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Dipping and Absorption in the stellar wind in GX 301-2

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We present a detailed study of the absorption and dipping behavior of the accreting High Mass X-ray Binary GX 301-2. We use data from the XMM-Newton observatory to study the low energy continuum and the iron line complex and data from the Rossi X-ray Timing Explorer (RXTE) to model the continuum and study lightcurves. The analysis of the RXTE data shows that the source is strongly variable: the source exhibits intense flaring as well as dipping activity. The source countrate as recorded by the RXTE-PCA drops to almost zero during some of the dips in the lightcurve. A similar dipping behavior has been observed in the Vela X-1 as well as a number of other massive wind accreting sources. We present a detailed spectral and temporal study of the dips and discuss possible scenarios to explain the dips.

The high quality XMM timing mode data are taken during the pre-periastron flare. We accumulate an overall spectrum with very high signal to noise ratio and model it with a partial covering model. The high signal allows us to obtain spectra as short as 30 s to track the evolution of the photoelectric absorption and thus the density of the material in the stellar wind.

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1. Introduction

GX 301−2 (also known as 4U 1123−62) is a High Mass X-ray Binary (HMXB) consisting of a neutron star and the early type companion BP Cru. The neutron star is in an eccentric orbit (e = 0.462) with an orbital period of about 41.5 days [4]. The companion star is was first classified as a B1.2Ia star [4], while it was later reclassified as B1 Iae+ hypergiant [3]. This more recent classification makes Wray 977 with a luminosity of $1.3 \times 10^6 L_\odot$ and a mass of at least $48\,M_\odot$ one of the most luminous stars in our galaxy. The star has a very high mass loss rate of $\dot{M} \sim 10^{-5}\,M_\odot\,\mathrm{yr}^{-1}$ resulting in a very dense but slow ($v_\infty = 400\,\mathrm{km\,s^{-1}}$) stellar wind.

The neutron star rotates with a period of approximately 686 s [14]. It accretes material directly from the dense stellar wind, resulting in a highly variable X-ray light curve, typical for wind accretion. X-ray luminosity changes by a factor of five or more within one hour are common in GX 301−2 [12]. The orbital light curve exhibits significant variability: shortly before periastron, the neutron star encounters a gas stream flowing from the optical companion to the neutron star resulting in intense flaring activity [11]. Following the periastron, the X-ray intensity reaches a minimum around orbital phase 0.2 as the neutron star passes through the dense inner regions of the stellar wind until it is almost eclipsed by the stellar companion [8]. The X-ray intensity increases again towards a weak secondary maximum near apastron.

The X-ray spectrum of GX 301−2 was usually described by a powerlaw modified at higher energies by an exponential cutoff. More recent studies, however, used a partial covering model as the spectrum of GX 301−2 is heavily absorbed [7, 6] with N_H ranging from 10^{23} up to $2 \times 10^{24}\,\mathrm{cm}^{-2}$ [7]. Around 6.4 keV a very strong iron fluorescence line with an equivalent width of up to 1800 eV is present [9]. At energies above 20 keV, the spectrum is further modified by the presence of a strongly pulse phase dependent cyclotron resonant scattering feature around ∼37 keV [10, 6].

2. Observations

We have obtained ∼50 ksec of high quality data with *XMM-Newton* on July 12, 2009 (MJD 55024.1037 to MJD 55024.6430). Since the source is extremely bright, the EPIC-PN camera of *XMM-Newton* was operated in the timing mode and the two EPIC-MOS cameras were switched off and the telemetry assigned to the EPIC-PN camera. The observations were performed during the pre-periastron flare around orbital phase 0.9 where the source is very bright and shows extreme variability and intense flaring activity.

In addition we analyzed 185 ksec of public Rossi X-ray Timing Explorer (RXTE) observations of GX 301−2 which were performed between 2010 May 26 and July 22. Several observations were unusally long: at least 10 ksec of uninterrupted data taking. We used data from all PCUs for timing studies while we used data collected with PCU2 only for time resolved spectral investigations to avoid calibration uncertainties.

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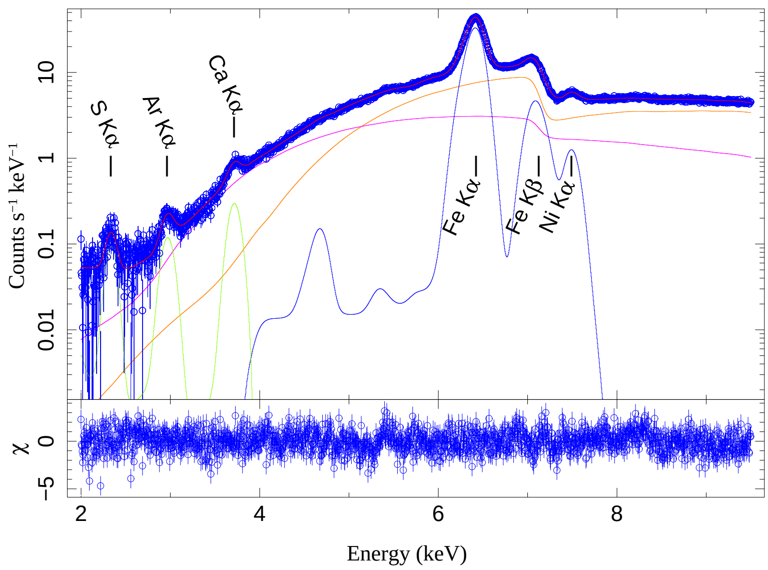

