black-hole candidate on the basis of masses deduced from the radial velocity curve of the secondary star (McClintock & Remillard 1986). Because of this similarity it was clear that it would be of great interest to determine the orbital period of GS2000 + 25 and (eventually) attempt to measure its system parameters.

However, during A0620 – 00’s discovery, outburst in 1975 and subsequent decline, there were modulations reported at X-ray and optical wavelengths (see Lloyd, Noble & Penston 1977, and references therein), but these proved not to be related to the binary period, which was only found when the source was in quiescence (McClintock *et al.* 1983). Nevertheless, optical searches for short-term periodicities in A0620 – 00 at outburst had been extremely limited, and we felt it worthwhile to undertake such a program for

GS2000 + 25 in case an eclipse, or disc structure were visible.

Our first photometric observations were made approximately 2 months after maximum (which occurred on 1988 April 28) when the source had declined by about 0.5 mag from its maximum brightness. Observations continued until shortly before solar conjunction. The object reached quiescence in $\sim$ mid-1989, and CCD photometry was again obtained in an attempt to study the companion star. The quiescent study forms the subject of Paper II (Callanan & Charles 1991).

2 OBSERVATIONS

2.1 Spectroscopy

We observed GS2000 + 25 using the Faint Object Spectrograph (FOS2, see Allington-Smith *et al.* 1989) on the 4.2-m William Herschel Telescope at the Observatorio del Roque de Los Muchachos on La Palma. FOS2 is a fixed-format, low-resolution ($13 \text{ \AA}$ first order; $6.5 \text{ \AA}$ second order) high-throughput spectrograph which covers most of the observable optical waveband ($\lambda\lambda 3400\text{--}10\,000$). The detector is a dye-coated GEC P8603 CCD, the data from which were optimally extracted (Mukai 1990), corrected for atmospheric extinction and absorption features, flux calibrated and merged into single spectra. Spectra were obtained on 9 nights in the period 1988 June 6–24, and we show in Fig. 1 a summed spectrum for the period 1988 June 6–14 when the source was brightest. This covers the range $\lambda\lambda 4000\text{--}9000$, as the data are too noisy to be of use outside this region.

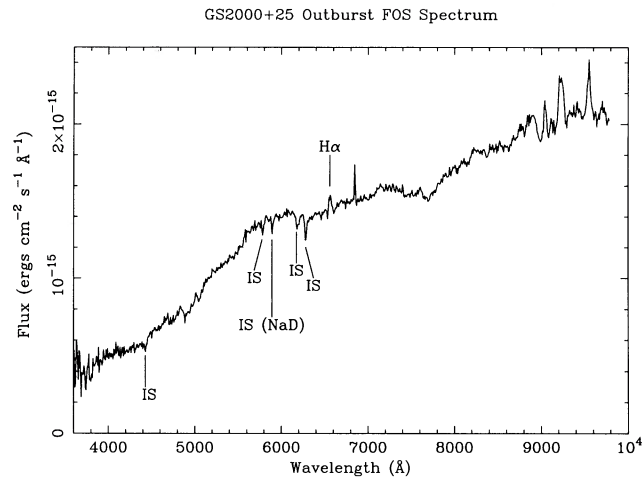


Figure 1. Low-resolution FOS spectrum of GS2000 + 25 obtained with the WHT in 1988 June. The principal features are indicated. Lines marked 'IS' are interstellar features (see Table 1); the feature at ~ 6848 Å is due to poor division of the atmospheric *B*-band.

Table 1. FOS Spectroscopy of GS2000 + 25.

Feature	E.W. (Angstroms)	Comments
H α	2-4	emission, variable
HeII 4684	12	(+ Bowen blend ?)
4430	6.8 ± 1	Interstellar
5778	1.4 ± 0.5	--
Na D	1.2 ± 0.2	--
6177	2.5 ± 0.5	--
6284	3.5 ± 0.5	--

The principal features evident are H α in emission, weak, broad He II $\lambda 4686$ (possibly contaminated by the Bowen blend at $\lambda\lambda 4640$ –50) and a number of interstellar features. The strengths of these lines are given in Table 1. They appear to be systematically larger than those given by Borisov *et al.* (1989), but are closer to the expected strengths on the basis of the observed X-ray absorption (see Section 4).

