Dynamical constraints on the neutron star mass in EXO 0748-676

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ABSTRACT

We present VLT intermediate resolution spectroscopy of UY Vol, the optical counterpart of the LMXB X-ray burster EXO 0748-676. By using Doppler tomography we detect narrow emission lines which have provided an excellent determination of the orbital period (P = 3.82 h) and the orbital inclination (i = 75° - 82°). On the other hand, Villarreal & Strohmayer (2004) have measured a burst oscillation at 45 Hz during type I X-ray burst events, which is associated with the neutron star (NS) spin frequency. Recently, Özel (2006) have suggested the presence of a massive NS with M\textsubscript{NS} \geq 1 M\textsubscript{⊙} and M\textsubscript{1} \leq 2.4 M\textsubscript{⊙} and 0.11 \leq q \leq 0.28. We find M\textsubscript{1} \geq 1.5 M\textsubscript{⊙} for the case of a main sequence companion star. Our results are consistent with the presence of a massive neutron star as has been suggested by Özel (2006), although we cannot discard the canonical value of \sim 1.4 M\textsubscript{⊙}.

Key words: accretion disks - binaries: close - stars: individual: EXO 0748-676 - X-rays: stars

1 INTRODUCTION

EXO 0748-676 (=UY Vol) is a Low Mass X-ray Binary (LMXB) discovered as a transient source by EXOSAT in 1985 (Parmar et al. 1985). Instead of returning to the quiescent state the system had remained in an active state ever since, showing typical properties of persistent LMXBs. However, it has returned to the off-state very recently (Hynes & Jones 2008).

EXO 0748-676 also exhibits irregular X-ray dips and periodic eclipses which have provided an excellent determination of the orbital period (P = 3.82 h) and the orbital inclination (i = 75° - 82°). Parmar et al. (1986). On the other hand, Villarreal & Strohmayer (2004) have detected a burst oscillation at 45 Hz during type I X-ray burst events which is associated with the neutron star (NS) spin frequency. Recently, Özel (2006) have suggested the presence of a massive NS with M\textsubscript{1} = 2.10 ± 0.28 M\textsubscript{⊙} and R\textsubscript{1} = 13.8 ± 1.8 km in EXO 0748-676. This result is based on the gravitational redshift measured in O and Fe absorption lines arising from the surface of the NS (Cottam et al. 2002) and the assumption that the strong thermonuclear X-ray bursts displayed by the system (Gottwald et al. 1986) can be modelled by a phase of symmetric expansion of the NS radius and a cooling phase where the X-ray emission is Eddington-limited. In contrast, Pearson et al. (2004) have reported He \textsubscript{II} \lambda 4686 Doppler tomograms which show a spot consistent with the expected gas stream position. These authors favor a NS of 1.35 M\textsubscript{⊙} by fitting different gas stream trajectories to the position of the spot.

In this paper we present VLT-FORS1 spectroscopy of the \sim 17 optical counterpart (UY Vol) of EXO 0748-676 which reveals the presence of narrow emission components within the He \textsubscript{II} emission lines. In recent years, narrow emission lines from the donor have been detected in several LMXBs (see Cornelisse et al. 2008 for details, also Casares 2009) since they were first discovered by Steeghs & Casares (2002) in Sco X-1. The Roche lobe filling donor star intercepts the energetic photons from the inner accretion disc resulting in the observed optical emission lines from its surface. The Doppler motion of these lines traces the orbit of the companion star, thereby providing the first constraints on the binary parameters for persistent systems where the photospheric light from the companion is otherwise swamped by the bright accretion disc. It is remarkable that this technique has proved the presence of a black hole with a mass \geq 6 M\textsubscript{⊙} in GX339-4 (Hynes et al. 2003, Muñoz-Darias et al. 2008), presented evidence for a massive NS in Aql X-1 (Cornelisse et al. 2007) and X1822-371 (Casares et al. 2003, Muñoz-Darias et al. 2005), and provided the first constraints on the binary parameters in six other LMXBs, including the prototypical system Sco X-1 (Steeghs & Casares 2002). In this letter we present the first dynamical constraints on the stellar masses in EXO.