Figure 1: Spectrum of GX 301−2 taken by *XMM-Newton*. The spectrum was modelled with a partial covering model. Note that the photoelectic absorption is so strong that almost no flux is present below 2 keV. The column density results furthermore in very strong iron and nickel fluorescence lines.

3. Data analysis

3.1 *XMM-Newton*

We used the complete *XMM-Newton* observation to obtain a spectrum with the best signal to noise ratio (see Fig. 1). The shape of the continuum is very complex and can not be fitted with simple models such as `cutoffpl` from XSPEC. We used a partial covering model with both components being strongly absorbed ($N_{\mathrm{H},1} \sim 130 \times 10^{22}\,\mathrm{cm}^{-2}$ and $N_{\mathrm{H},2} \sim 50 \times 10^{22}\,\mathrm{cm}^{-2}$) plus four Gaussians to model the iron line complex: a neutral iron K_α line at 6.4 keV plus a Compton shoulder, iron K_β line at 7.1 keV, and Nickel K_α at 7.5 keV (the individual components are shown in Fig. 1). The excellent statistics allow us to obtain spectra with an exposure time of only 30 s. Keeping most continuum parameters fixed, we obtain the N_H for each individual spectrum, i.e. an N_H lightcurve which shows the strong variability of the N_H.

3.2 *RXTE*

The analysis of the *RXTE*/PCA lightcurve reveals a highly unusual behavior on May 28, 2010 [2]: while the source was strongly pulsating with a period of ∼686 s, the X-ray intensity was decreasing smoothly, until a flux level of only ∼10% of the original level was reached. This dip itself was about 1000 s (from MJD 55344.044 to 55344.055) long. During this dip, the pulsations could not be detected (see Fig. 2). After the dip, the X-ray intensity of the source gradually increased again and immediately pulsations resumed. We analyzed all other pointings of GX 301−2, but found no other dipping episode.

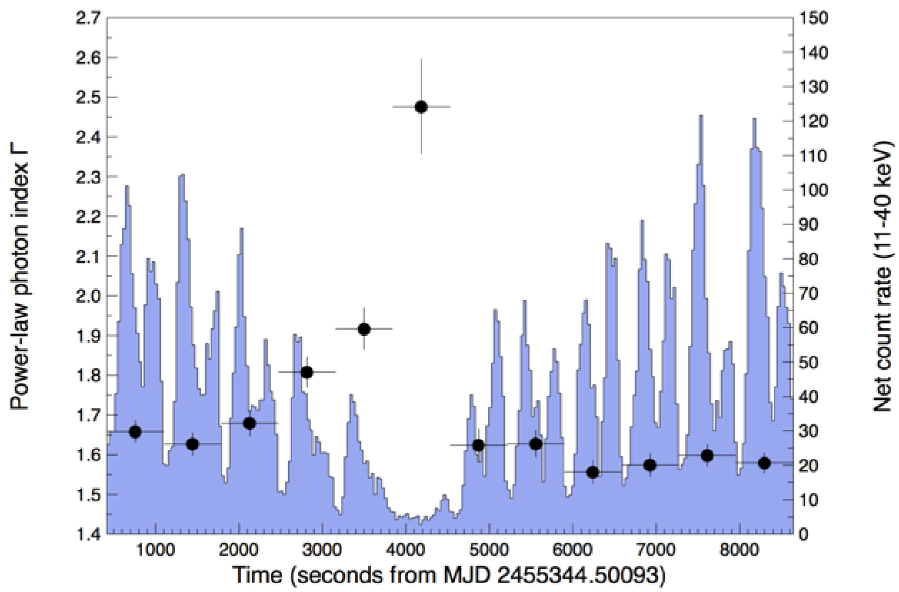

Figure 2: Light curve of RXTE/PCA observations in the 11–40 keV range of GX 301−2 on 2010 May 28 (histogram). A spectrum for each single pulse was extracted and the circles indicate the value of the powerlaw index Γ for the individual spectra.

The pulse profile of GX 301−2 exhibits two pulses: a main pulse and a slightly weaker secondary pulse. Up to the dip, the secondary peak is as usual weaker than the main pulse and furthermore the secondary peak decays faster towards the dip than the main peak. During the dip, no significant pulse profile is visible. After the dip, both peaks are abruptly present again, however, the secondary peak is now stronger than the main peak for the next four pulses. After that, the pulse shape of the source resembles its typical long term appearance again.

