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Optical spectroscopy of GX 339−4 during the high–soft and low–hard states – I

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ABSTRACT

We carried out spectroscopic observations of the candidate black hole binary GX 339−4 during its low–hard and high–soft X-ray states. We have found that the spectrum is dominated by emission lines of neutral elements with asymmetric, round-topped profiles in the low–hard state. In the high–soft state, however, the emission lines from both neutral and ionized elements have unambiguously resolved double-peaked profiles. The detection of double-peaked emission lines in the high–soft state, with a larger peak separation for higher ionization lines, indicates the presence of an irradiatively heated accretion disc. The round-topped lines in the low–hard state are probably caused by a dense matter outflow from an inflated non-Keplerian accretion disc. Our data do not show velocity modulations of the line centres caused by the orbital motion of the compact object, neither do the line basewidths show substantial variations in each observational epoch. There are no detectable absorption lines from the companion star. All these features are consistent with those of a system with a low-mass companion star and low orbital inclination.

Key words: accretion, accretion discs – black hole physics – binaries: spectroscopic – stars: individual: GX 339−4.

1 INTRODUCTION

Almost all known black hole candidates (BHCs) in our Galaxy are X-ray transients. Although the triggering for the X-ray outbursts is not fully understood, models invoking accretion disc instability seem to provide an explanation. Other important issues concerning the BHCs are the transition between the X-ray spectral states and its relation to the physical conditions at the accretion disc.

GX 339−4 is an X-ray transient (Markert et al. 1973; Harmon et al. 1994) and also a radio source (e.g. Hannikainen et al. 1998), which shows jet-like features (Fender et al. 1997). It is classified as a BHC because of its short-term X-ray and optical variability (Makishima et al. 1986), the transition between high–soft and low–hard X-ray spectral states (Markert et al. 1973) and the extended high-energy power-law tail in its X-ray spectrum (Rubin et al. 1998). In fact, it is also one of the few BHCs that have shown four X-ray spectral states: *off, low–hard, high–soft and ultrahigh.* Its off state is generally characterized by very weak, hard X-ray emission. The optical counterpart is faint with $V \sim 19$–21. In the low–hard state, the source has a very hard X-ray spectrum, with an extended power-law component with a photon index ~ 1.5. The 2–10 keV X-ray flux is about $\sim 0.4 \times 10^{-9}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. The optical brightness is $V \sim 16$. In the high–soft state, the X-ray spectrum is dominated by a soft thermal component. The power-law tail is weaker than that in the low–hard state and has a photon index ~ 2. The 2–10 keV X-ray flux is about 20 times higher than that of the low–hard state. The optical brightness is $V \sim 16$, similar to that in the low–hard state. In the ultrahigh state, both thermal and power-law components are very strong in the X-ray spectrum. The 2–10 keV X-ray flux is about 50 times the X-ray flux in the low state, and the photon index of the power law is ~ 2.5. On one occasion Mendez & van der Klis (1997) reported that the source was in a state intermediate between the low–hard and the high–soft state, in which the 2–10 keV X-ray flux is about a factor of 5 below the X-ray flux in the high state. (For reviews of the optical and X-ray properties of the system, see e.g. Motch et al. 1985; Ilovaisky et al. 1986; Makishima et al. 1986; Corbet et al. 1987, Tanaka & Lewin 1995 and Mendez & van der Klis 1997.)

Despite the fact that GX 339−4 is optically bright ($V \sim 16$) when it is X-ray active, it is not well studied in the optical bands. Its mass function has not yet been determined, and so the black hole candidacy is not verified in terms of the orbital dynamics. From a photometric observation during the off state, Callanan et al. (1992) detected a periodicity of 14.8 h, and attributed it to the orbital period. If this is true, the companion star would be a late-type star with a mass $< 1.6\,\mathrm{M_\odot}$.

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Optical spectra taken by Smith, Filippenko & Leonard (1999) in 1996 May, when the system was in a low–hard state, show a strong Hα emission line with a broad flat-topped profile. Within the resolution and the signal-to-noise ratio limit of the spectra, the line resembles the double-peaked lines that characterize the accretion disc in binary systems. By fitting two Gaussians to the Hα line profile, a velocity separation of $370 \pm 40\,\mathrm{km\,s^{-1}}$ is deduced. As the separation of the peak in this data set is not as clearly seen as in the other BHCs, e.g. GRO J1655−40 (Soria, Wu & Hunstead 1999a) and A0620−00 (Johnston, Kulkarni & Oke 1989), there is a possibility that the flat-topped profile seen in 1996 May is not intrinsically double-peaked, just as in the case of Cyg X-1 (Smith et al. 1999).