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Figure 1. Average spectrum of EXO 0748-676 after combining 21 exposures obtained with good seeing conditions (≤ 0.6 arc-sec) and out of eclipse. The most prominent lines are indicated for clarity.

0748-676 based on the study of the narrow components present within the He II λ4541, 4686 and 5412 emission profiles. In section 2 we describe the observations and data reduction process, whereas the data analysis is presented in section 3. Results are discussed in sections 4 and 5.

2 OBSERVATIONS AND DATA REDUCTION

We observed EXO 0748-676 on 22 Jan 2008 using the Focal Reducer and low dispersion Spectrograph-1 (FORS1) attached to the VLT-UT2 (Kueyen) telescope at the Observatorio Astronómico Cerro Paranal (Chile). We used the GRIS_1200g holographic grating obtaining a total of 28 spectra of 600s each. The slit width was fixed at 0.51-arsec resulting in a spectral resolution of ∼ 90 km s⁻¹ and a wavelength coverage of λλ 4185 − 5600 Å. The seeing stayed between 0.4-0.6-arsec during the first 4 hours but it increased up to 1-arsec during the last hour of the run, making slit losses significant and absolute flux calibration unreliable for this part of the night. In total we covered ∼ 1.3 binary orbits (i.e. ∼ 5 h of data). The images were de-biased and flat-fielded and the spectra extracted using conventional IRAF routines. The wavelength calibration was performed by fitting a fourth-order polynomial to an arc image taken during daytime. This resulted in a dispersion of 0.73 Å pix⁻¹ and rms scatter ≤ 0.04 Å. We used the sky spectra to correct for velocity drifts due to instrumental flexure which were found to be ≤ 10 km s⁻¹ (i.e. ≤ 0.25 pix). The zero point of the wavelength scale was established from the position of the strong OI λ5577.338 sky-line. The spectra were finally flux calibrated using observations of the flux standard LTT 1788 and exported into our analysis software (MOLLY).

3 DATA ANALYSIS

Fig. 1 shows the average spectrum of EXO 0748-676. In order to produce this figure we used the 21 out-of-eclipse spectra taken with good seeing conditions, comparable to the slit-width. The Hγ and Hβ double peak emission lines together with the strong He II λ4542, λ4686, λ5412 features and the Bowen blend at λλ 4630 – 50 are clearly seen in the spectrum. He I λ4922, λ5016, and Fe II λ5284 are also detected, although they are less prominent.

In this paper we will focus on the analysis of the He II emission lines where narrow components are found. In order to compute the orbital phase of each spectrum we used the constant-period ephemeris given by Wolff et al. (2002). The zero-phase has been refined by fitting the mid-eclipse time of an eclipse observed by RXTE on 30 Jan 2008 (i.e. only 8 days after our observations). We find an error of ∼ 0.012 in orbital phase which has been corrected in the ephemeris. We finally adopted:

\[ T_0(HJD) = 2446111.57285(3) + 0.1593378191(1) \times N \]

3.1 Systemic velocity

As in our previous work, we decided to apply the double gaussian technique (Schneider & Young 1980) to the wings of the He II λ4686 emission line in order to obtain a first estimate of the orbital parameters of the NS. We have used relative Gaussian separations between a = 800 – 2000 km s⁻¹ in steps of 25 km s⁻¹.
This range has been chosen to avoid low velocity components associated with the companion star and the outer disc. After fitting the expression

\[ V(\phi) = \gamma + K_1 \sin 2\pi(\phi - \phi_0) \]  

(1)

to the radial velocity curves extracted for each value of \( a \), we obtain the diagnostic diagram presented in Fig. 2. We adopt the value of \( a \sim 1700 \text{ km s}^{-1} \) where the phase is correct and also happen to occur near the plateau in the diagnostic parameter \( \sigma(K_1)/K_1 \) (Shafter et al. 1986). This results in \( \gamma = 30 \pm 10 \text{ km s}^{-1} \) and \( K_1 = 100 \pm 20 \text{ km s}^{-1} \).

