

VLT optical observations of V821 Ara(=GX339–4) in an extended “off” state^{*}

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Abstract. We report on low-resolution spectroscopy of GX339–4 during its current, extended X-ray “off” state in May 2000 ($r = 20.1$) obtained with the VLT Focal Reducer/low dispersion Spectrograph (FORIS1). Although we do not positively detect the secondary star in GX339–4 we place an upper limit of 30 percent on the contribution of a “normal” K-type secondary star spectrum to the observed flux. Using this limit for the observed magnitude of the secondary star, we find a lower limit for the distance of GX339–4 to be 5.6 kpc.

Key words. stars: individual: GX339–4 stars X-rays: stars accretion, accretion disks black hole physics

1. Introduction

The optical counterpart of GX339–4 was identified by Doxsey et al. (1979) as a $V \sim 18$ blue star. Subsequent observations showed that it exhibited a wide range of variability depending on its X-ray state; from $V = 15.4$ to 20.2 (Motch et al. 1985; Corbet et al. 1987) when it is in the X-ray “low” and “off” states, while $V = 16$ –18 (Motch et al. 1985) when it is in the X-ray “high” state. Simultaneous optical and soft X-ray (3–6 keV) observations showed a remarkable anti-correlation during a transition from an X-ray “low” to “high” state (Motch et al. 1985), the cause of which was unknown. However, Ilovaisky et al. (1986) showed that there are times when the optical and X-ray fluxes are correlated. Callanan et al. (1992) reported a possible orbital period of 14.8 h from optical photometry.

GX339–4 is of great interest in the class of black hole X-ray binaries, because its black hole candidacy is established by its Cyg X–1-like X-ray variability and multiple states, yet it is the only low-mass X-ray binary member in its class to be “steady” (apart from the occasional “off” state it is usually X-ray active) as opposed to transient (i.e. systems which undergo episodic X-ray outbursts and which usually last for several months and then are X-ray quiet for many years; see e.g. Charles 1998). This

Table 1. Log of VLT observations.

Object	Date (2000)	UT start	Exposure time (s)	Seeing (")	Comments
HD 157423	05/11	08:57	2 × 3	0.63	K1III
HD 155111	05/11	08:40	2 × 3	0.68	K5III
HR 5265	08/23	23:07	1 × 2	0.00	K3III
HR 5178	08/22	08:57	1 × 5	0.00	K5III
HR 6169	08/23	08:57	1 × 0.6	0.00	K7III
V821 Ara	06/04	06:52	1200	0.74	GX339–4
V821 Ara	06/04	07:16	1200	0.69	GX339–4

may be related to the mass of the compact object but, at present, there is no dynamical mass estimate available (which would establish its black-hole nature), since there has been no spectroscopic detection of the mass-losing star. This is very difficult during X-ray “on” states due to the brightness of the X-ray irradiated disc, but GX339–4 occasionally enters an extended “off” state when the disc contribution is greatly reduced. In this letter we report on VLT medium resolution spectroscopy of GX339–4 taken during its current “off” state in order to search for the spectral signature of the mass-losing star.

2. Observations and data reduction

2.1. Imaging

We obtained r -band Gunn images of GX339–4 prior to the spectroscopic observations for acquisition purposes.

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^{*} Based on observations performed at the European Southern Observatory, Paranal, Chile.