Here we report spectroscopic observations of GX 339−4 which we carried out in 1997 May and in 1998 April and August. The system was in a low–hard state in 1997 May and was in a high–soft state in 1998 April and August (see Fig. 1). During the 1998 August observations, we also obtained simultaneous photometric data. Our data show that GX 339−4 has distinct optical spectral features in the low–hard and high–soft states, an indication of different physical conditions in the line-emission regions or perhaps different line-emission regions in the two X-ray spectral states.

2 OBSERVATIONS AND DATA REDUCTION

The 1997 May 6 and 8 observations of GX 339−4 were carried out with the Royal Greenwich Observatory (RGO) spectrograph and Tektronix 1k × 1k thinned CCD on the 3.9-m Anglo-Australian Telescope (AAT). The seeing was 2 arcsec. Series of 600-s spectra were taken in the 5355–6950 Å region. A grating with 300 groove $\mathrm{mm^{-1}}$ was used with the 25-cm camera, giving a resolution of 3 Å full width at half-maximum (FWHM).

On 1998 April 28–30 we observed the system again, with the Double Beam Spectrograph (DBS) on the Australian National University (ANU) 2.3-m Telescope at Siding Spring Observatory. The detectors on the two arms of the spectrograph were SITe 1752 × 532 CCDs. Gratings with 1200 groove $\mathrm{mm^{-1}}$ were used for both the blue (4150–5115 Å) and red (6200–7150 Å) bands, giving a resolution of 1.3 Å FWHM. The average seeing on each of the three nights was about 2 arcsec. Further observations were carried out on 1998 August 20 and 23, with the same instrumental setup as in the April observations. Simultaneous photometric observation were conducted with the ANU 40-inch telescope on 1998 August 20 and 23. The seeing was 2 and 3 arcsec on the two nights respectively. A log of our spectroscopic observations is shown in Table 1.

Standard data reduction procedures were followed, using the IRAF tasks. After removing the bias and pixel-to-pixel gain variations from each exposure, we subtracted the sky background and extracted the spectra with the APALL routine. CuAr and FeAr lamp spectra were taken to carry out wavelength calibration. We removed atmospheric spectral features using the standard star LTT 7379.

3 RESULTS

3.1 Spectrum in the low–hard state

Fig. 2 shows the summed spectrum from the observations we conducted on 1997 May 6. The total exposure time was 19 800 s. The Hα, He I λ6678 and He I λ5876 emission lines are easily identified. The emission feature at about 6500 Å is probably the N II λ6505 emission line. (The main features identified in the spectra and their equivalent widths are listed in Table 2.) Our data do not reveal two clearly resolved peaks for Hα, He I λ5876 and He I λ6678. Although the suspected N II λ6505 line appears to have two maxima, it is uncertain whether they are purely statistical or intrinsic. We do not detect the Li I λ6708 absorption line, which was present in the spectra of the BHCs GRO J1655−40, A0620−00, V404 Cyg and Cen X-4 (Martin et al. 1992; Shahbaz et al. 1999; Smith et al. 1999), nor any other obvious stellar absorption lines. All absorption features in our spectra appear to be interstellar.

The Hα line is asymmetric, with its peak slightly skewed towards the red. The line profile is more appropriately described as asymmetric and round-topped than as unevenly double-peaked. The equivalent width (EW) of the line is -7.2 ± 0.3 Å (negative values are taken to indicate emission). The EW and the overall shape are similar to those found in the spectra obtained by Smith et al. (1999) on 1996 May 12, when the system was also in a low–hard state, except for the fact that in those observations the line peak was skewed towards the blue instead. We considered a two-Gaussian fit using the QDP routine (Tennant 1991) and obtained the Gaussian centres at 6560.15 and 6567.57 Å. If we assume that the line truly has a double-peaked profile, the deconvolved peak separation is then roughly 7.4 Å. This value is consistent with the 8.0 ± 0.8 Å separation obtained by Smith et al. (1999) with a two-Gaussian fit to their 1996 data.