This method assumes that the emission line gas orbits the compact object and correctly traces its orbital dynamics. Non-isotropic emission and/or significant disk asymmetries are known to lead to significant distortions in the radial velocity curves and thus the inferred \( K_1 \). For this reason the values provided by the diagnostic diagram should be taken as a rough approximation to the real ones, as will be discussed in the next section.

3.2 Doppler mapping

Extracting radial velocities of faint short-period systems is not straightforward. The situation is even more difficult when dealing with narrow spectral lines which require high spectral resolution. The spectral resolution also degrades with exposure time due to orbital smearing, whereas the signal-to-noise ratio (S/N) obviously increases for longer integrations. Therefore, in order to avoid significant orbital smearing one has to use short exposures (600 s in our case) which results in data sets with good orbital sampling but poor S/N.

Using Doppler tomography (Marsh & Horne 1988) instead of standard radial velocity curves has the benefit of using all the spectra at the same time, allowing one to map the brightness distribution of a weak emission line in velocity space. This method has been used in almost all previous studies of narrow emission lines (see e.g. Casares et al. 2006), and only for Sco X-1 (with \( V \sim 12 \) and \( P=18.9 \text{ h} \)) has the application of both techniques separately (i.e. radial velocity curves and Doppler mapping) been possible. In that case a good agreement between the two methods was found (Steeghs & Casares 2002).

Fig. 3 shows the evolution of the He II \( \lambda 4542 \), \( \lambda 4686 \) and \( \lambda 5412 \) spectral lines along the orbit. An S-wave with a maximum radial velocity of \( \sim 500 \text{ km s}^{-1} \) at orbital phase \( \sim 0.5 \) appears in the 3 maps. This translates into bright spots at \( V(V_X, V_Y)=(-300,200) \text{ km s}^{-1} \) in the Doppler maps of the three He II lines (Fig. 4). Similar spots were also found by Pearson et al. (2006) in several emission lines (e.g He II \( \lambda 4686 \)). However, in this study we also detect in the three maps compact spots at the position of the donor (i.e. \( V_X = 0 \text{ km s}^{-1} \)). The velocities associated with these spots are in the range \( V_Y = 270-339 \text{ km s}^{-1} \) and are shown in table 1.

We have computed Doppler maps for a wide range of \( \gamma \) values bracketing \( \gamma = 30 \text{ km s}^{-1} \), the value favored by the diagnostic diagram. We swept between \( \gamma = -50 \) and \( 100 \text{ km s}^{-1} \) in steps of \( 10 \text{ km s}^{-1} \). The effect of using a wrong value of \( \gamma \) when computing the maps is to obtain out-of-focus spots, which become compact when approaching the correct value. By fitting 2D Gaussians to the spots as a function of \( \gamma \), we favor systemic velocities in the range \( 20 \leq \gamma \leq 80 \text{ km s}^{-1} \). We finally selected \( \gamma = 70 \text{ km s}^{-1} \) because it produces significantly more compact spots in the three maps. In any case, the velocity measurements (table 1) derived with \( \gamma = 70 \text{ km s}^{-1} \) are consistent within the errors with those obtained with \( \gamma = 30 \text{ km s}^{-1} \).

The \( K_{\text{em}} \) velocity of a given irradiation line depends on the disc thickness and how transparent it is for the irradiating photons. The three He II lines that we study here have similar ionization potentials and, hence, one should expect them to show the same \( K_{\text{em}} \) value. This is consistent within the error bars with the results that we have obtained. Therefore, we decided to take the weighted mean value of the three lines as our best estimate of \( K_{\text{em}} \), which results in \( K_{\text{em}} = 310 \pm 10 \text{ km s}^{-1} \). Hence, we will use \( K_{\text{em}} = 300 \text{ km s}^{-1} \) as 1-sigma lower limit to \( K_2 \).

