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Letter to the Editor

Phase-resolved spectroscopy of the accreting millisecond X-ray pulsar SAX J1808.4–3658 during the 2008 outburst*

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ABSTRACT

Aims. We obtained phase-resolved spectroscopy of the accreting millisecond X-ray pulsar SAX J1808.4-3658 during its outburst in 2008 to find a signature of the donor star, constrain its radial velocity semi-amplitude (K_2), and derive estimates for the pulsar mass.
Methods. Using Doppler images of the Bowen region, we find a significant ($\geq 8\sigma$) compact spot at a position where the donor star is expected. If this is a signature of the donor star, we measure $K_{em} = 248 \pm 20$ km s^{-1} (1σ confidence), which represents a strict lower limit to K_2. Also, the Doppler map of He II λ4686 shows the characteristic signature of the accretion disc, and there is a hint of enhanced emission that may be a result of tidal distortions in the accretion disc that are expected in very low mass-ratio interacting binaries.
Results. The lower limit on K_2 leads to a lower limit on the mass function of $f(M_1) \geq 0.10\ M_\odot$. Applying the maximum K-correction gives $228 < K_2 < 322$ km s^{-1} and a mass ratio of $0.051 < q < 0.072$.
Conclusions. Despite the limited S/N of the data, we were able to detect a signature of the donor star in SAX J1808.4−3658, although future observations during a new outburst are still needed to confirm this. If the derived K_{em} is correct, the largest uncertainty in determining of the mass of the neutron star in SAX J1808.4-3658 using dynamical studies lies with the poorly known inclination.

Key words. accretion, accretion disks – X-rays: binaries – stars: individual: SAX J1808.4−3658

1. Introduction

Low-mass X-ray binaries (LMXBs) are systems in which a compact object (a neutron star or a black hole) is accreting matter, via Roche lobe overflow, from a low-mass (<1 $M_\odot$) star. Some LMXBs exhibit sporadic outburst activity but for most of their time remain in a state of low-level activity (White et al. 1984); we refer to these systems as transients. In April 1998, a coherent 2.49 ms X-ray pulsation was discovered with the *Rossi X-ray Timing Explorer* (*RXTE*) satellite in the transient SAX J1808.4−3658 (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998). This was the first detection of an accreting millisecond X-ray pulsar (AMXP). Seven more of these systems have been discovered since then, all of which are transients with orbital periods in the range between 40 min and 4.3 h and spin frequencies from 1.7 to 5.4 ms. These findings directly confirmed evolutionary models that link the neutron stars of LMXBs to those of millisecond radio pulsars via the spinning up of the neutron star due to accretion during their LMXB phase (e.g. Wijnands 2006).

To date, six episodes of activity have been detected from SAX J1808.4−3658 with a 2–3 year recurrence cycle. During the 1998 outburst, a detailed analysis of the coherent timing behaviour showed that the neutron star was in a tight binary system with a 2.01 h orbital period (Chakrabarty & Morgan 1998; Hartman et al. 2008). The mass function derived from X-ray data ($4 \times 10^{-5}\ M_\odot$) and the requirement that the companion fills its Roche lobe led to the conclusion that it must be a rather low-mass star, possibly a brown dwarf (Chakrabarty & Morgan 1998; Bildsten & Chakrabarty 2001).

We present here optical spectroscopy of SAX J1808.4−3658 obtained during the 2008 outburst. One of the key issues in dynamical studies is to measure the radial velocity of the companion star (K_2) and use this value to constrain the optical mass function of the system. During quiescence, these goals can be achieved by tracing the absorption features originating in the photosphere of the companion star. However, the intrinsic faintness of the low-mass companion stars in AMXPs makes such an analysis very difficult. To overcome this problem, Steeghs & Casares (2002) have shown that during phases of high mass-accretion rates, Bowen-blend lines emitted by the irradiated face of the companion star can be used. A precise measurement of K_2