3.2 Spectrum in the high–soft state

In Fig. 3 we show the summed spectrum in the Hα region for the data obtained on 1998 April 28–30; in Fig. 4, we show the summed spectrum in the Hβ/He II region for the data obtained on

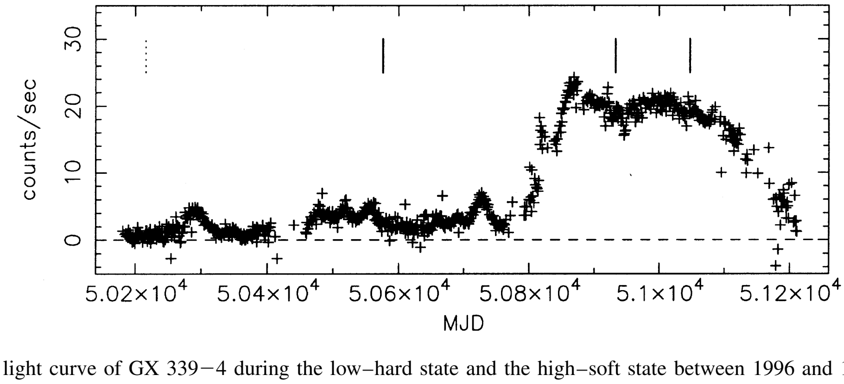

Figure 1. The RXTE/ASM light curve of GX 339−4 during the low–hard state and the high–soft state between 1996 and 1998. The dates at which our observations were carried out are marked by solid vertical lines and that of the observation by Smith et al. (1999) is marked by a dotted vertical line.

Table 1. Log of our spectroscopic observations of GX 339−4.

Date	HJD range (HJD −245 0000)	Wavelength range (Å)	Resolution (Å FWHM)
	AAT 3.9-m		
1997 May 6	574.966–575.226	5355–6950	3
1997 May 8	576.974–577.042	5355–6950	3
	ANU 2.3-m		
1998 April 28	931.953–932.318	4150–5115	1.3
		6200–7150	1.3
1998 April 29	932.943–933.268	4150–5115	1.3
		6200–7150	1.3
1998 April 30	934.106–934.233	4150–5115	1.3
		6200–7150	1.3
1998 August 20	1045.864–1046.140	4150–5115	1.3
		6200–7150	1.3
1998 August 23	1048.860–1049.103	4150–5115	2
		6200–7150	2

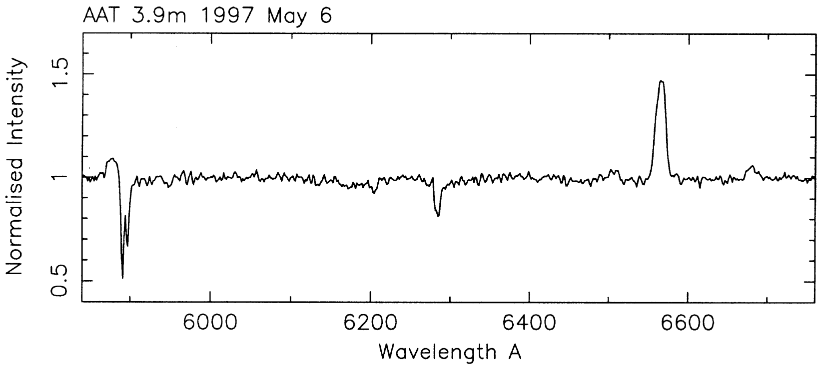

Figure 2. The summed spectra of GX 339−4 in the Hα region. The data were obtained by the AAT on 1997 May 6, when the system was in a low–hard X-ray state. The spectrum is normalized to the continuum, and wavelengths are vacuum, heliocentric.

the same nights. The total exposure times in both cases were 25 500 s on the first night, 19 500 s on the second and 4000 s on the third. Strong H I Balmer emission lines are seen in the spectra. Other prominent emission lines are He I λ6678, He I λ7065, He II λ4686 and N III λλ4641,4642.

The Hα, Hβ, Hγ, He I λ6678, He II λ4686 and N III λλ4641,4642 lines all show double-peaked profiles, and the peaks are resolved visually. The peaks are still clearly separated even when we bin the data to mimic a spectrum with a resolution of 4 Å FWHM, lower than the 3 Å resolution of our 1997 May spectra (see Fig. 2, cf. also Smith et al. 1999). It is therefore the first time that double-peaked lines have been unambiguously detected in the optical spectra of GX 339−4. The peak separations of the emission lines are listed in Table 3.

We note that while Hα and Hβ have similar velocity separations, that of Hγ is significantly larger. As the signal-to-noise ratio of the Hγ line is relatively low, the unexpectedly large velocity separation is probably caused by contamination.