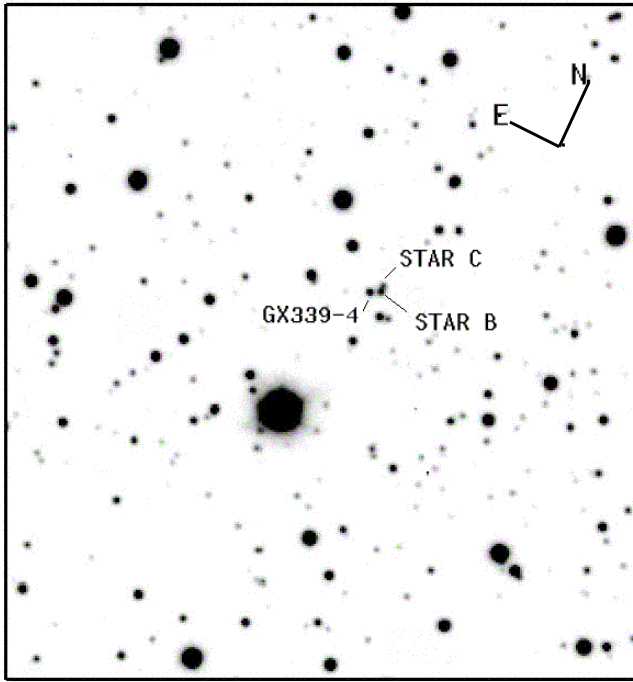


Fig. 1. *R*-band image of GX339-4 taken with the VLT on 4th June 2000. The exposure time was 30 s and the field of view is 2×2 arcmins. For GX339-4 $r = 20.1 \pm 0.1$. North and East are marked.

The integration time was 30 s and the images were corrected for the bias level and flat-fielded in the standard way. We performed optimal aperture photometry (Naylor 1998) on GX339-4, which is clearly resolved (see Fig. 1), and several nearby comparison stars. The seeing during these observations was ~ 0.7 arcsecs. We calibrated the data using photometric standard stars taken on the same night as part of the ESO calibration programme. We find $r = 20.1 \pm 0.1$ for GX339-4.

2.2. Spectroscopy

Spectroscopic observations of GX339-4 were obtained using ESO’s Very Large Telescope (VLT) Unit Telescope 1 equipped with the Focal Reducer Low Dispersion Spectrograph FORS1 (see Table 1 for a log of the observations). The data were obtained in service mode and were taken with the 600R grism, a 0.7 arcsec slit and the standard resolution collimator, resulting in a spectral resolution of 3.4 \AA (FWHM). The dispersion was 1.08 \AA per pixel and we obtained a wavelength coverage from 5225–7417 \AA . Some template stars were obtained during a different observing run in August 2000 using the same setup.

Acquisition images (see Sect. 2.1) of the GX339-4 field (see Fig. 1), clearly revealed the star 1.06 arcsecs North-West of GX339-4 in the chart published by Callanan et al. (1992). However, under the excellent observing conditions, our new image reveals that this object can actually be resolved into two stars. These stars were close enough to pose a potential problem in the spectroscopic data

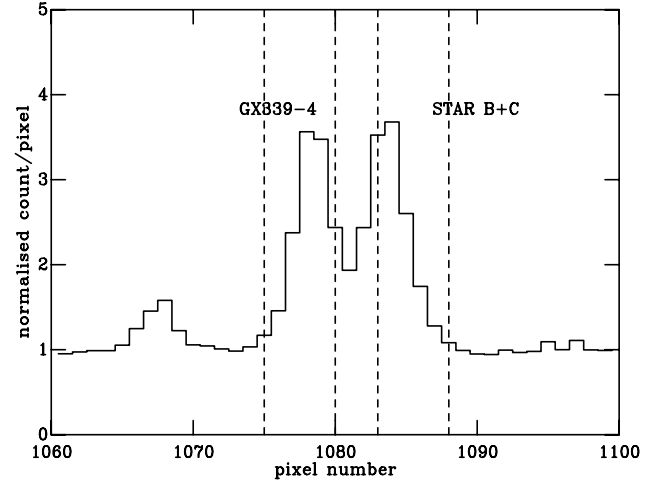


Fig. 2. A cut along the slit showing the spatial profile of GX339-4 and the blend of stars B+C. Only rows 1075 to 1080 which are clear from contamination were used in the extraction of the spectrum.

analysis, and so the slit was rotated to a position angle of 112.8 degrees East of North, to avoid them contaminating the GX339-4 spectrum.

The data reduction and analysis was performed using the Starlink FIGARO package, the PAMELA routines of K. Horne and the MOLLY package of T. R. Marsh. Removal of the individual bias signal was achieved through subtraction of a median bias frame. Small scale pixel-to-pixel sensitivity variations were removed with a flat-field frame prepared from observations of a tungsten lamp. Calibration of the wavelength scale was achieved using 4th order polynomial fits. The stability of the final calibration was verified with the OH sky lines at 6300.3 \AA and 6363.8 \AA whose position was accurate to within 0.6 \AA .