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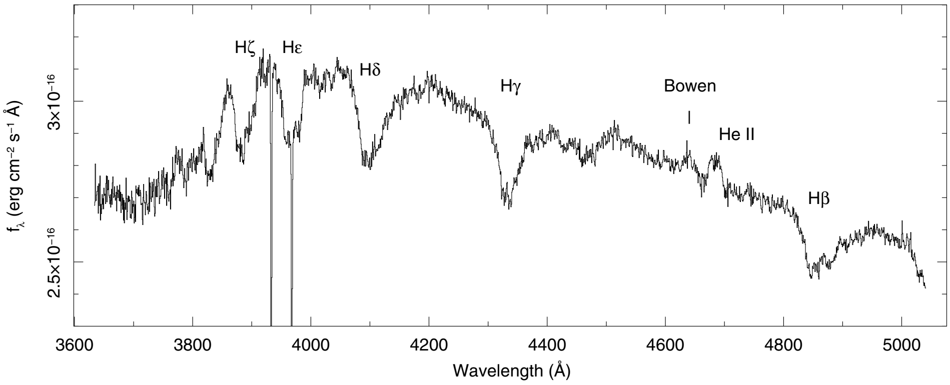

Fig. 1. Average flux-calibrated spectrum of SAX J1808.4−3658. We have labelled the most important features that are present. The strong absorption features around 3940 and 3980 Å are due to diffuse interstellar bands.

represents the only way to determine the optical mass function of the system and ultimately constrain the neutron star mass.

2. Observations and data reduction

Optical spectroscopic observations of SAX J1808.4−3658 were carried out on 27 September 2008 with the ESO Very Large Telescope (VLT), using the 1200B grism on FORS1 with a slit width of 0.7 arcsec. We obtained 16 spectra of 360 s integration each, which corresponds to one orbital period. The seeing during the observations was in the range 0.8″−1.1″.

Image reduction was carried out following standard procedures: subtraction of an averaged bias frame and division by a normalised flat frame. The extraction of the spectra was performed with the ESO-MIDAS[1] software package. Wavelength and flux calibration of the spectra were achieved using a helium-argon lamp and by observing spectrophotometric standard stars. Our final reduced spectra have a wavelength range from 3600–5000 Å, a dispersion of 0.72 Å pixel^{-1}, and resolution of $R = 2200$. Cross correlation of the spectral lines and the Doppler tomograms were obtained using the MOLLY and DOPPLER packages developed by Tom Marsh[2].

3. Data analysis

We present the average spectrum of SAX J1808.4−3658 in Fig. 1. The spectrum is dominated by strong Balmer lines in absorption, which are due to the optically thick disc in the high state and are a typical signature of a low-to-intermediate inclination system. The He II λ4686 and the Bowen complex (at $\lambda\lambda$4630–4660) are also clearly detected as emission features, and we have indicated the most important lines.

For other bright LMXBs, narrow components in the Bowen emission have been reported that are thought to arise on the irradiated surface of the donor star (e.g. Steeghs & Casares 2002; Casares et al. 2006; Cornelisse et al. 2007; see also Cornelisse et al. 2008, for an overview), and here we attempt to find similar features in SAX J1808.4−3658. To calculate the orbital phase for each spectrum, we used the recent ephemeris by Hartman et al. (2008), but added 0.25 orbital phase to their phase zero so that it represents inferior conjunction of the secondary. Unfortunately, the individual spectra do not have high enough S/N to identify the narrow features, so we must resort to the technique of Doppler tomography (Marsh & Horne 1988). This technique uses all the spectra simultaneously to probe the structure of the accretion disc and identify compact emission features from specific locations in the binary system. However, for this technique to work, an estimate of the systemic velocity of the system, γ, is crucial. We do want to note that, by changing the phase zero of the accurate Hartman et al. (2008) ephemeris, any potential donor star feature in the map must now lie along the positive y-axis in the Doppler tomogram. Thus finding a significant feature there will give strong support to an emission site located on the irradiated donor star.

To find γ we started by applying the double-Gaussian technique of Schneider & Young (1980) to He II λ4686. Since the wings of the emission line should trace the inner-accretion disc, it should give us an estimate of not only the already known radial velocity of the compact object (Chakrabarty & Morgan 1998), but also γ. Using a Gaussian band pass with *FWHM* of 400 km s^{-1} and separations between 500 and 1800 km s^{-1} in steps of 50 km s^{-1}, we find that, between a separation of 1400 and 1600 km s^{-1}, our values for K_1 are close to the one obtained by Chakrabarty & Morgan (1998), while at larger separations we are reaching the end of the emission line (see Fig. 2). Also in this range, our fitted orbital phase zero (ϕ_0) is close to 0.5, further suggesting that we are tracing the radial velocities of a region close to the neutron star, while the systemic velocity is stable around –50 km s^{-1}. Despite the large errors on our fits, we do think this test already gives a good first estimate of γ around –50 km s^{-1}.