2.2 Photometry

Observations were taken over a total period of five months between 1988 July and December using telescopes on La Palma and at the Crimean Astrophysical Observatory in Russia. On La Palma we used the CCD camera at the $f/15$ Cassegrain focus of the 1-m Jacobus Kapteyn Telescope. These data include 2 nights on which single points in *B*, *V* and *R* were obtained in order to determine the colours of the object. As these single points are not included in the data for the period search, the actual extent of the light curve coverage consists of 207 points taken on six nights over a two and a half month period. The journal of observations is given below in Table 2. We also include here one night in 1989 March on which observations were made with the WHT at Cassegrain using Taurus II as a focal reducer to give an effective f ratio of $f/4$. At this time the counterpart had faded substantially compared to the pre-Xmas observations and was not observable with the JKT.

The Russian observations were made principally with the Crimean Astrophysical Observatory's 0.5-m telescope equipped with a TV detector operating in white light

Table 2. Journal of observations of GS2000 + 25.

(a) La Palma					
Date	Tel.	CCD*	No.Points	Filter(s)	Duration
18-19/07/88	JKT	GEC3	1	B, V, R	-
29-30/07/88	--	GEC3	61	R	7.5hrs
03-04/08/88	--	GEC3	35	R	
			34	V	8.0hrs
05-06/08/88	--	GEC3	23	R	2.0hrs
20-21/09/88	--	RCA2	21	R	2.0hrs
21-22/09/88	--	RCA2	28	R	3.0hrs
18-19/10/88	--	GEC3	37	R	4.3hrs
12-13/12/88	--	GEC4	1	B, V, R	-
28-29/03/89	WHT	GEC5	1	R	-
Totals			207	R	26.8hrs
			36	V	8.0hrs
			2	B	-

(b) Crimea

Date	No.Points
19-20/07/88	5
24-25/07/88	3
07-08/08/88	3
08-09/08/88	8
09-10/08/88	3
11-12/08/88	2
12-13/08/88	11
13-14/08/88	8
14-15/08/88	8
15-16/08/88	9
16-17/08/88	11
17-18/08/88	12
19-20/08/88	6
20-21/08/88	7
10-11/09/88	8

*The GEC3, GEC4 and GEC5 are identical, dye-coated, blue-sensitive P8603 CCDs with minimal two-dimensional structure. The RCA2 chip is a thinned RCA SID501 CCD which also has some blue sensitivity. Both have their maximum relative quantum efficiency close to the central wavelength of the broad-band *R* filter used for the majority of the observations.

($\lambda\lambda 3500$ –8000 with maximum sensitivity at $\lambda 4000$) between 1988 July and November. The longest runs of observations were from August 12 to September 10 on 9 nights in which 4.5–6.5 hr of data were obtained each night. For further details see Pavlenko, Prokofieva & Dolgushin (1989; also Borisov *et al.* 1989).

3 DATA REDUCTION

Given the relative brightness at this time of the optical counterpart of GS2000 + 25, it was unnecessary to consider bias removal and application of a flat field (these having been shown to have no discernible effect on the results, to a level of 0.01 mag). The data of GS2000 + 25 obtained with both CCDs were therefore extracted and reduced at the telescope using the on-line routine STARFIT (written by C. J. Mayer). This performs a two-dimensional Gaussian fit to the stellar profile (selected interactively) after centroiding and determines the local background around the star. The comparison stars *X* and *Y* (see Fig. 1 of Paper II) were measured in an identical fashion, and the magnitudes of GS2000 + 25 were calculated relative to star *Y*. On photometric nights, observations of standard stars were used to put these measures on an absolute scale. These are summarized in Table 3. From these

Table 3. Photometric results.