One-dimensional spectra were extracted using the optimal-extraction algorithm of Horne (1986). However, to minimize contamination from the blend of stars B and C, we extracted only a few rows of the CCD; as shown in Fig. 2, these were rows 1075 to 1080. The signal-to-noise ratio of the final extracted GX339-4 spectrum was ~ 50 in the continuum.

3. The X-ray state

The RXTE All-Sky Monitor (ASM) has been continuously observing bright X-ray sources in the ~ 2 to 10 keV range since 1996 February 20. The X-ray observations (one-day averages) of GX339-4 presented herein are extracted from the “quick-look results” public archive provided on the World Wide Web by the ASM/RXTE team (Fig. 3). During the time of our VLT observations, GX339-4 was not detected by the ASM. SAX observations during March 2000 revealed the source to be 3 times fainter than in August 1999 (E. Kuulkers, private communication).

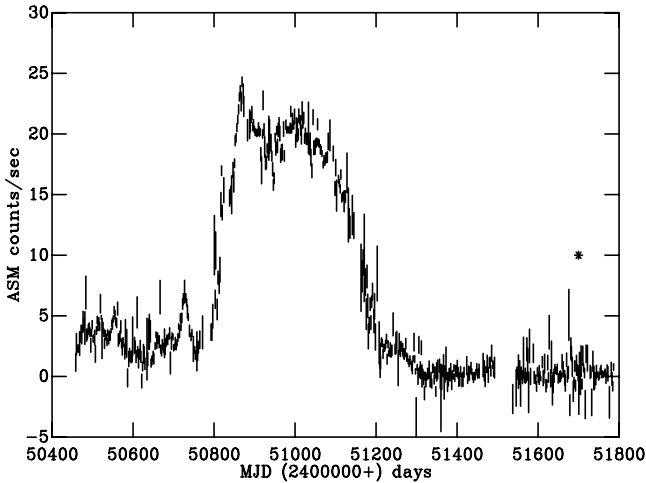


Fig. 3. RXTE ASM soft X-ray (2–10 keV) light curve of GX339-4 spanning the period 1 January 1997–1 September 2000 (1 Crab \simeq 75 cts/s). The star marks the time of our VLT spectroscopic observations.

Table 2. Emission line equivalent widths for GX339-4.

Line	EW (Å)
HeI λ 7065	-5.2 ± 0.2
HeI λ 6678	-4.8 ± 0.2
H α λ 6563	-55.9 ± 0.2

4. The emission lines

The H α , HeI λ 5876, HeI λ 6678, HeI λ 7065 emission lines are clearly visible in the weighted-average spectrum of GX339-4. The H α line is asymmetric, with its peak skewed towards the red with a round top (see Figs. 4 and 5). It is difficult to say convincingly whether the profile is double-peaked, given the low resolution of the data. However, if we assume that it is, then a double Gaussian fit gives a peak-to-peak separation of 448 ± 10 km s $^{-1}$ ($\simeq 9.8$ Å) which is consistent with the values of 7.4 Å and 8.0 Å obtained by Soria et al. (1999) and Smith et al. (1999) respectively when GX339-4 was in an “active” state. The observed H α equivalent width of ~ 56 Å (see Table 2) is a factor of ~ 8 larger than when the source is in its high state, and is similar to that observed in the soft X-ray transients when they are in their quiescent state (40–60 Å). The HeI λ 5876 line appears to be double-peaked, although it is contaminated by the NaI interstellar absorption doublet (see Fig. 5). Fitting a double-Gaussian to the HeI line gives a peak-to-peak separation of ~ 600 km s $^{-1}$, similar to that observed in the HeII λ 4686 emission line when GX339-4 is in its low-hard state (Wu et al. 2001).

Wu et al. (2001) have recently suggested that the H α profiles are different in the high-soft and low-hard states; the high-soft state being characterized by a double-peaked profile which arises from the irradiated accretion disc,

whereas in the low-hard state the single-peaked profiles arise from an outflow. However, it should be noted that if there is a bright spot in GX339-4 then H α emission from this would fill-in the double-peaked profile arising from the accretion disc, resulting in a single-peaked profile. A bright spot is a common feature in most of the X-ray transients (e.g. A0620-00; Marsh et al. 1994). Phase-resolved high spectral resolution data will be necessary to investigate this further.