To further investigate this dip, we performed a time resolved spectral analysis to study the nature of the X-ray emission from GX 301−2 prior to, during, and after the dip. We accumulated pulse phase integrated source and background spectra for the 12 consecutive pulses prior to, during, and following the dip. We modeled the X-ray spectra in the 3–30 keV band, fitting first each spectrum individually with an absorbed power law plus a Gaussian at 6.4 keV to account for the iron fluorescence line. Although this model is rather simple, it describes the data sufficiently well ($0.6 < \chi^2_\nu < 1.3$). The hydrogen column density is consistent with a constant value within uncertainties: it varies between 1.3×10^{23} and 1.7×10^{23} cm^{-2}. In the next step, we therefore performed a simultaneous fit of all 12 spectra together, using the same absorption column density, iron line energy and width and leaving only the power law index and the two normalizations free. The resulting best fit yields $N_H = (1.6\pm0.2)\times10^{23}$ cm^{-2} with a $\chi^2_{red} = 0.96$. Most interestingly, however, we observe a significant softening of the spectrum of the source already prior and especially during the dip (see Fig. 2). After the dip, the spectrum immediately resumes its pre-dip shape. A more detailed discussion is given in [2].

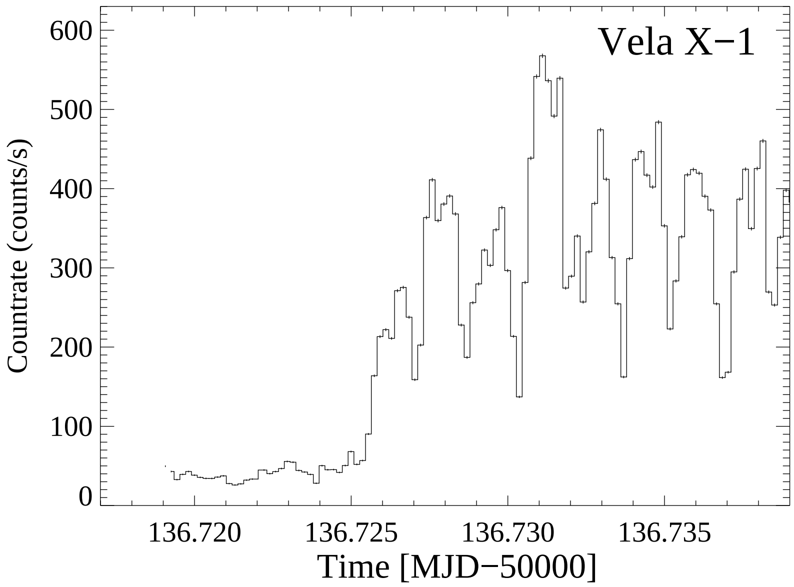

Figure 3: Lightcurve of an observation *RXTE* observation of Vela X-1 from February 23, 1996. At the beginning of the observation also no pulsations are visible and the overall flux level is very low. After the dip (or off-state) Vela X-1 resumes the normal pulsating behavior.

4. Discussion

Although the observed dip in GX 301−2 is rather unique, similar dips or offstates have been observed in other massive wind accreting X-ray binaries.

A very interesting dip was observed in a short *RXTE* observation of Vela X-1 in 1996 [5]: our re-analysis of these data shows no pulsations are present at the beginning of the observation and the flux was at a very low level ($\sim$37 counts/s/PCU in the 3−25 keV band compared to $\sim$300 counts/s/PCU during the normal bright state; see Fig. 3). We extracted X-ray spectra from the dim non-pulsating state and from the bright pulsating state later in the same observation (see Fig. 3). The spectrum of Vela X-1 is significantly softer during the dim non-pulsating state compared to the normal state. Therefore, GX 301−2 and Vela X-1 show the same behavior: they both exhibit short periods of time during which they are very dim and no pulsations are seen.

The gradual reduction and disappearance of the X-ray pulsations in GX 301−suggests that the X-ray emitting regions of the source were blocked by a dense blob in the stellar wind of the companion. However, the spectrum during such a dip caused by photoelectric absorption is expected to be significantly harder as only the softer X-ray photons are absorbed. Since we observe significant spectral softening during these dips, they can not be caused by simple photoelectric absorption. [1] reported the disappearence of X-ray pulsations in GX 1+4 during low luminosity states and suggested that they are caused by the propeller effect. Since GX 301−2 is known to have a very high magnetic field strength of the order of 3×10^{12} G [6], it is possible that the infalling material can be expelled via the propeller effect. Unlike the offstates in Vela X-1, the dip in GX 301−2, however, is probably not caused by the propeller effect alone, as the system would be expected to remain in the propeller regime for a longer time than just one pulse period. Another possibility is that there could be a short interruption in the accretion stream due to e.g. fluctuations in the stellar wind. In this scenario, the observed low level emission would originate from the surface of the neutron star. During the normal pulsating mode, it would not be possible to disentangle the radiation from the accretion column and the radiation from the surface of the neutron star. Also in this scenario it is not straightforward to explain why the dip lasts exactly one pulse period, however, the time scales predicted for such density fluctuations in the stellar wind match the duration of the dip [13].

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