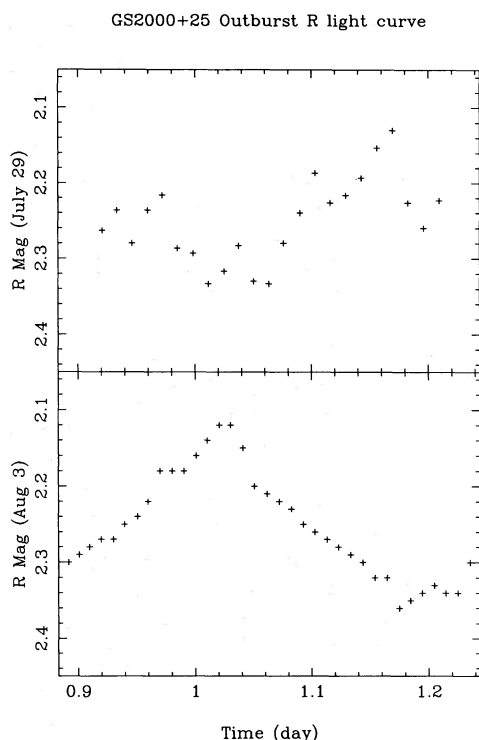
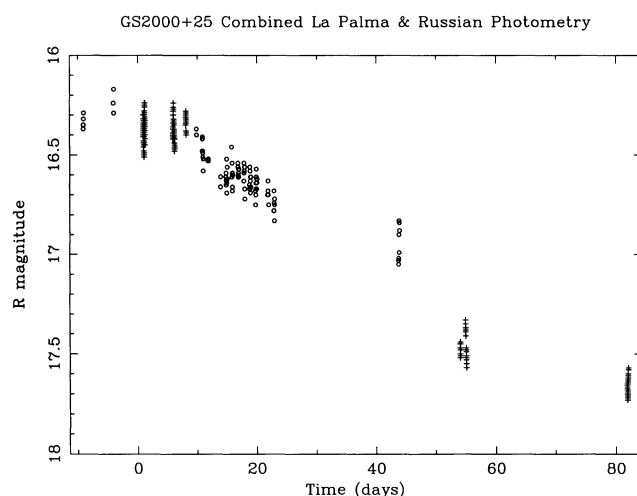
Date	Star	B	V	R
18-19/07/88	GS2000+25	17.99	16.84	15.85
12-13/12/88	--	--	--	18.41
18-19/10/88	X	-	-	16.50
18-19/10/88	Y	-	-	14.12

The accuracy of the GS2000+25 measurements is ± 0.05 mag. That of star Y is ± 0.02 mag.

it is clear that GS2000+25 varied in R from 15.8 to 18 (with an error of ± 0.05), and it continued to fade to $R=21.2$ during the following year (Paper II). This long-term trend over the several months of observations was removed from our data set by subtracting a fifth-order polynomial fit.

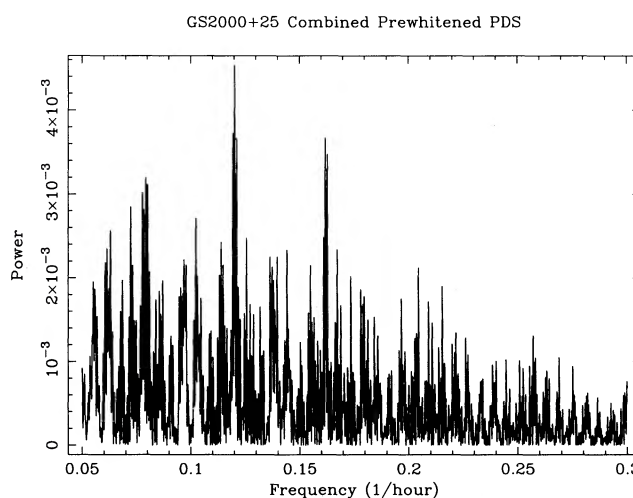
The light curves from the first 2 nights of La Palma observations (July 29 and August 3) are presented in Fig. 2. There is modulation clearly present which prompted us to undertake the extended observations given here. In particular the August 3 light curve suggests a modulation on a timescale of 6–8 hr.

As can be seen from the overall light curve (Fig. 3) the La Palma and Russian data sets complement each other well and greatly extend the uniformity of coverage. The integration of the two data sets was achieved under the assumption of constant colour during the outburst and decay. The Russian data are weighted towards the blue, whereas the La Palma observations are mostly R . This assumption is justified by all the colour observations reported during this time. The Russian reference star is number 1 (of Pavlenko *et al.* 1989) which has $B=18.37$. However, given the very different colours in

**Figure 2.** Light curves in R for each of the first 2 nights of monitoring from La Palma (July 29, August 3).**Figure 3.** Overall light curve of GS2000+25 from the combined La Palma (crosses) and Crimean (circles) photometry. The data are effectively R -band (the Russian data were transformed as described in the text) and cover the period from 1988 end July to December. The origin of the time axis is July 29 0.00 UT. Note the slight increase towards the end of the decay which is very similar to that observed in A0620–00.

which GS2000+25 was observed at the two sites, we compared the La Palma data for GS2000+25 taken on July 18/19 (see Table 3) with the Russian data for July 19/20. This enabled them to be combined as shown in Fig. 3 by applying a colour correction of -2.31 to the Russian data to obtain an equivalent R magnitude.

