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Asymmetric $H\alpha$ disk emission dominates the HST/FOS spectrum of Circinus X-1*

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Abstract. CircinusX-1 is an highly variable X/radio binary source showing regular flux modulations with a periodicity of $\sim$ 16.6 days, probably coincident with the orbital period of the binary system. Here we present HST/FOS spectra of the optical counterpart taken around the predicted X-ray maximum. Strong $H\alpha$ in emission, itself accounting for almost 50 % of the optical flux between 5000 and 6800 Å, is visible. The $H\alpha$ profile, entirely ascribable to the accretion disk, is characterized by a remarkable asymmetry, pointing to the presence of at least two different components, i.e. a broad one at rest plus a narrower redshifted ($v \sim 400\ km/s$) one.
No other emission/absorption line is clearly visible superimposed on the source continuum, thus making troublesome any tentative spectral classification of the companion star. Furthermore, the noisy background together with a substantial, although uncertain, interstellar reddening, makes it difficult to fit reliably any continuum spectrum at the source.

Key words: stars: Cir X-1 – X-rays: binaries – accretion

1. Introduction

Circinus X-1 is one of the most interesting X-ray binary sources, one of the very few showing radio emission. It has also been considered for a long time a good black hole candidate, owing to its wide range of variability and its transitions from different spectral states. It was first discovered in X rays in 1969 (Margon et al. 1971) and a few years later a possible radio counterpart was identified by Clark et al. (1975) in the X-ray error box at about 25 arcmin from the center of the nearby supernova remnant G321.9-0.3.

Periodic (P=16.6 d) modulations of the X ray flux were discovered by ARIEL V (Kaluzienski et al. 1976) and soon confirmed by COS-B X-ray data (Bignami et al., 1977). The association between Circinus X-1 and the radio source of Clark et al. (1975) was confirmed with the discovery of radio flares modulated with the same X-ray period, but occurring with a short, frequency-dependent, delay with respect to the X-ray ephemeris (Haynes et al. 1978). Radio measurements of the 21cm absorption have fixed the source distance to 8-10 kpc (Goss and Mebold, 1977). More recent radio observations of the Circinus X-1 region (Haynes et al., 1986 - Haynes, 1987) detected a radio nebula around the point source extending towards the center of the SNR G321.09 and also some smaller structures, possibly radio jets (Stewart et al., 1993).

The black hole hypothesis vanished when EXOSAT discovered type I bursts (Tennant,Fabian and Shafer, 1986a,b). X-ray emission features typical of Low Mass X-ray Binaries (LMXBs) were also observed such as high frequency (5-17 Hz) intensity-dependent and low frequency (1.4 Hz) QPO (Tennant, 1987,1988) with a complex dependance on the source spectral shape (Oosterbroek et al., 1995). Recently the X ray emission of Circinus X-1 has been observed by ROSAT (Predhel and Schmitt, 1995) and ASCA (Brandt et al., 1996). Fits to the spectral data of both instruments converge towards an interstellar absorption of $\sim$ 2 10^{22} cm^{-2} corresponding to $A_V \sim 11$, a value used in the past (see e.g. Bradt and McClintock, 1983) and later discarded in favour of a lower one ($A_V \sim 4$; Stewart, 1991) which appears now incompatible with the analysis of the ROSAT as well as ASCA data.

The first optical observations of Circinus X-1 identified a possible counterpart in star L of Whelan et al. (1977), very bright in R, due to the strong interstellar absorption in the galactic plane, and characterized by a prominent $H\alpha$ emission variable during the X/radio cycle (Nicolson, Feast and Glass, 1980). The identification of Circinus X-1 with star L was disputed by new optical observations (Argue et al., 1984) which showed the elongated shape of star L, with its southern brighter exten-

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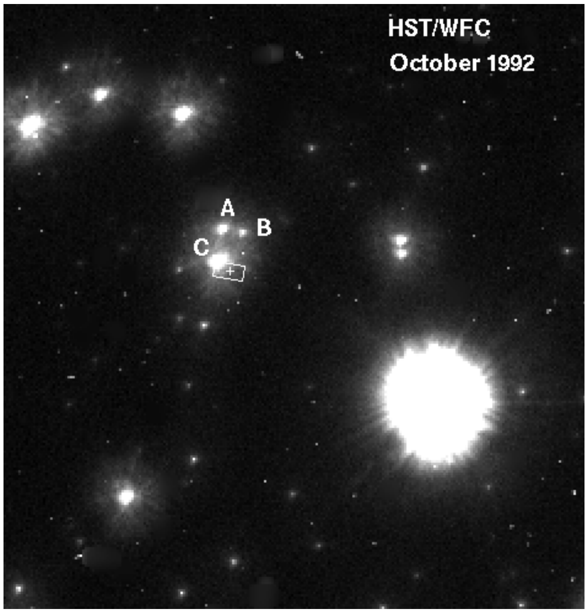

Fig. 1. 20×20 arcsec "early acquisition" image of the field of Circinus X-1 taken through the F785LP "I" filter of the WFC and 5 min exposure time. The angular resolution is 0.1 arcsec/pixel. The box marks the error on the VLBI radio position of Circinus X-1 taken from Argue et al. (1984). North is at top, East is at left. (The frame il tilted 13° westward).

sion coincident with the new VLBI position of the radio source (Argue et el., 1984).