Another test to obtain γ is to create Doppler maps for He II λ4686. Contrary to the Bowen region (which is very complex due to the presence of many different lines), He II is a single line that is usually a good tracer of the accretion disc (see e.g. Cornelisse et al. 2007; Casares et al. 2006). We searched for γ between –160 and 0 km s^{-1} in steps of 20 km s^{-1}, and all the maps show the expected accretion disc structure (see Fig. 3). We must unfortunately conclude that He II is not very sensitive to γ and only suggests a range between –160 and 0 km s^{-1}. We note that the maps are dominated by an emission feature in the top-left quarter of the map, which we interpret as the gas-stream impact point. We also note that further downstream there is enhanced emission, which might be due to matter streaming along the edge of the disc as was observed, for example in EXO 0748−676 (Pearson et al. 2006). Finally we note that there is some enhanced emission in the top-right corner, which might be due to strong tidal interaction (see below).

Cornelisse et al. (2008) have shown that the strongest narrow component in the Bowen emission is usually N III λ4641. Our

[1] http://www.eso.org/projects/esomidas/
[2] http://deneb.astro.warwick.ac.uk/phsaap/software/

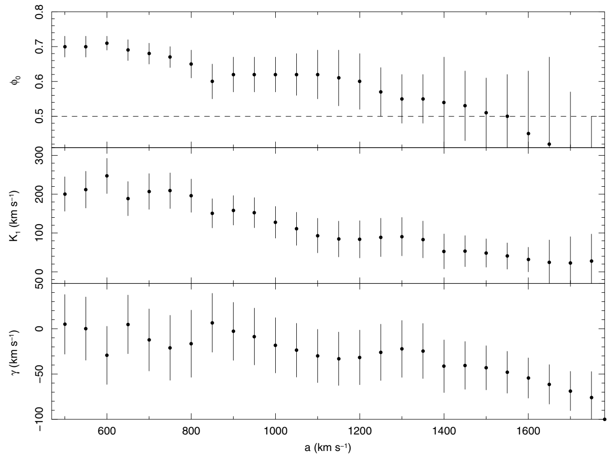

Fig. 2. The derived fit parameters of the radial velocity curve of the He II λ4686 emission as traced by a double Gaussian with separation a. The free parameters are the orbital phase zero ϕ_0, compared to the ephemeris of Hartman et al. (2008), its radial velocity K_1, and its systemic velocity γ. The dotted line in the top panel indicates the expected phase zero for the compact object.

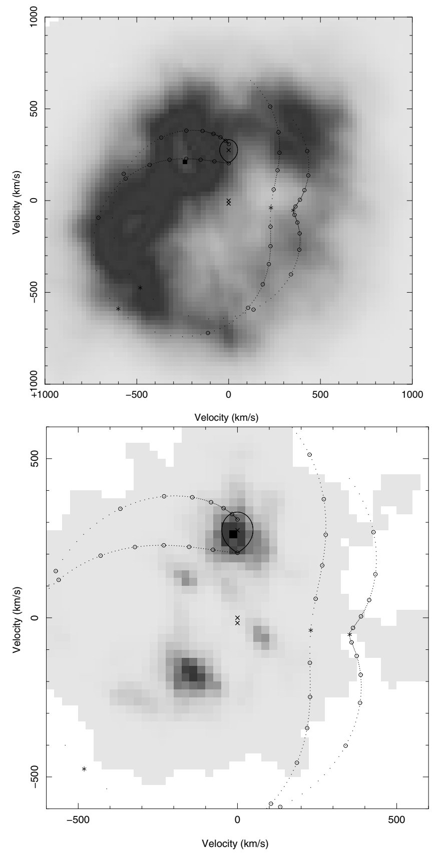

Fig. 3. Doppler maps of He II λ4686 (*top*) and the Bowen complex (*bottom*). Indicated on both maps is the Roche lobe, gas stream leaving the L_1 point, and the Keplerian velocity along the stream for the assumptions $q = 0.059$ and $K_2 = 275$ km s^{-1}.