A Fourier analysis of the combined data sets yielded a periodogram (Fig. 4) that has considerable power at two frequencies, corresponding to periods of 8.33 hr and its one-day alias of 6.18 hr. This is most clearly shown in Fig. 5, in which we have tested the data for constancy as a function of period. All peaks at periods longer than 9 hr were found to be dominated by the window function, and gave folded light curves that were essentially scatter diagrams (but dominated by the data clustering at particular phases). Also, given the

**Figure 4.** Periodogram for the combined photometry data set. The two principal peaks are at 6.18 and 8.33 hr.

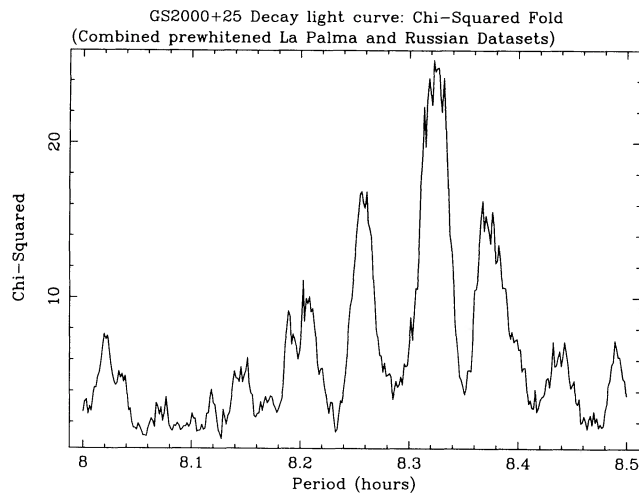


Figure 5. χ^2 folds to test for constancy and accurately determine the position of the peaks in Fig. 4.

shortness of most of our observing runs, the fact that we observed so many peaks or ‘humps’ strongly suggested that the period must be in the range 6–9 hr.

The dominant peak in the χ^2 fold diagram is at 8.3225 hr: the $1-\sigma$ error determined following the formula of Fernie (1989) from the χ^2 peak is 0.0037 hr (the width of the Gaussian peak fitted to the χ^2 peak is 0.013 hr). Fitting a sine wave to the data yielded a period of 8.326 ± 0.0016 hr ($1-\sigma$ error, following the prescription of Lampton, Margon & Bowyer 1976). We estimate T_0 to be 2447371.462 ± 0.006 . The data were then folded on the 6.18 and 8.326 periods and are shown in Fig. 6.

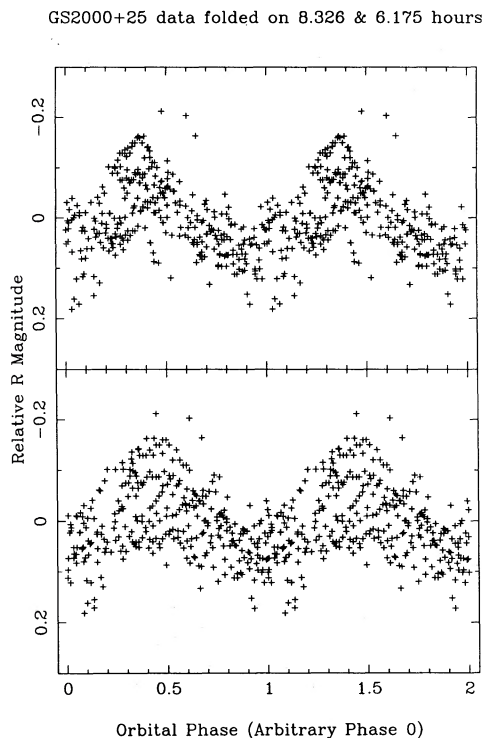


Figure 6. The photometry of GS2000+25 folded on periods of 8.33 hr (upper panel) and 6.18 hr (lower panel). The data have been pre-whitened.