The general features of the 1998 August spectra (not shown) are similar to those of the 1998 April spectra. The Hα, Hβ, Hγ, He I λ6678, He II λ4686 and N III λλ4641,4642 lines are prominently seen in emission and generally have double-peaked profiles. Because of poorer observing conditions – cloudy nights – the peaks are not as well resolved as those appearing in the 1998 April spectra.

3.3 Line profile morphology

In Fig. 5, we show a sequence of Hα line profiles from the 1997 May 6 and 8 observations. The Hα line profiles are asymmetric, with a slightly redshifted peak and a round top. There is no strong indication of double-peaked profiles in any set of data obtained in 1997 May (cf. the Hα and He II 4686 lines in Fig. 6, where the double-peaked structure is instead very clear). The line shows detectable variations from night to night. If the line profiles are fitted with a single Gaussian, one may obtain a series of velocity shifts. Judging from the central location of the line bases, we argue that such variations are statistical, i.e. our data do not show systematic velocity modulation as a result of orbital motion. The basewidth of the line does not show obvious variations over the two nights of observations, either. The variations in the line top are therefore likely to be caused by opacity rather than kinematic effects.

The signal-to-noise ratios of the He I λ6678 line profiles in the 1997 May observations (not shown) are not as good as those measured at Hα. In spite of this, the properties of the He I λ6678 line profile sequence are still consistent with no systematic velocity modulations and no linewidth variations.

The sequence of Hα and He II λ4686 line profiles from the 1998 April observations are shown in Fig. 6. The presence of a double peak in each profile is not as obvious as it appears in the summed spectra. However, the trace of two peaks can still be easily seen. The relative prominence of the two peaks varies from one spectrum to another. As changes of the relative contribution of the two peaks have also been observed in other BHCs, e.g. GRO J1665−40, when they were in a high–soft state (see Soria et al. 1999a), this may imply that similar activities are occurring in the accretion discs of these BHCs during that state.

The profile of the Hα line is slightly skewed, with an apparently wider blue wing. We suspect that the skewness is caused by the presence of a weak broad component, the red wing of which is partially obscured/absorbed along the line of sight, an indication that opacity effects play a significant role in the high–soft state as well as in the low–hard state. A hint of a third peak superimposed on the blue wing is detected in some spectra, particularly in the last series of observations from April 28. The profile sequence in Fig. 5 reveals that the strength of the emission above the continuum increased from the first to the second night, and then decreased to the previous levels from the second to the third night. The average EW of the Hα line was -6.6 ± 0.3 Å on April 28, -9.0 ± 0.2 Å on April 29, and -6.0 ± 0.3 Å on April 30. We do not have photometric data from 1998 April, and we are therefore unable to determine whether the variations in the EW are a consequence of changes in the intensity of the continuum or of the emission line itself.

The presence of two peaks in the He II λ4686 line is more obvious than in the case of Hα. They are clearly separated most of the time, and their separation is wider than that of the two peaks in the Hα line profile. The red and blue wings are more symmetric with respect to each other, in comparison with the wings of the Hα line. The average EW of He II λ4686 was -5.5 ± 0.2 Å on April 28, -6.0 ± 0.4 Å on April 29, and -4.5 ± 0.3 Å on April 30.

In Fig. 7 we show the profiles of the Hα and He II λ4686 lines from the 1998 August observations. The corresponding peak locations are consistent with those found in April. The red peak is generally weaker than that observed in 1998 April, while the blue peak seems to be stronger.

Table 2. The equivalent widths (in Å) of the most prominent emission lines from GX 339−4 and the interstellar absorption lines.

	1997 May	1998 Apr	1998 Aug
Emission lines from GX 339−4			
Hγ λ4340		−2.0	−1.8
N III λλ4641,4642		−2.5	−3.0
He II λ4686		−5.3	−5.1
Hβ λ4661		−3.0	−3.5
He I λ4922		−0.9	−1.2
He I λ5876	−1.8		
N II λ6505	−0.7	***	
Hα λ6563	−7.2	−6.7	−7.4
He I λ6678	−1.0	−1.3	−1.3
He I λ7065		−1.0	−1.0
Interstellar (IS) lines†			
λ4428		0.7	0.6
λ4502		0.3	0.4
λ4726		***	0.4
λλ5778,5780	1.1		
NaD_2 λ5890	2.1		
NaD_1 λ5896	1.6		
λ6202	0.6	0.3	0.3
λ6270	0.2	0.2	0.2
λ6284	1.8	1.7	1.6
λ6613	0.2	0.2	0.2

Notes.
*** Too weak to be accurately measured.
† Classified as IS lines according to Herbig (1975).