5. Upper limit to the secondary star contribution

The average density of a star that fills its Roche lobe is determined solely by its orbital period. Assuming that the orbital period of GX339-4 is 14.83 hr (Callanan et al. 1992) and that the secondary star does fill its Roche lobe, then the mean density of the star is $\rho = 0.5$ g cm $^{-3}$. A K1 main sequence star would have $\rho = 1.9$ g cm $^{-3}$, implying that the radius of the secondary must be a factor of 1.6 greater than that of a main sequence star in order for it to fill its Roche lobe. It is therefore most likely to be evolved, similar to the secondary star in Cen X-4 (Shahbaz et al. 1993).

The GX339-4 spectrum does not show any signs of obvious absorption features from the secondary star (see Fig. 4). However, it is still possible to determine an *upper* limit to the contribution of such a star (Dhillon et al. 2000). This is done by subtracting a constant times the normalized template spectrum from the normalized GX339-4 spectrum, until spectral absorption features from the template star appear in emission in the GX339-4 spectrum. The value of the constant f at this point represents an upper limit to the fractional contribution of the secondary star. The contribution also depends on the spectral type of the template used. As the spectral type of the secondary star in GX339-4 is unknown, we used stars in the range K1III–K7III and find upper limits to the secondary star contribution to lie in the range 20–30%. It should be noted that giant stars have weaker metallic absorption lines (near H α) compared to sub-giant stars. This implies that our estimates for the secondary star’s contribution are upper limits.

6. Lower limit for the distance

We can place a lower limit to the distance of GX339-4, by comparing our observed upper limit for the secondary star’s magnitude with that expected for a Roche-lobe filling secondary star in orbit around a black hole. Using the observed magnitude of $r = 20.1$ (the H α emission line contribution to the observed flux is negligible and so all the light is assumed to arise from the secondary star) and our upper limit for the secondary star’s contribution to the observed light, $f < 30\%$, we find that the secondary star must have a r -band magnitude fainter than 20.4. Using the ellipsoidal model described in Shahbaz et al. (1993) we determine a lower limit to the magnitude of the secondary star and the distance to the source. Although there

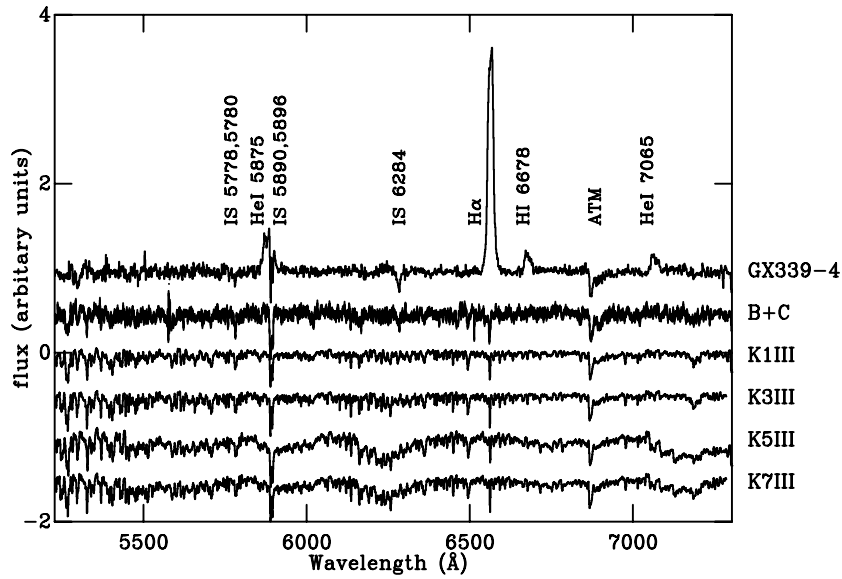


Fig. 4. From top to bottom: Variance-weighted average spectrum of GX339-4, the blend of stars B+C; K1III, K3III, K5III and K7III template stars. The spectra have been normalized and shifted vertically for clarity. IS and ATM indicate interstellar and atmospheric features respectively.