next step was therefore to create Doppler maps of the Bowen region for γ between 0 and –120 km s^{-1} (again in steps of 20 km s^{-1}) including only this line. Only when γ was between −80 and –20 km s^{-1} was a clear spot present and centred on the $x = 0$ axis. For this range we estimated the peak value and *FWHM* of the spot as a function of γ, and in Fig. 4 we show how the ratio of these values change. Around $\gamma = -50\pm15$ km s^{-1} (1σ confidence), the *FWHM*/peak value reaches a minimum, suggesting that here the spot is most compact, and this is the value we adopt for the systemic velocity. Furthermore, we also noted that, in the range from –35 to –65 km s^{-1}, the velocity centroid of the spot was stable between V_y = 240–260 km s^{-1}.

To decrease the noise present in the Bowen Doppler map, we included the most important other lines that are most often present in other LMXBs (N III λ4634 and C III λ4647/4650), and present this map in Fig. 3. To estimate the significance of the compact spot, we measured the standard deviation of the brightness of the pixels in the background. We find that the central pixels of the compact spot are 18σ above the background, and even 8σ above the second most prominent feature in the map, namely the one at (–150, –200) in the Bowen map of Fig. 3 (for which it is unclear whether it is real or an artifact of the tomogram). This strongly suggests that the compact spot is real.

Finally, to optimise our estimate for $K_{\rm em}$, we created average spectra in the rest frame of the donor star, changing $K_{\rm em}$ in steps of 2 km s^{-1} within our error range. We find that N III λ4640 is most pronounced for $K_{\rm em}$ = 248 ± 20 km s^{-1} (1σ confidence), and adopt this as our final value, and in Fig. 5 show the final average spectrum in the rest-frame of the donor star. We do note that this value is lower than the ≃300 km s^{-1} obtained by Ramsay et al. (2008) from the same dataset, since they provide no errors, we cannot tell if this difference is significant. However, as stated above, the location of the spot remains within the quoted error range for a range of assumed γ velocities. To search for variability in the Bowen lines as a function of orbital phase, we created an average spectrum in the rest-frame of the donor using only spectra taken between orbital phases 0.25 and 0.75, and another corresponding to phases 0.75 and 1.25. The strength of N III λ4640 did not change between these spectra, but it is unclear if this is real (suggesting that the inclination is low) or due to the limited S/N of the dataset.

4. Discussion

We have presented phase-resolved spectroscopy of the accreting millisecond X-ray pulsar SAX J1808.4−3658, and detected a compact feature in the Doppler map of the Bowen complex. Although the S/N of the data is limited, this spot is the most stable and significant feature for a wide range of γ velocities. Furthermore, thanks to the very accurate ephemeris (Hartman et al. 2008), the spot is at a position where the donor star is expected, and we conclude that it is real. Therefore, following detections of a donor star signature in other X-ray binaries (e.g. Steeghs & Casares 2002; Casares et al. 2006; Cornelisse et al. 2007; see Cornelisse et al. 2008, for an overview), we also identify this feature as being produced on the irradiated surface of the donor star. We note that in Fig. 5 most peaks in the Bowen region appear to line up with known N III and C III lines (e.g. Steeghs & Casares 2002) when using our derived values for γ and $K_{\rm em}$.

Since the donor star surface must have a lower velocity than the centre of mass, the observed $K_{\rm em} = 248\pm20$ km s^{-1} (1σ confidence) is a lower limit on the true K_2 velocity. However, it still gives us a strict lower limit on the mass function of $f(M) = M_1 \sin^3 i/(1+q)^2 \geq 0.10\ M_{\odot}$, where q is the binary mass ratio M_2/M_1 and i the inclination of the system. We can further constrain the mass function by applying the so-called K-correction (Muñoz-Darias et al. 2005) and using the fact that

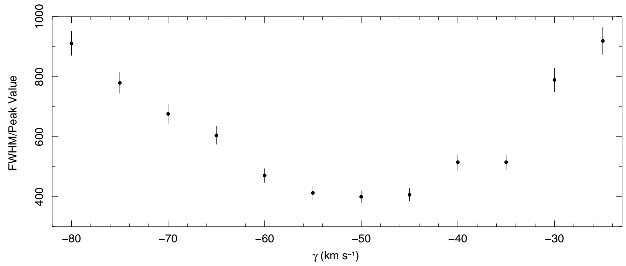

Fig. 4. The ratio of the *FWHM* over the peak value for the compact spot in the Bowen map (using only N III λ4661) as a function of the systemic velocity (γ).

