Orbital Phase Spectroscopy of four High Mass X-ray Binary Pulsars to Study the Stellar Wind of the Companion

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Abstract

Our work focuses on a comprehensive orbital phase dependent spectroscopy of the four High Mass X-ray Binary Pulsars (HMXBPs) 4U 1538-52, GX 301-2, OAO 1657-415 & Vela X-1. We hereby report the measurements of the variation of the absorption column density and iron-line flux along with other spectral parameters over the binary orbit for the above-mentioned HMXBPs in elliptical orbits, as observed with the Rossi X-ray Timing Explorer (RXTE) and the BeppoSAX satellites. A spherically symmetric wind profile was used as a model to compare the observed column density variations. Out of the four pulsars, only in 4U 1538-52, we find the model having a reasonable corroboration with the observations, whereas in the remaining three the stellar wind seems to be clumpy and a smooth symmetric stellar wind model appears to be quite inadequate in explaining the data. Moreover, in GX 301-2, neither the presence of a disk nor a gas stream from the companion was validated. Furthermore, the spectral results obtained in the case of OAO 1657-415 & Vela X-1 were more or less similar to that of GX 301-2.

Key words: pulsars : individual (4U 1538-52, GX 301-2, OAO 1657-415 & Vela X-1) – stars : circumstellar matter – X-rays: stars

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The Pulsars, Observations & Analysis

**4U 1538–52** was first detected with the UHURU satellite (Giacconi et al. 1974). The spin period and orbital period of the pulsar were first estimated to be 529 s and 3.73 days, respectively, from the observations with Ariel 5 and OSO-8 (Davision et al. 1977). Using data from the RXTE, the eccentricity of the binary orbit was calculated to be $\sim 0.18$ (Mukherjee et al. 2006). The X-ray spectrum has a prominent iron K-line (Makishima et al. 1987) and a pulse phase-dependent cyclotron resonance feature at 20 keV (Clark et al. 1990). It has a moderate X-ray luminosity of $\sim 10^{36}$ erg s$^{-1}$. The optical counterpart was found to be an early B type supergiant star (QV Nor) with H$\alpha$ emission lines (Parkes et al. 1978). The mass-loss rate and the terminal wind velocity were estimated as $\sim 10^{-6}$ M$_\odot$ yr$^{-1}$ and $\sim 1000$ km s$^{-1}$ respectively.

**GX 301–2 (4U 1223-62)** was discovered by White et al. (1976). Using data from BATSE observations, the orbital period and eccentricity of the binary system were determined as $\sim 41.5$ days and $\sim 0.46$, respectively (Koh et al. 1997). The companion star Wray 977 has a B1 Ia+ spectral classification with a mass of 39 M$_\odot$ (Kaper et al. 2006). The mass-loss rate and terminal velocity of the stellar wind are $10^{-5}$ M$_\odot$ yr$^{-1}$ and 305 km s$^{-1}$, respectively. GX 301-2 shows a variable X-ray luminosity in the range $(2-400) \times 10^{35}$ erg s$^{-1}$, depending on the amount of the stellar wind captured, which in turn depends on the density and velocity of the wind.

**OAO 1657–415** was discovered by the Copernicus satellite (Polidan et al. 1978). White & Pravdo (1979) detected a $\sim 38$ s pulsation period for the neutron star. A steady spin-up time scale of 125 yr with short-term fluctuations are observed from the period measurements from RXTE and BATSE (Baykal 2000). BATSE observations also aided the discovery of X-ray eclipses by the stellar companion and the determination of a $\sim 10.44$ day orbital period (Chakrabarty et al. 1993). They in turn used the orbital parameters to infer that the companion is a supergiant of spectral class B0–B6. OAO 1657-415 is unique among the known HMXBs in that it appears to occupy a transition region between mass transfer via a stellar wind and Roche lobe overflow (Chakrabarty et al. 1993).

**Vela X-1** is also an eclipsing HMXBP with an orbital period of $\sim 8.96$ days (Barziv et al. 2001). It exhibits X-ray pulsations with a pulse period of 283 s (McClintock et al. 1976). The companion is an early-type primary star HD 77581, which is a massive B0.5Ib-type supergiant (Brucato & Kristian 1972). The inferred mass-loss rate of the stellar wind of the companion is of the order of $10^{-7}$ M$_\odot$ yr$^{-1}$ (Sako et al. 1999). Moreover, the terminal wind velocity has been determined to be 1700 km s$^{-1}$ (Dupree et al. 1980). The pulsar orbits about the center of mass of the system at a distance of only about 0.6 stellar
radii from the surface of the supergiant, which has a radius of 53.4 R⊙. This implies that the neutron star is deeply embedded within the influence of the stellar wind. The typical X-ray luminosity of Vela X-1 is $4 \times 10^{36}$ erg s$^{-1}$, but large flux variations have been observed (Kreykenbohm et al. 1999).