The situation was clarified by NTT/EFOSC2 observations (Moneti, 1992), done under sub arcsec seeing conditions. The structure of star L was resolved into three objects the southernmost of which was quite faint in V ($m_V > 21$), but brighter at longer wavelengths owing to the strong interstellar reddening ($m_R \sim 19.5$; $m_I \sim 18.6$; $m_K \sim 11$.). The optical counterpart was variable in V and R ($\Delta m \sim 0.5$), somehow correlated with the 16.6 days cycle of the X-ray source (Moneti, 1992). No modulation was observed in I. Variability in phase with the X ray period was also reported by Glass (1994) in the near IR (J,H,K), after folding data collected during twelve years.

The system is supposed to be a LMXB from its X-ray behaviour (bursts, QPOs). If the orbital period of Circinus X-1 were 16.6 d, it would be the longer ever measured for a LMXB. Thus, it would suggest that the companion be a cool, late-type, Red Giant. However no reliable classification of the optical counterpart is available so far. Indeed, ground based spectroscopy would require unrealistic seeing conditions in order to resolve the emission from star C. Ground based spectra have been taken by Duncan, Stewart and Haynes (1993), but the results were not conclusive.

2. The observations

Here we report the spectroscopy of the Circinus X-1 optical counterpart performed with the HST *Faint Object Spectrograph (FOS)* during Cycle 4. Fig. 1 shows an early acquisition image of the field taken on october 20^{th} 1992 with the *Wide Field camera (WFC)*. The exposure (5 min.) was obtained through the F785LP filter (λ = 8894.55Å; $\Delta\lambda$ = 1571Å) roughly correspondent to the Johnson I filter where ground based observations (Moneti, 1992) have shown the source to be brighter. Albeit taken with the PRE-COSTAR *Optical Telescope Assembly*, the image appears to be the best picture of the region available so far. Owing to the angular resolution of the HST/WFC (0.1 arcsec/pixel), the three stars of Moneti (identified as A,B and C in Fig. 1) are clearly resolved in a 1.5 arcsec diameter region.

The southernmost member of the triplet (star C, α_{2000} = $15^h 20^m 40^s.844 \pm 0^s.011$; δ_{2000} = $-57^o 9' 59".99 \pm 0".25$) is coincident, within the astrometry error budget, with the radio position of Circinus X-1. The computed magnitude of star C in the F785LP filter is 18 ± 0.1, in agreement with the values measured by Moneti (1992) after correcting for the difference between the HST magnitudes and the standard Johnson one (Harris et al. 1991).

FOS observations of star C were performed on June 1995 after the refurbishment mission. Two spectra of 43 min each were taken, around the predicted radio/X-ray maximum computed according to the ephemeris of Stewart et al. (1991). In order to minimize any possible light contamination from stars A and B, the target has been centered in a round aperture of 0.5 arcsec diameter. The centering of the target was achieved using the position of a nearby star as reference. The *FOS* Red Digicon detector was selected since it gives the highest throughput in the Red where the source is brighter. The G570H grating was used, covering the wavelength range $4569 - 6818$Å, providing a spectral resolution of 1.1 Å$/pixel$. An average of the two resulting spectra is shown in Fig.2 after background subtraction, wavelength and flux calibration. Due to the strong interstellar extinction, the spectrum is heavily absorbed for $\lambda \leq$ 5000Å, with most of the flux appearing at longer wavelengths. Strong $H\alpha$ in emission is observed, in itself accounting for about 50 % of the integrated flux, dominating a noisy and ill defined continuum. No other emission/absorption feature is clearly visible. The low signal-to-noise of the continuum prevents the detection of interstellar absorption features.

The lack of features other than $H\alpha$ renders troublesome any tentative spectral classification of the companion. We have tried to assess the source temperature by fitting different black body curves to the continuum. However, the substantial interstellar reddening, coupled with the very low S/N of our spectra, make the task very difficult. The continuum temperature ranges from a lower limit of 2400 K, obtained with A_V = 4 to $\sim$ 20000 K, obtained with A_V = 6, i.e. spanning from a late type star to a heated accretion disk.