4 REPROCESSED EMISSION FROM THE COMPANION

Using our \( K_{\text{em}} \) value derived from the He II lines and the refined orbital ephemeris it is possible to remove the orbital velocity from each spectrum and compute the average spectrum in the rest frame of the companion. Fig. 5 shows this spectrum, where narrow components standing out in the broad He II \( \lambda 4542 \), \( \lambda 4686 \) and \( \lambda 4542 \) emission lines are clearly seen. As an independent test to the Doppler analysis, we have computed the spectrum in the rest frame of the donor sweeping a wide range of \( K_{\text{em}} \) values. We find...
5 SYSTEM PARAMETERS

EXO 0748-676 offers important advantages with respect to other persistent LMXBs. The binary inclination is a known function of the mass ratio owing to the X-ray eclipses (Hynes et al. 2006). For instance, \( i = 82^\circ \) yields \( q = 0.12 \), whereas \( i = 75^\circ \) implies \( q = 0.4 \). Moreover, since X-ray eclipses and X-ray bursts from the NS surface are observed, the NS must be visible, and hence the disc opening angle \( \alpha \), which obscures part of the irradiated face of the donor, is also related to the inclination through \( \alpha \lesssim 90^\circ - i \). Therefore for a given \( q \), the inclination angle and an upper limit to \( \alpha \) are set. This is very useful in order to compute the K-correction. Emission lines formed on the inner hemisphere of the donor star as a result of X-ray reprocessing only provide a lower limit \( (K_{em}) \) to the true \( K_\text{II} \)-velocity. In Muñoz-Darias et al. (2005) we model the deviation between the light-center of the reprocessed lines and the center of mass of a Roche lobe filling star in a persistent LMXB, including screening effects by a flared accretion disc (i.e., the K-correction). We find that this correction depends on \( q \), \( \alpha \) and weakly on the orbital inclination. We now apply the K-correction to EXO 0748-676 as a function of \( q \), including the above limits on \( q \) and \( i \).

5.1 The mass of the neutron star

Fig. 6 shows the lower limit to the NS mass as a function of \( q \) obtained from \( K_{em} = 300 \text{ km s}^{-1} \) (lower solid line). Assuming that, for a range of \( K_{em} \) values around \( \sim 310 \pm 10 \text{ km s}^{-1} \), the narrow components show the highest intensities together with narrow widths consistent with the spectral resolution of \( \sim 90 \text{ km s}^{-1} \). Taking into account the position of the spots in the Doppler maps (i.e. orbital phase and velocity), the narrowness of the components and the presence of similar high excitation features in all the persistent LMXBs that we have studied (see Cornelisse et al. 2008) we associate these features with X-ray reprocessing from the irradiated hemisphere of the donor.

It is also noteworthy that we have a tentative detection of the N\textsc{iii} and C\textsc{iii} components within the Bowen blend in the rest frame of the companion star (left panel in Fig. 5). The weakness of these lines is probably due to the reduced number of spectra. We only cover one orbit and at least two orbits of data are usually required to clearly detect these transitions (e.g. see Casares et al. 2006). However, the He\textsc{ii} emission lines are very strong in this system compared to previous studies and show narrow components that provide us with the opportunity to measure \( K_{em} \). It is especially interesting to note that EXO 0748-676 is the only system in the Bowen survey where He\textsc{ii} \( \lambda 4542 \) is as strong as the Bowen blend. He\textsc{ii} \( \lambda 4686 \) emission from the donor was also reported by Steeghs & Casares (2002) in Sco X-1, with a \( K_{em} \) value similar to that obtained from the Bowen lines. However, in other bright systems where high signal-to-noise studies have been performed (e.g. X1822-371; Casares et al. 2003) no He\textsc{ii} emission from the donor was found.