4 DISTANCE OF GS2000 + 25

The colours of GS2000+25 given in Table 3 confirm the reddened nature of the spectrum which is apparent in Fig. 1. This obscuration was measured directly by Tsunemi *et al.* (1989) in its effect on the observed X-ray spectrum. They derived a column density of $1.1 \times 10^{22} \text{ cm}^{-2}$, which, using the Ryter, Cesarsky & Audouze (1975) relation, gives $E(B-V) = 1.69$ and hence $A_V = 5.1$ mag (for $R = 3$). Unfortunately, the interstellar features in the spectrum listed in Table 1 give a wide range of implied $E(B-V)$ values, a problem that also plagued Whelan *et al.* (1977) in interpreting the optical spectrum of A0620–00. However, our observed $B-V$ colour of 1.15 can be used to estimate the reddening under the assumption that GS2000+25 has an intrinsic $B-V$ of 0.0, by analogy with other LMXBs (see Bradt & McClintock 1983). This gives an A_V of 3.5 mag. An A_V in the range 4–5 mag implies a distance greater than 1–2 kpc on the basis of the reddening in this direction of the plane (see Neckel & Klare 1980).

We can also estimate the distance from a comparison with other bright X-ray sources and by assuming that the flux at maximum was Eddington limited. Tsunemi *et al.* (1989) report a peak X-ray flux of 12 Crab in the 1–6 keV band, which corresponds to a flux of $2.7 \times 10^{-7} \text{ erg cm}^{-2} \text{ s}^{-1}$. Correcting for interstellar absorption, this becomes an *intrinsic* GS2000+25 flux of $4 \times 10^{-7} \text{ erg cm}^{-2} \text{ s}^{-1}$. Taking the Eddington limiting luminosity for accretion onto a compact object of mass M_x solar masses as $1.4 \times 10^{38} M_x \text{ erg s}^{-1}$, then the observed GS2000+25 flux implies a distance of $1.8 M_x^{0.5}$ kpc. Hence if GS2000+25 contains a neutron star or black hole with M_x in the range $1.5\text{--}5 M_\odot$ then its distance is in the range 2–4 kpc. Even if we assign an X-ray luminosity to GS2000+25 comparable to that of the brightest stellar X-ray sources known (those in the LMC and Cir X-1 with L_x up to $\sim 10^{39} \text{ erg s}^{-1}$) then its distance must still be less than 5 kpc.

5 DISCUSSION

The similarity of our overall light curve and spectrum (Figs 1 and 3) with those of A0620–00 (Lloyd *et al.* 1977; Whelan *et al.* 1977), and its large range of optical brightness (at least 6 mag), confirm that we are dealing with an LMXB whose period is likely to be less than 1 d. (It is worth noting that the similarity of the light curves extends to the ‘notch’ in the decay that occurs $\sim 100\text{--}150$ d after maximum, a feature that remains unexplained.) Can we then associate the 8.33-hr modulation with the binary period, and what is the physical mechanism that is producing it? We can rule out an ellipsoidal modulation of the secondary star as being responsible on the grounds of the faintness of this star in quiescence. Indeed, such a modulation (at approximately $1/2$ our 8.33 hr period) has been found in quiescence (Paper II), thereby confirming that the binary period is close to 8.3 hr. We are then left with explaining the variations observed in outburst by X-ray heating of the secondary star or outer disc, or a variation associated with the disc itself. In the latter case, if the variation is geometrical, then it would also require a fairly high inclination.

X-ray heating has been shown to be occurring in a number of LMXBs, the most well known of which are Her X-1 and Cyg X-2. In those cases the heating of the face of the com-

panion star shows up as an optical modulation with an associated colour and spectral type variation (see van Paradijs 1983, and references therein). This is easiest to detect in the ultraviolet where the modulation can be very large, but this is not possible with GS2000 + 25 because of its considerable interstellar reddening. To see if such an explanation is relevant here, we have made a simple calculation based on the following assumptions: an interstellar extinction of 1.27 mag kpc⁻¹ (in R), a heated face temperature of 10 000 K (with a bolometric correction of -0.5) and a 20 per cent modulation that is entirely due to blackbody radiation from the heated surface of the mass-losing star. Taking $R = 16.3$ from our first observation of the presence of the modulation yields the relation $d \times 10^{0.25d} = 27R$, where the companion star radius, R , is in solar radii and d is in kpc. In addition, our period of 8.33 hr constrains the size of the system to be $2.5\text{--}3 R_{\odot}$ for an assumed system mass round $3 M_{\odot}$. This restricts the distance of GS2000 + 25 to about 4 kpc, which is consistent with the colours and spectra that have been discussed in Section 4.

In favour of the heating model is the fact that the modulation occupies a substantial fraction of the binary cycle; however, it is not sinusoidal in appearance. It must also be noted that our limited colour information (in V and R through one maximum) does not provide any evidence for a colour change through maximum, which is difficult to interpret in this model.