A zoom of a FOS spectrum is shown in Fig.3, centered on the $H\alpha$ wavelength. The $H\alpha$ profile exhibits a remarkable asymmetry. Following a hint for a two-component $H\alpha$ profile observed by Nicolson, Feast and Glass (1980) in the unresolved star triplet, we investigate an explanation of the asymmetry as due to the presence of two components. A double-gaussian model was fitted to the FOS spectrum. The first is a broad feature (σ = 11.4Å) centered at the $H\alpha$ rest wavelength

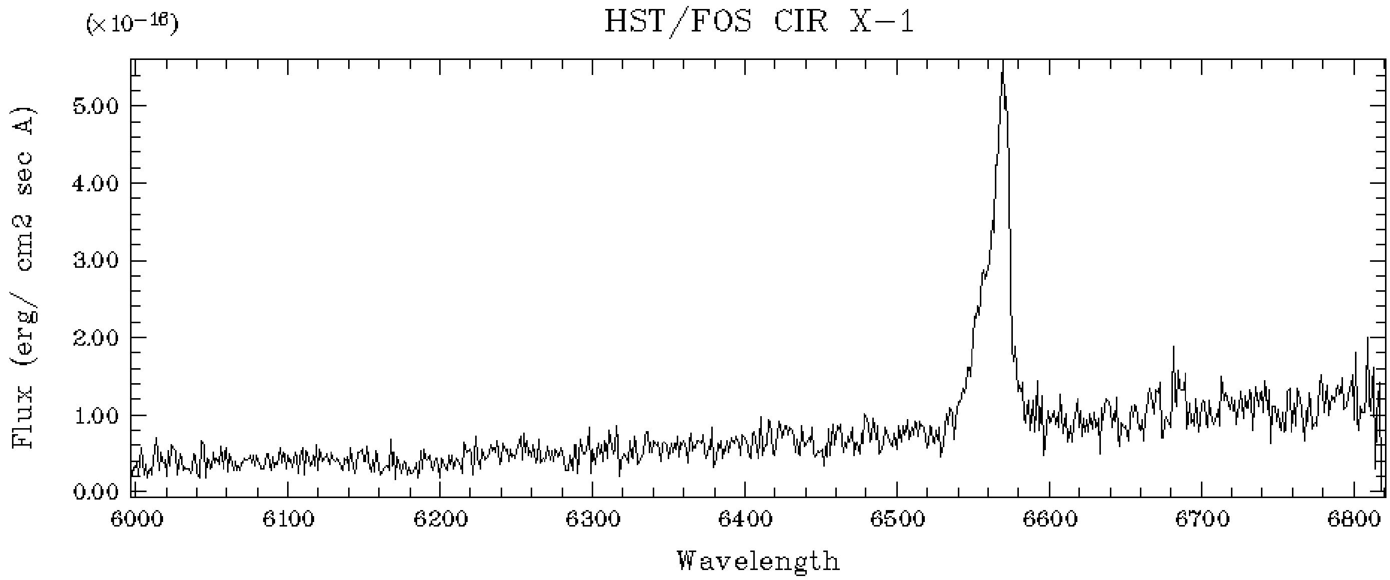

Fig. 2. Average spectrum (43 min) of the optical counterpart of Circinus X-1 taken with the HST/FOS mounting the grating G570H. The spectral resolution is 1.1 Å.