5.2 The nature of the donor star

The parameter constraint for EXO 0748-676 are consistent with a main sequence donor (favored by the diagnostic diagram) we obtain \( q \lesssim 0.35 \), in agreement with Hynes et al. (2006). On the other hand, if we use the maximum K-correction (\( \alpha = 0^\circ \)) and the upper limit \( K_{em} = 320 \text{ km s}^{-1} \) we obtain an upper limit to the NS mass (upper solid line in Fig. 6). Meyer & Meyer-Hofmeister (1982) suggest that, even in the absence of irradiation, accretion discs in LMXBs have \( \alpha > 6^\circ \) which is also consistent with the results by D’Avanzo et al. (2006) for Cen X-4 in quiescence. Applying the the K-correction with \( \alpha > 6^\circ \) and \( K_{em} = 320 \text{ km s}^{-1} \) we obtain a less conservative upper limit represented by the dotted-dashed line in Fig. 6.

Pearson et al. (2006) favored \( q = 0.34 \) y \( M_1 \approx 1.35 M_\odot \) by fitting gas stream trajectories to the extended spot observed in the He\textsc{ii} Doppler map. This pair of values, which is marked by the dotted line in Fig. 6, is not consistent with our results. Conversely, our results are consistent with those derived by Özel (2006), which are represented by the grey region in Fig. 6. Nevertheless, our values are also consistent with the presence of a canonical NS with \( \sim 1.4 M_\odot \) in EXO 0748-676. However, for this case to work we need \( q \lesssim 0.24 \).

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
\( \lambda 4542 \) & He\textsc{ii} \( \lambda 4686 \) & He\textsc{ii} \( \lambda 5412 \) \\
\hline
(28,300) \( \pm 18 \) & (7,325) \( \pm 14 \) & (–14,290) \( \pm 20 \) \\
\hline
\end{tabular}
\caption{\( K_{em} \) (\( V_{X1}, V_{Y} \)) measurements (\( \text{km s}^{-1} \)) in EXO 0748-676.}
\end{table}
Dynamical constraints on the neutron star mass in EXO 0748-676

6 CONCLUSIONS

We present the first dynamical determination of the NS mass in EXO 0748-676. Assuming that the narrow components detected within the He II λ4542, λ4686 and λ5412 emission lines arise from the irradiated hemisphere of the donor we measure \( K_{\text{em}} = 300 \pm 10 \, \text{km} \, \text{s}^{-1} \) which results in \( 1 \, M_{\odot} \leq M_1 \leq 2.4 \, M_{\odot} \) and \( 0.11 \leq q \leq 0.28 \). On the other hand, the mass of the donor star is constrained to \( 0.16 \, M_{\odot} \leq M_2 \leq 0.42 \, M_{\odot} \) through unstable mass-transfer/main sequence models. For the case of a main sequence donor we find \( M_1 \geq 1.5 \, M_{\odot} \).

Our results are consistent with the Ozel (2006) scenario and rule out other system parameters proposed by Pearson et al. (2006). However, our observations are also consistent with a canonical mass NS and more observations are required to further constrain the mass of the NS in EXO 0748-676. Recently, EXO 0748+676 has been reported to reach quiescence at \( R = 21.9 \) after \( \approx 22 \) years of activity (Hynes & Jones 2008). This provides an excellent opportunity to measure the orbit of the companion star and determine the mass of the NS.

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Figure 6. \( M_1 \) vs \( q \) obtained from \( K_{\text{em}} = 300 \pm 10 \, \text{km} \, \text{s}^{-1} \). The solid lines represent the lower and upper limits to the NS mass for \( \alpha_{\text{em}}, \alpha = 0 \) respectively, whereas the dotted-dashed line corresponds to the upper limit for \( \alpha > 6^\circ \) (Meyer & Meyer-Hofmeister 1982). The grey region shows the mass range determined by Özel (2006) and the solid circle with dotted lines the values favored by Pearson et al. (2006). The dashed lines are obtained assuming that the donor is either a \( M_2 \sim 0.42 \, M_{\odot} \) main sequence star or it is considerably evolved before the onset of mass transfer. The shadowed region indicates our constraints on \( q \) and \( M_1 \).