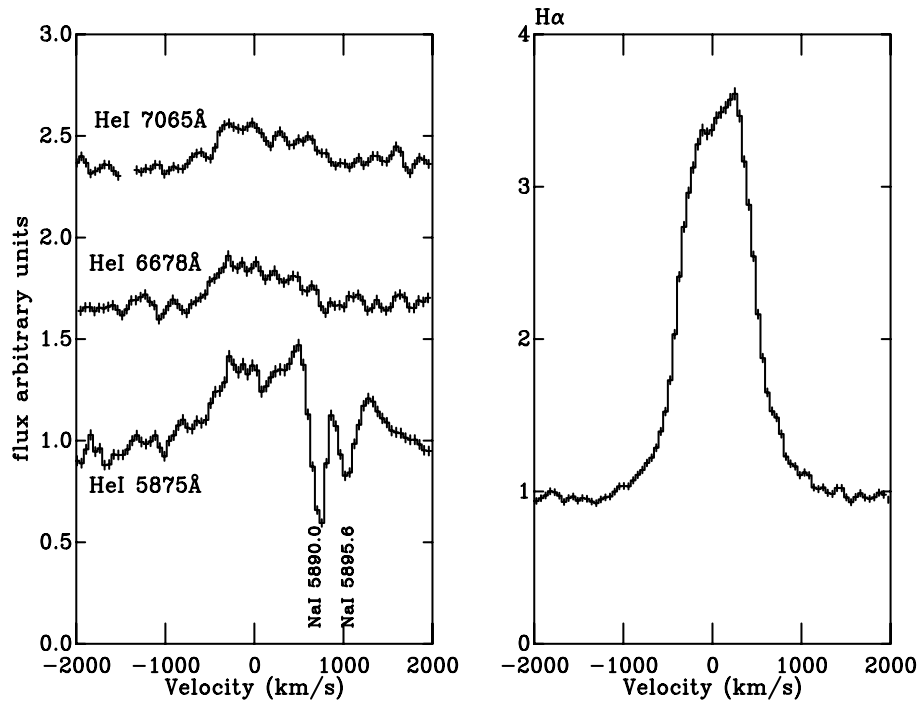


Fig. 5. Left: Close-up of the HeI 5876 Å + NaI interstellar absorption doublet, 6678 Å and 7065 Å emission lines. The spectra have been normalized and offset for clarity. The HeI 5876 Å line is clearly double-peaked. Right: A close-up of the H α emission line. The profile has a round top profile. The low resolution of the data makes it difficult to say whether the profile is single- or double-peaked.

were no X-ray measurements during the time of Callanan’s optical observations, the X-ray luminosity of GX339-4 in its “off” state, within a few years of their observations was reported to be $\sim 2 \times 10^{35}$ erg s $^{-1}$ (Ilovaisky et al. 1986). If we assume that the X-ray luminosity of GX339-4 in its “off” state was similar, then the optical light

curve of a system with this X-ray luminosity would be dominated by X-ray heating and thus would appear single-humped and would be modulated on the orbital period. Hence, the interpretation of Callanan et al. (1992) that the modulation they observe is the orbital period would seem correct. If the orbital period is 14.8 hrs

(Callanan et al. 1992) and assuming a binary mass ratio of 10 (black hole mass/secondary star mass), a black hole of $10 M_{\odot}$ (median mass observed; Miller et al. 1998), an inclination of 15 degrees (Wu et al. 2001) and a mean secondary star temperature of 4300K [cf. the secondary star in Cen X-4 (Chevalier et al. 1989) which has a similar orbital period to GX339-4] and a colour excess of $E_{B-V} = 1.2$ (Zdziarski et al. 1998) we find a lower limit to the distance of 5.6 kpc. This value is consistent with crude distance estimates determined from the systemic velocity of GX339-4; 4 ± 1 kpc (Zdziarski 1998).

The lack of absorption line features in our GX339-4 spectrum is puzzling. One possibility, that cannot be ruled out is that the secondary star has a much earlier spectral type. We can use the average scale height of black hole X-ray binaries and the Galactic latitude to estimate the distance to GX339-4. Using a scale height of ~ 500 pc (White & van Paradijs 1996) and $b = -4.3$ degrees, the distance is ~ 7 kpc. At this distance, and given our observed magnitude, the secondary star would require a spectral type later than F8 (i.e. < 6200 K). Note that the optical spectrum of such a star near $H\alpha$ would appear featureless, i.e. one would not expect to see strong absorption lines.

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