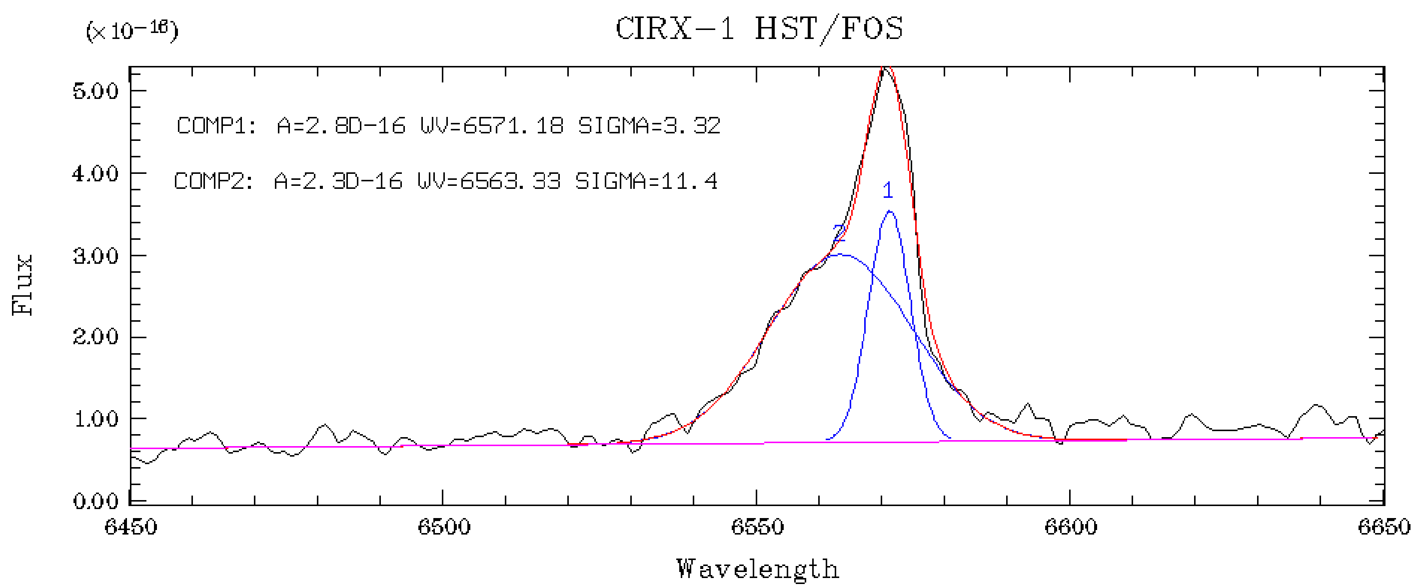

Fig. 3. Zoom of Fig. 2 showing the double profile of the H_α line. The two gaussians fitting the line profile are also shown as well as their corresponding amplitudes, wavelengths and FWHM.

(λ = 6563.3Å). The second is a narrower (σ = 3.32Å) redshifted component (λ = 6571.2Å). The flux integrated along the line profile is roughly equal for the two components. As apparent, this yields a good fit to the data.

3. Discussion

The nature of the $H\alpha$ profile is a challenging problem. Up to now, $H\alpha$ emission has been observed only in a few other LMXBs i.e. X1735-444, GS2023+338, Cyg X-2, 4U1822-371 and LMCX-2 (see Van Paradijs, 1995 for a complete review). In all of these cases, however, when a double structure was present, it was due to the superposition of two narrow red/blueshifted components. In the case of Circinus X-1 we indeed seem to observe a strong redshifted component. After radial velocity corrections we deduce that the line must originate in matter moving with a rotational velocity of $\sim$ 400$km\ s^{-1}$. This is a value typical for accretion disks around neutron stars. However, the blue component is not present as would be expected if the $H\alpha$ originates uniformly in a fully visible accretion disk. This could be explained assuming that the observed line arises from a small region of a highly inclined accretion disk, e.g. a hot spot at the location where the accretion flow from the companion impacts on the disk itself. If this is the case, we would expect to observe only the red/blueshifted component of the feature, depending on the orbital phase.

On the other hand, recent ASCA data (Brandt et al., 1996) suggest the presence of substantial covering of the source by cold material. A phase-dependent shadowing could explain equally well the lack of a blue shifted component. Disk tilting and/or partial covering do not affect the component at rest, which arises naturally in the accretion disk. Its observed broadening would point to temperatures of the order of $\sim 20,000\ K$, typical of X-ray heated accretion disks of LMXBs. While this temperature is considerably higher than that obtained from the continuum fit for $A_V = 4$, it is certainly compatible with the results obtained for higher absorption, actually more probable.

Since no evidence of a stellar spectrum is seen, our data could be totally ascribed to the accretion disk. The nature of the companion thus remains an open point.

If Circinus X-1 is really a LMXB, we expect from its orbital period (16.6. d) that the companion could be a Red Giant of spectral type gK0 (Webbink, Rappaport and Savonije, 1983). With strong interstellar absorption and in the presence of an active disk, its spectrum could go totally undetected.

4. Conclusions

Our HST/FOS observations provide the best spectrum of the optical counterpart of Circinus X-1 available so far. Strong H_α in emission is observed, clearly dominating a featureless continuum. The observed asymmetry in the H_α structure can be explained as the superposition of two single components i.e. a broad one at rest plus a narrower redshifted one. This can be enterely due to an X-ray heated accretion disk which should be either tilted or partially occulted to explain the lack of the blueshifted component. The broadening of the H_α component at rest points towards a disk temperature of $\sim 20,000\ K$, which is in agreement with the continuum temperature obtained for $A_V \geq 6$, making the accretion disk responsible for all of the optical emission from Circinus X-1. Observations of comparable quality taken at different orbital phases appears the next step to apply a Doppler tomoghraphy technique (Marsh and Horne, 1988) to this enigmatic source.

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