We observed 4U 1538-52 with RXTE from 2003-07-31 to 2003-08-07 covering out of eclipse phases for two binary orbits. We also used the archival data from BeppoSAX obtained between 1998-07-29 to 1998-08-01, covering one binary orbit. GX 301-2 was observed by RXTE first from 1996-05-10 to 1996-06-15 and secondly from 2000-10-12 to 2000-11-19. For OAO 1657-415, we analyzed the archival data as observed with RXTE from 1997-10-31 to 1997-11-11. In addition to these, we also analyzed an archival BeppoSAX Medium Energy Concentrator Spectrometer (MECS) observation taken on 2001-08-14 for $\sim$104 ks exposure. Vela X-1 was observed with the Proportional Counter Array (PCA) of RXTE from 2005-01-01 to 2005-01-09. For the RXTE data, we took Standard-2 data products of the PCA and extracted the source and background spectra using the tool saextrct v 4.2d. The BeppoSAX data products were extracted from the MECS and Low Energy Concentrator Spectrometers (LECS) using circular regions of radius 4′ and 8′ respectively. The background subtracted source spectra were analyzed with the spectral analysis package XSPEC v 11.2.0. Since PCU0 had lost the propane layer, we did not use the data from it in any further analysis for Vela X-1. This was not a major issue for such a highly luminous pulsar since it did not affect the statistics.

For 4U 1538-52, the spectral model used was a simple power law along with a line-of-sight absorption, a high energy cut off and a Gaussian line with center energy $\sim$6.4 keV. However in case of GX 301-2, the Partial Covering Absorber Model (PCAM, Endo et al. 2002) with a high energy exponential cutoff and two Gaussian functions for iron Kα and Kβ lines was found to fit the RXTE data well compared to other models. The PCAM is described as two different power law components with the same photon index but different normalizations, being absorbed by different column densities ($N_{H1}$ & $N_{H2}$) respectively. The analytical form of the PCAM that we have used for spectral fitting is: $N(E) = e^{-\sigma(E)N_{H1}}(S_1 + S_2e^{-\sigma(E)N_{H2}})E^{-\Gamma}$, where $N(E)$ is the intensity, $\Gamma$ is the photon index, $N_{H1}$ and $N_{H2}$ are the two equivalent hydrogen column densities, $\sigma$ is the photo-electric cross-section, $S_1$ and $S_2$ are the respective normalizations of the power law. For OAO 1657-415 & Vela X-1 too, we observed that the PCAM was providing the best fit for both MECS and the RXTE spectra. Moreover, since RXTE is a non–imaging instrument and OAO 1657-415 lies under the influence of the Galactic ridge emission, we had to explicitly incorporate the ridge emission as a separate background spectral component. We put that in XSPEC as a sum of Raymond-Smith plasma and a power-law with appropriate normalizations (Valinia & Marshall 1998).
Fig. 1. Variation of Column Density versus Orbital Phase. The dashed line represents the model for inclination angle of 65°, the dashed-dotted line for 75° and the dotted line for 85°. Diamonds, filled squares, and circles denote measurements from the observations with RXTE in 1997, BeppoSAX in 1998, and RXTE in 2003 respectively.

2 Results & Discussion

4U 1538-52: The photon index, iron-line flux, cut-off energy and the e-folding energy measured with the pulse average spectrum taken over 2-3 ks did not show any substantial variation along the orbit which suggests that the continuum X-ray spectrum of the pulsar is hardly affected during its revolution. An important detection was a notably variation in $N_H$. It shows a smooth variation over orbital phase, increasing gradually by an order of magnitude as the pulsar approaches eclipse (Fig 1: mid-eclipse is defined by phase zero). At orbital phases far from the eclipse, the column density has a value of $\sim 1.5 \times 10^{22}$ atoms cm$^{-2}$. Moreover, we compare the observed column density profile with a model estimated by assuming a spherically symmetric Castor, Abbott & Klein (CAK 1975) wind from the companion star. The velocity profile of the line-driven wind is: $v_{\text{wind}} = v_\infty \sqrt{1 - \frac{R_c}{r}}$, where $v_\infty$ is the terminal velocity for the stellar wind, $R_c$ is the radius of the companion and $r$ is the radial distance from center of the companion star. The column density profiles were derived using a numerical integration along the line of sight from the pulsar to the observer. With a mass-loss rate of $\sim 10^{-6} \, M_\odot \, \text{yr}^{-1}$ and $v_\infty \sim 1000$ km s$^{-1}$, the model calculations of $N_H$ for different inclination angles when super-
Fig. 2. The figure shows the $N_H$ variation for GX 301-2 with the uppermost panel depicting the model variation, the middle panel showing the observed variation of $N_{H1}$ and the lower panel shows the observed variation of $N_{H2}$. The error-bars shown correspond to 90% confidence interval.