4 DISCUSSION

4.1 Accretion disc and line emission

The non-detection of Li I λ6708 and of other stellar absorption lines above the noise level ($S/N \sim 30$) suggests that the emission from the companion star gives a negligible contribution to the optical continuum. This is not surprising: in 1981 the system was observed at an optical brightness as low as $V \sim 21$ mag (Hutchings, Cowley & Crampton 1981; Ilovaisky & Chevalier 1981), which is approximately the brightness of a 1-$M_\odot$ main-sequence star at a distance of ~ 4 kpc (Zdziarski et al. 1998); if that is the intrinsic brightness of the companion star, it would have contributed only ~ 1/50 of the optical flux detected in our observations ($V \sim 16.5$).

The spectra are dominated by emission lines in both low–hard and high–soft states. We argue that these lines are emitted from the accretion disc and/or its corona and wind. Thus, the accretion disc is present and active in both X-ray spectral states.

The emission lines in the 1997 May spectra appear to have a round-topped profile, skewed towards the red. Although we cannot rule out the interpretation that the round-topped lines actually consist of two components, we do not see clearly resolved peaks in our data. An alternative explanation is that the round-topped lines are the consequences of an outflow, a dense wind from an inflated non-Keplerian disc or an evaporating corona. If the outflowing matter is sufficiently dense to produce a large opacity, lines emitted from the accretion disc beneath can be masked. The lines will then be dominated by emission from the outflowing material instead of by emission from the accretion disc. As the kinematic velocity of the outflowing matter should be of the same order of magnitude as the local Keplerian velocities, the widths of the lines from the outflowing material may not differ much from the widths of lines from the accretion disc. However,

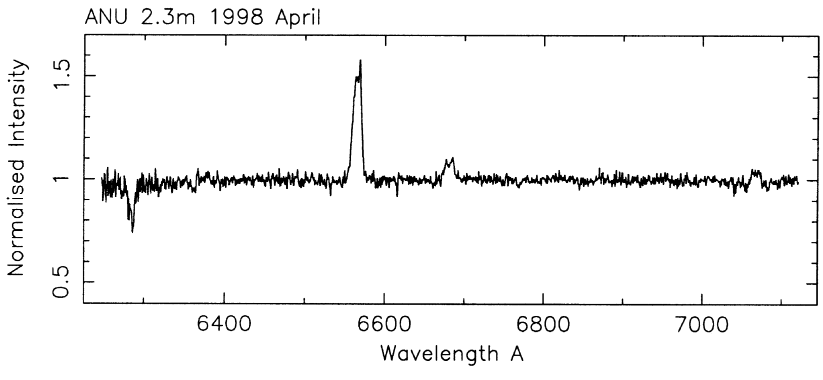

Figure 3. The summed spectra of GX 339−4 in the Hα region with the same scale as in Fig. 2. The data were obtained by the ANU 2.3-m telescope on 1998 April 28–30, when the system was in a high–soft X-ray state.

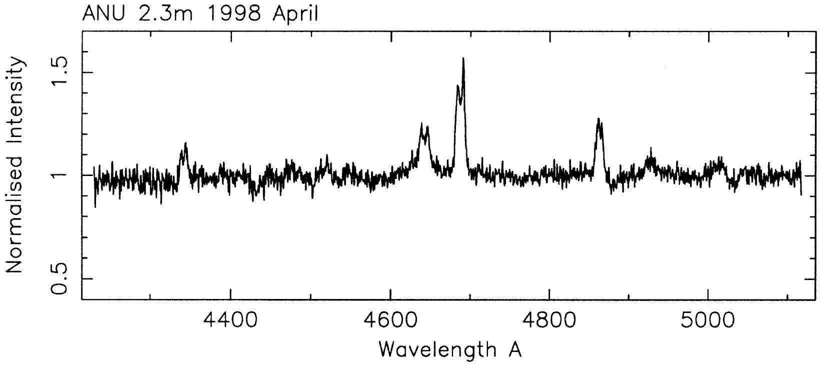

Figure 4. Same as Fig. 3, for the Hβ/He II region.

the lines will not show double-peaked profiles, and will instead appear to be round-topped or flat-topped, depending on the outflow velocity and density profiles (see chapter 14 in Mihalas 1978), as in the case of emission lines from windy massive stars.

