Orbital phase spectroscopy of X-ray pulsars to study the stellar wind of the companion

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Abstract

High Mass X-ray Binary Pulsars (HMXBP), in which the companion star is a source of supersonic stellar wind, provide a laboratory to probe the velocity and density profile of such winds. Here, we have measured the variation of the absorption column density along with other spectral parameters over the binary orbit for two HMXBP 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. In 4U 1538-52, we find the model corroborating the observations; whereas in GX 301-2, the stellar wind appears to be very clumpy and a smooth symmetric wind model seems to be inadequate in explaining the variation in column density.

Key words:
pulsars : individual (GX 301-2 & 4U 1538-52) — stars : stellar wind — X-rays : stars

4U 1538-52 (Giacconi et al. 1974) and GX 301-2 (White et al. 1976) are both luminous (∼10^{35}-10^{37} ergs s^{-1}) pulsars in elliptical orbits. They emit X-rays due to the accreted matter from the stellar wind of their respective companion stars (Parkes et al. 1978, Kaper et al. 1995). Since both have well defined orbital measurements (Clark 2000, Koh et al. 1997), it enables us to inspect the variation of the X-ray spectral parameters at different orbital phases to gain useful insight into the morphology of the stellar wind. In this work, we have measured the X-ray spectral evolution of these two HMXBP as observed with the RXTE and BeppoSAX satellites and the parameters of the spectral model were examined along the orbit for any possible variations. We have also compared the equivalent hydrogen column density (N_H) variations over the

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orbit with a model variation, assuming a spherically symmetric stellar wind emanating from the companion star.

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 again from 2000-10-12 to 2000-11-19. For more details, refer to Mukherjee and Paul (2004) and Mukherjee et al. (2005).

For the RXTE data, we took Standard 2 data products of the Proportional Counter Array (PCA) and extracted the source spectra using the tool saextract v 4.2d. The BeppoSAX data products were extracted from the Medium Energy Concentrator Spectrometers (MECS) and Low Energy Concentrator Spectrometers (LECS) using circular regions of radii 4' and 8' respectively. The background subtracted source spectra were analyzed with XSPEC v 11.2.0 (Shafer, Haberl & Arnaud 1989) using appropriate spectral models. For 4U 1538-52, we used a power law along with a line-of-sight absorption and a gaussian line with centre energy $\sim 6.4$ keV. We also applied a high energy cut-off component. And for GX 301-2, we used the Partial Covering Absorber Model (PCAM, Endo et al. 2002) along with the addition of a high energy exponential cutoff. The PCAM is described as two different power law components with the same photon index but different normalizations (Norm1 & Norm2); being absorbed by different column densities, $N_{H1}$ & $N_{H2}$ respectively. $N_{H2}$ is interpreted as the column density of the material local to the X-ray source, while $N_{H1}$ accounts for the rest of the material (along with galactic absorption). In this case, iron Kα and Kβ lines and an absorption edge at 7.1 keV due to neutral iron were also included in the model.

Results & Discussion

**4U 1538-52**: The photon index, fluorescent iron-line flux, cut-off energy and the e-folding energy measured with the average spectrum taken over 2–3 ks does not show any substantial variation along the orbit. This suggests that the continuum X-ray spectrum of the pulsar is hardly affected during its revolution along the orbit. But we detected a notably smooth variation in $N_H$ with orbital phase, increasing gradually by an order of magnitude as the pulsar approaches eclipse (near phases 0.3 and 0.5; as measured from the periastron passage, Fig. 1). At orbital phases far from the eclipse, the column density has a value of $\sim 1.5 \times 10^{22}$ H atoms cm$^{-2}$. 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 wind is $v_{\text{wind}} = v_{\infty} \sqrt{1 - \frac{v_c}{v_{\infty}}}$, where $v_{\infty}$ : terminal velocity of the stellar wind,
Fig. 1. The variation of column density ($10^{22}$ H atoms cm$^{-2}$) with orbital (binary) phase for 4U 1538-52 (left) and GX 301-2 (right) are shown. In the former, the dashed line, the dashed-dotted and the dotted line represents the model $N_H$ values for the inclination angles of 65°, 75° & 85° respectively. In the latter, the three panels show the model variation due to the wind and the measured variations of $N_{H1}$ and $N_{H2}$ respectively. In both the figures, different symbols are used for different observations.

$R_c$: radius of the companion and $r$: radial distance from the centre 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 for three different inclination angles of 65°, 75° and 85° respectively. With a mass-loss rate of $\sim 10^{-6}$ M$_\odot$ yr$^{-1}$ and $v_\infty \sim 1000$ km s$^{-1}$, the model calculations of $N_H$ for different inclination angles when superposed on the observed values show fairly reasonable agreement (Fig. 1), indicating that a spherically symmetric stellar wind from the companion star may produce the observed orbital dependence of the column density for certain range of the orbital inclination.

GX 301-2: In most cases, the spectrum was fitted well with the PCAM. The average values of the free parameters measured here over the full binary orbit; viz. photon index, e-folding energy and cut-off energy follow the general trend which were earlier measured only in some phases of the binary period (White et al. 1983, Orlandini et al. 2000). But 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. 1). It is also seen from Fig. 2 that the covering fraction (C.F., defined as $N_{Norm2}/[N_{Norm1}+N_{Norm2}]$) remains substantially high almost throughout the orbit. This means that there is dense and clumpy material present all through. As in the case of 4U 1538-52, we compared the measured values of column densities with a model variation using a CAK wind. The model values were of the order of $10^{22}$ to $10^{23}$ atoms cm$^{-2}$ (Fig. 1). The peak between phases 0.1 and 0.2 was expected since the line of sight passes through the densest parts of the wind during these phases. Thus it is clear that the observed variation in column density cannot be explained by a spherically symmetric CAK wind only, indicating probably strong inhomogeneities in the wind. Now, as can be seen from Fig. 2, the two iron lines included in our model show large increase in flux near periastron (phase $\sim 0.9$) and a possible small increase near phase 0.1 (at least for 1996, filled squares).
Fig. 2. The variation of C.F. (left) and the iron-line flux (right) with the binary phase for GX 301-2 are shown with different symbols for different observations.

The peak near periastron is not very evident in the 1996 data due to the lack of enough observations, though an increasing trend can possibly be inferred. Moreover, the equivalent width of the 6.4 keV iron-line showed a correlation with $N_{\text{H}_2}$, suggesting that most of it is produced by the local clumpy matter surrounding the neutron star.

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