posed on the observed values, it shows fairly reasonable agreement for three different inclination angles $65^\circ$, $75^\circ$ and $85^\circ$ respectively (Fig. 1), indicating that a CAK wind from the companion star may produce the observed orbital dependence of the column density for a certain range of the orbital inclination ($>65^\circ$). We note here that, in Fig. 1, we have not done any fitting of the measured column densities and the model calculated column densities at different orbital phases are rather plotted together. The phase resolved column density values for the wind density model used here depend on the rate of mass loss, the terminal velocity and the inclination angle of the binary orbit. The data presented here, however, is not suitable for such a detailed analysis but only shows the consistency of the model with the observations.

**GX 301-2**: As in 4U 1538-52, the continuum parameters do not show any orbital modulation in GX 301-2. In this case, the variation of $N_{H1}$ & $N_{H2}$ with orbital phase was not smooth. The values were very high with a large variation throughout the binary orbit (from $10^{22}$ to $10^{24}$ atoms cm$^{-2}$), indicating a clumpy nature of the stellar wind (Fig. 2). It is also seen that the covering fraction (defined as $\text{Norm2}/[\text{Norm1}+\text{Norm2}]$) remains substantially high almost throughout the orbit which means that there is dense and clumpy...
material present throughout. This is also supported by the detection of a strong Compton recoil component detected with the Chandra grating spectrum and its successful reproduction by Monte Carlo simulations (Watanabe et al. 2003). Thus it is clear that the observed variation in column density cannot be explained by a spherically symmetric CAK wind only, indicating the presence of strong inhomogeneities in the wind. There are two proposed models in this regard: a gas-stream model by Leahy (1991) and the equatorial disk model by Pravdo & Ghosh (2001). However, the orbital dependence of the absorption column densities measured by us is very different from their predictions. Now, for the iron K-line fluxes, we obtained peaks near periastron (Fig. 3). The line equivalent width had a correlation with the column density ($N_{H_2}$), suggesting that most of the iron line is produced by the local clumpy matter surrounding the neutron star.

**OAO 1657-415 & Vela X-1**: The average values of the free spectral parameters measured here over the out-of-eclipse phases of the binary orbit; viz. photon index, e-folding energy and cut-off energy, do not exhibit any modulation due to the revolution of both the pulsars. These results seem to be in conformity with that obtained for GX 301-2 & 4U 1538-52. The column density ($N_{H_2}$) of the material that absorbs the primary X-ray emission is found to be high for both the pulsars (Fig 4). A large variation of the column densities throughout the out-of-eclipse phases (from $10^{22}$ to $10^{24}$ atoms cm$^{-2}$) characterizes their X-ray spectra. There were instances of moderate to high

![Figure 3](image-url)
values of covering fraction. Here, it should be mentioned that the number of out-of-eclipse measurements for OAO 1657-415 are probably not sufficient to arrive at a strong conclusion.

We do not attempt to compare the variations of the observed column densities with the CAK model variation as we had done in case of 4U 1538-52 and GX 301-2 since it is clear from the measurements that such a comparison would definitely rule out the said model. In this context, we may point out that the spectral measurements for these two pulsars are similar in case of GX 301-2 (Mukherjee & Paul 2004). For GX 301-2 though, formation of clumped blobs of matter could be accounted for the unusually low wind velocity and high mass loss rate, but for the present case, such an inference is probably not possible. Moreover, unlike GX 301-2, we do not observe any systematic orbital modulation for the Iron-line fluxes. Furthermore, the iron-line equivalent width also does not show any definite correlation with $N_{H2}$.

In view of the above exposition, we may conclude as follows:

1. The PCAM appears to be somewhat generic for pulsars which have variable column density, at least when observed with RXTE or BeppoSAX.
2. For highly luminous supergiant binaries, the CAK Model of stellar wind does not suffice to describe the column density variations. This is corroborated by the results of GX 301-2, OAO 1657-415 & Vela X-1 in this work and of 4U 1700–37 (Haberl et al. 1989) and 4U 1907+09 (Roberts et al. 2001).
3. Moderately luminous pulsars probably validate the spherical wind model, as in the case of 4U 1538-52 (this work) and X 1908+075 (Levine et al. 2004).

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Fig. 4. The figure shows the variation of $N_{H_2}$ with orbital orbital phase for OAO 1657-415 (top) and Vela X-1 (bottom). It may be observed that sufficient number of observations are lacking for OAO 1657-415. The error-bars shown correspond to 90% confidence interval.

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