$K_1 = 16.32$ km s^{-1} (Chakrabarty & Morgan 1998). The largest K-correction possible is when we assume that there is no accretion disc and almost all radiation is produced in the L_1 point. Applying the polynomials by Muñoz-Darias et al. (2005) for $K_{\rm em} = 248 \pm 20$ km s^{-1} gives $K_2 = 299 \pm 23$ km s^{-1}, which should be independent of the inclination of the system.

This gives conservative estimates of $228 < K_2 < 322$ km s^{-1} and $0.051 < q < 0.072$, which we used to create the Roche lobe and gas streams on the Bowen Doppler map in Fig. 3. We note that our obtained mass ratio is rather extreme and would suggest that tidal interaction in SAX J1808.4−3658 is important enough to produce a precessing accretion disc and thereby a superhump (see e.g. O'Donoghue & Charles 1996). This might be the explanation of the enhanced emission in the top-right quarter of the He II map (Fig. 3/top), which was for example also observed in LMC X-2 (Cornelisse et al. 2007). Such a superhump should be moving through the accretion disc on the precession time scale, and therefore changes position in the Doppler map over time. Unfortunately, since we only have one orbit of data we cannot test this, and future observations will be needed to see if the spot is long-lived and moves, in order to confirm the presence of the superhump.

Despite our wide range of K_2 we nonetheless will review the implications for the mass of the neutron star. First of all we can improve our estimate of K_2 by taking the results by Meyer & Meyer-Hofmeister (1982) into account. They analysed the effects of X-ray heating on the accretion disc and found that there is a minimal disc opening angle of $\simeq 6°$, even in the absence of irradiation. Using this value to estimate the K-correction, the polynomials by Muñoz-Darias (2005) suggest that $K_2 \leq 310$ km s^{-1}, which is still comparable to the maximum correction possible. Deloye et al. (2008) used photometry of SAX J1808.4−3658 in quiescence to constrain the inclination between 36 and 67 degrees. Using these extreme values for their inclination and $228 < K_2 < 322$ km s^{-1} leads to a neutron star mass between 0.15 and 1.58 $M_\odot$. Although these values are not very constraining for the neutron star mass, they favour a mass near the canonical value rather than a massive neutron star. We also note that our values are lower than the >1.8 $M_\odot$ estimated by Deloye et al. (2008, for a 10% error in the distance estimate), but since this corresponds to a 1.7σ difference (only taking our errors into account), we conclude that this disagreement is marginal.

5. Conclusions

The observations presented here provide evidence that a signature of the irradiated donor star in SAX J1808.4−3658 is detected. Clearly a similar experiment, but at higher S/N and spectral resolution, must be carried out again during a future outburst to obtain more than a single orbital period of data and resolve the narrow lines. This will not only allow us to unambiguously claim the presence of narrow components in the spectra of SAX J1808.4−3658, but also to measure the rotational broadening of the narrow components to further constrain K_2 via the relation in Wade & Horne (2003). With these data we have shown a promising way toward constraining K_2, and in combination with more quiescent data, we should be able to better constrain the inclination, thereby obtaining the mass of the neutron star in SAX J1808.4−3658.

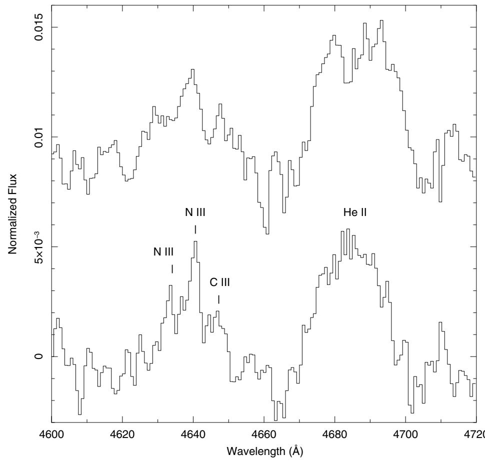

Fig. 5. Blow-up of the Bowen region for the average spectrum (*top*) and the average in the rest-frame of the donor star (*bottom*). The bottom spectrum clearly shows the narrow components. Indicated are the most important N III (λ4634/4640) and C III (λ4647) lines.

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