An alternative explanation is to invoke geometrical effects. Structure in the outer disc rim is known to be responsible for X-ray dips (Parmer & White 1988) and it can cause optical variations also. In the case of GS2000 + 25 we see no dips or eclipses or even partial eclipses, but the inclination may be low enough to exclude this behaviour, and yet high enough to still have the outer disc modulate the brighter inner regions. This would require the minimum in the light curve to be explained as due to such obscuration, but it would have to be unusually extended around the disc. Thus, although we cannot rule it out, we regard this possibility as unlikely.

A more likely explanation for our outburst light curve is to suggest an analogy with the behaviour of the SU UMa subclass of cataclysmic variables (CVs). A full review of their properties is given by Warner (1985), but the important one here is that SU UMa systems undergo, in addition to ‘normal’ dwarf nova outbursts, rare extended ‘superoutbursts’. The similarity of the time-scales of recurrent X-ray transients and SU UMa systems has already led Friedhorsky (1985) to suggest a common physical basis for the causes of the transient outbursts. During such superoutbursts, the light curves of SU UMa systems display ‘superhumps’, an extended (0.3–0.4 binary phase) maximum which is very similar to the light curve observed for GS2000 + 25. Could these have a common origin?

The superhump is not due to the accretion stream impact region as in quiescent dwarf novae (see Wade & Ward 1985), but is instead the result of a precessing, elliptical disc which suffers maximum tidal stresses at particular binary orientations (see Whitehurst 1988). Whitehurst’s work shows that this behaviour is entirely due to the extreme mass ratio of the system, and does not occur in lower mass ratio binaries because such an elliptical disc cannot then be formed (it would lie outside its own stability radius).

The shape and binary phase duration of the ‘hump’ in

GS2000 + 25 is indeed comparable to those in SU UMa systems, but is the scale correct? In a CV, the disc itself generates a substantial fraction of the optical/UV light, and the Whitehurst mechanism for a precessing disc produces a ~ 30 per cent modulation of the disc’s total output. Now Whitehurst made no assumptions about the nature of the compact object itself, save that it made no direct contribution to the light output. But in LMXBs, the much higher X-ray luminosity attainable by a neutron star means that X-ray heating of the disc will normally dominate the disc’s own contribution. What then is the intrinsic disc brightness in an LMXB?

To answer this point we appeal to the recent observations of a high inclination LMXB in the LMC, CAL87 (Callanan *et al.* 1989). This source has an ultra-soft X-ray spectrum and no detectable hard X-rays (to a limit of 4×10^{36} erg s⁻¹). Modelling of the CAL87 optical light curve suggests that there are three components: an outer disc wall, an inner disc and the X-ray heated face of the secondary. The high inclination prevents us from directly observing the compact object and will also reduce the heated part of the disc that is visible to us. Assuming that the outer disc wall represents the disc’s own brightness (~ 50 per cent of the total) and taking the observed V of 18.7 and a distance of 55 kpc, yields an absolute magnitude of $M_V = 0.7$.

Now the maximum V of GS2000 + 25 was ~ 16 , which we correct for $A_V = 5$ to $V_0 \sim 11$. Assuming a distance of 2 kpc then gives $M_V = -1$. If the GS2000 + 25 disc has an intrinsic M_V of 0.7, then a 30 per cent ‘superhump’ modulation of this would have $M_V = 2.0$. This would represent a $\sim 5\text{--}10$ per cent hump on the total light output, which is close to that actually seen.

However, these must be treated as order of magnitude estimates at this stage as there are many uncertainties in our knowledge of LMXB accretion discs. If we were to perform this same calculation relative to a SU UMa (white dwarf) system such as Z Cha or OY Car, then the superhump contribution would be barely 1 per cent of the light seen from GS2000 + 25. The most stringent test of this suggestion will come from an accurate determination of the quiescent period from much more extensive observations than have been undertaken so far.

ACKNOWLEDGMENTS

We are grateful to Jeremy Allington-Smith, Barbara Hassall, Graham Machin, Keith Mason, Koji Mukai, Tim Naylor, Alan Smale and Jan van Paradijs, who took part in the FOS commissioning run on the WHT which produced the spectra reported here. The reduced FOS spectra of GS2000 + 25 were provided by Koji Mukai. We also thank Robin Corbet for communicating the results of the *Ginga* observations to us shortly after the outburst began. The Isaac Newton Group of telescopes are operated on the island of La Palma by the Royal Greenwich Observatory in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

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