The 1998 spectra show a strong optical continuum originated from an optically thick accretion disc. For a Keplerian disc, the rotational velocity and the temperature increase radially inward. If the disc is only viscously heated from its middle layer, a temperature gradient will be set up, such that the temperature decreases from the central plane to the disc surface. This will result in a spectrum dominated by absorption lines (see e.g. la Dous 1989). However, if there is a temperature inversion near the disc surface – which may be caused by external irradiation – the spectrum will then be dominated by emission lines. The 1998 April spectra clearly show prominent emission lines with resolved double peaks superimposed on a strong continuum. This implies that the accretion disc is irradiatively heated. The increase in the velocity separation with the ionization state of the accreting matter is strong evidence that the disc is irradiated by a central source, as the higher excitation lines originate from the inner regions, where the Keplerian velocities are larger and the temperature higher because of the smaller distance from the irradiation source. For a discussion on irradiation heating of accretion discs, see e.g. Dubus et al. (1999).

The velocity separation of the Hα peaks in the high–soft state is smaller than the velocity separation obtained by a two-Gaussian fit to the line profiles obtained in the low–hard state (see also Smith et al. 1999). It is, however, roughly the same as the velocity separation of the Hβ line observed in the same epoch. As the velocity separation of the peaks in the low–hard state is not well defined, we cannot draw any firm conclusions from the comparison. However, we have found that the velocity separation of the peaks in the Hα line in the high–soft state is a factor of 2 smaller than that observed in GRO J1655−40 in the same X-ray spectral state (Soria et al. 1999a). The latter is a high orbital inclination system ($i \approx 70°$, e.g. van der Hooft et al. 1998). If the masses of the black holes in GX 339−4 and GRO J1655−40 are similar, say 7–10 $M_{\odot}$, the smaller velocity separation for GX 339−4 implies that either the accretion disc in GX 339−4 is larger or the orbital inclination of GX 339−4 is lower. As the companion star of GX 339−4 is not visible during its off state (Callanan et al. 1992), it is likely to be a low-mass star, less massive than the companion star in GRO J1655−40. This leads us to propose that GX 339−4 is a system with a low orbital inclination. A low orbital inclination for GX 339−4 is in fact consistent with the null detection of the orbital modulation in our 1997/1998 spectroscopic data. It is also supported by the fact that the radio spectrum of GX 339−4 is relatively flat (Fender et al. 1997), unlike the steep spectra expected from a superluminal synchrotron jet source.

Table 3. The peak-to-peak velocity separation of the double-peaked emission lines from GX 339−4 in the summed spectrum from 1998 April, with a 2σ uncertainty estimated from the individual spectra.

Line	Δv (km s^{-1})
Hα λ6563	250 ± 20
Hβ λ4861	260 ± 30
Hγ λ4340	350 ± 30
He I λ6678	380 ± 20
He I λ7065	390 ± 20
He II λ4686	480 ± 20
N III λλ4641,4642	490 ± 15

Although a 14.8-h periodicity was detected when GX 339−4 was observed in an off state (Callanan et al. 1992), neither our 1997/1998 spectroscopic data nor our 1998/1999 photometric data (Soria, Wu & Johnston 1999b) show any obvious periodicities. The photometric observations that we carried out in 1998 August show variations in the brightness of the source similar to the flaring activities seen in a previous observation by Corbet et al. (1987). On August 20 its brightness varied between $V = 16.45 \pm 0.01$ and $V = 16.52 \pm 0.01$, while on August 23 the source brightened up from $V = 16.61 \pm 0.01$ at the beginning of the night to a maximum of $V = 16.22 \pm 0.015$ h later, then started to decline again. Further photometric observations during the off state are required to verify whether GX 339−4 has a 14.8-h orbital period. If we accept the argument that GX 339−4 has a low orbital inclination, the 14.8-h periodicity detected by Callanan et al. (1992) may perhaps also be caused by the precession of a weak accretion disc and/or its associated jet.

4.2 Summary

We carried out spectroscopic observations of the BHC binary GX 339−4 during its low–hard and high–soft states. Our data show that the optical spectra in the low–hard state are characterized by emission lines with slightly asymmetric, round-topped profiles; on the other hand, the spectra in the high–soft state show emission lines with unambiguously resolved double-peaked profiles. We do not see obvious stellar absorption lines: this implies that the

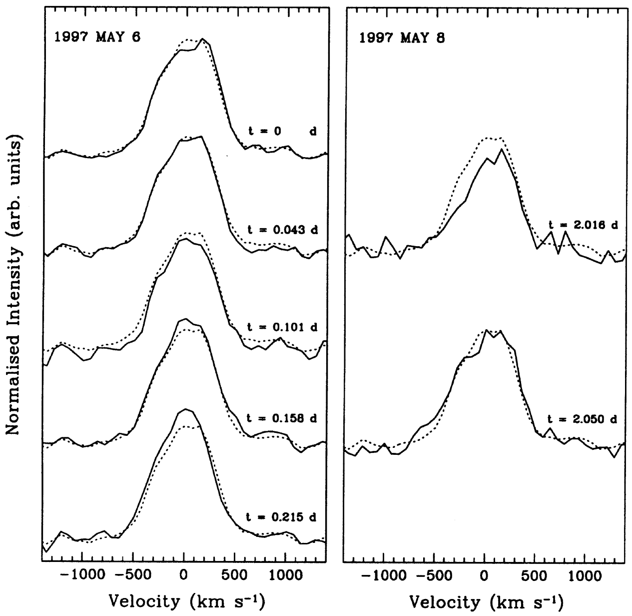

Figure 5. Hα line profiles for the 1997 May 6 and 8 observations. The zero velocity is defined by the wavelength of the line in its rest frame. The continuum is normalized to unity. The time reference is chosen such that '$t = 0$' corresponds to the mid-time of the first series of observations on May 6. The total integration times for each of the combined profiles, plotted here from top to bottom, are 2400, 3600, 4800, 4200 and 4800 s for the May 6 spectra, and 3600 and 1800 s for the May 8 spectra. The averaged line profile for all the 1997 May observations is shown as a dotted line for comparison.

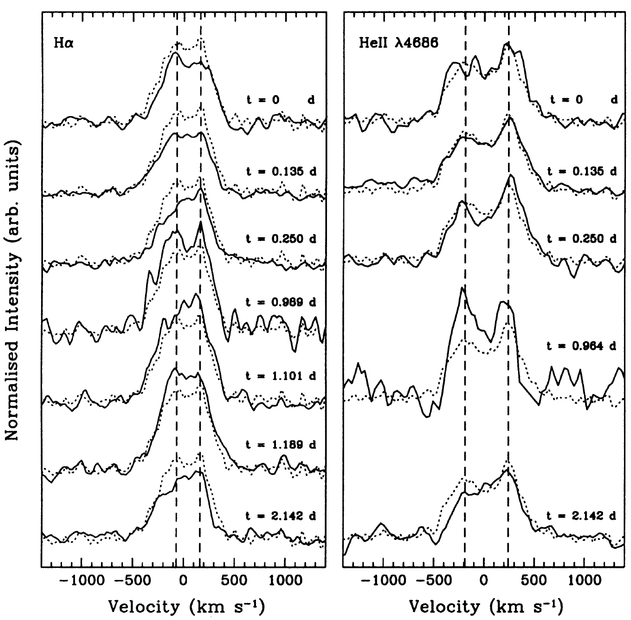

Figure 6. The profiles of the Hα and the He II λ4686 lines in the 1998 April observations, with the zero velocity and continuum normalization defined as in Fig. 5. The time reference '$t = 0$' corresponds to the mid-point of the first observation on April 28. The averaged line profiles (dotted lines) and the locations of the peaks (vertical dashed lines) are shown for comparison.

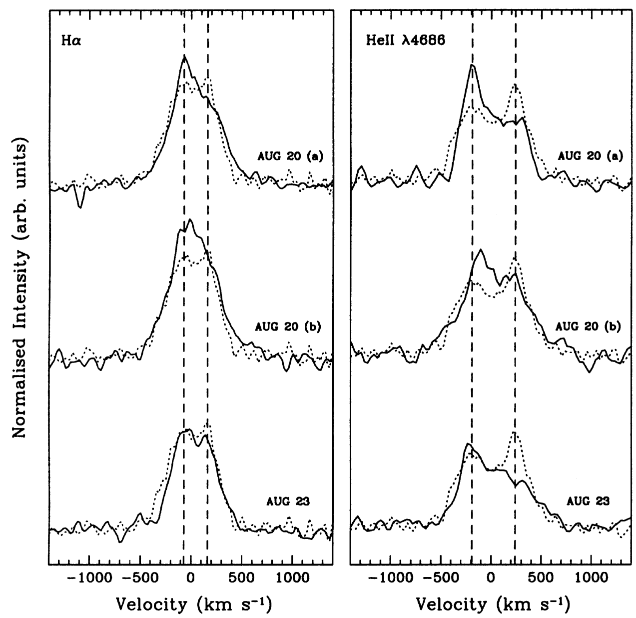

Figure 7. Same as Fig. 6 for the 1998 August 20 and 23 observations. The averaged profile from the first half of the August 20 night is labelled 'AUG 20 (a)', and the one from the second half 'AUG 20 (b)'. The time separation between the mid-points of the two series of spectra is about 4 h. The averaged line profiles of the 1998 April observations (dotted lines) and the corresponding locations of the peaks (vertical dashed lines) are shown for comparison.

optical spectrum in both X-ray spectral states is dominated by emission from accreting matter around the black hole. The round-topped lines seen in the low–hard state are probably formed in opaque matter outflowing from the central black hole and/or the accretion disc. The double-peaked lines seen in the high–soft state, however, indicate the presence of a bright, active accretion disc. The trend of increasing velocity separation with line ionization supports the model of an accretion disc irradiatively heated by soft X-rays from a central source. We do not see 14.8-h modulations in our spectroscopic data and we are therefore unable to verify the 14.8-h orbital period. The null detection of the 14.8-h periodicity and of stellar absorption lines, together with the relatively small velocity separation of the line peaks, lead us to believe that GX 339−4 is low-mass system with a low orbital inclination.

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REFERENCES

Callanan P. J., Charles P. A., Honey W. B., Thorstensen J. R., 1992, MNRAS, 259, 395

Corbet R. H. D., Thorstensen J. R., Charles P. A., Honey W. B., Smale A. P., Menzies J. W., 1987, MNRAS, 227, 1055

Dubus G., Lasota J.-P., Hameury J.-M., Charles P. A., 1999, MNRAS, 303, 139

Fender R. P., Spencer R. E., Newell S. J., Tzioumis A. K., 1997, MNRAS, 286, L29

Hannikainen D. C., Hunstead R. W., Campbell-Wilson D., Sood R. K., 1998, A&A, 337, 460
Harmon B. A. et al., 1994, ApJ, 425, L17
Herbig G. H., 1975, ApJ, 196, 129
Hutchings J. B., Cowley A. P., Crampton D., 1981, IAU Circ., 3585
Ilovaisky S. A., Chevalier C., 1981, IAU Circ., 3586
Ilovaisky S. A., Chevalier C., Motch C., Chiappetti L., 1986, A&A, 164, 67
Johnston H. M., Kulkarni S. R., Oke J. B., 1989, ApJ, 345, 492
la Dous C., 1989, A&A, 211, 131
Makishima K., Maejma Y., Mitsuda K., Bradt H.V., Remillard R. A., Tuohy I. R., Hoshi R., NaKagawa M., 1986, ApJ, 308, 635
Markert T. H., Canizares C. R., Clark G. W., Lewin W. H. G., Schnopper H. W., Sprott G. F., 1973, ApJ, 184, L67
Martin E. L., Rebolo R., Casares J., Charles P. A., 1992, Nat, 358, 129
Mendez M., van der Klis M., 1997, ApJ, 479, 926
Mihalas D., 1978, Stellar Atmosphere, 2nd edn. Freeman, San Francisco
Motch C., Ilovaisky S. A., Chevalier C., Angebault P., 1985, Space Sci. Rev., 40, 219
Rubin B. C., Harmon B. A., Paciesas W. S., Robinson C. R., Zhang S. N., Fishman G. J., 1998, ApJ, 492, L67
Shahbaz T., van der Hooft F., Casares J., Charles P. A., van Paradijs J., 1999, MNRAS, 306, 89
Smith I. A., Filippenko A. V., Leonard D. C., 1999, ApJ, 519, 779
Soria R., Wu K., Hunstead R. W., 1999a, ApJ, submitted
Soria R., Wu K., Johnston H. M., 1999b, in 19th Texas Symp. on Relativistic Astrophysics and Cosmology, CD-ROM,
Tanaka Y., Lewin W. H. G., 1995, in Lewin W. H. G., van Paradijs J., van den Heuvel E. P. J., X-ray Binaries. Cambridge Univ. Press, Cambridge, p. 126
Tennant A. F., 1991, NASA Technical Memorandum, 4301
van der Hooft F., Heemskerk M. H. M., Alberts F., van Paradijs J., 1998, A&A, 329, 538
Zdziarski A. A., Poutanen J., Mikołajewska J., Gierliński M., Ebisawa K., Neil Johnson W., 1998, MNRAS, 301, 435

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