Spectral Changes During Dipping in Low-mass X-ray Binaries Due to Highly-ionized Absorbers

M. Díaz Trigo [a] A. Parmar [a] L. Boirin [b] M. Méndez [c] J. Kaastra [c]

[a]Research and Scientific Support Department of ESA, ESTEC, Postbus 299, 2200 AG Noordwijk, The Netherlands

[b]Observatoire Astronomique de Strasbourg, 11 rue de l'Université, F-67000 Strasbourg, France

[c]SRON, National Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands

X-ray observations have revealed that many low-mass X-ray binaries (LMXBs) exhibit narrow absorption features identified with Fe XXV and Fe XXVI. We successfully model the changes in both the X-ray continuum and the Fe absorption features during dips from all the bright dipping LMXBs observed by XMM-Newton (EXO 0748-676, XB 1254-690, X 1624-490, MXB 1659-298, 4U 1746-371 and XB 1916-053) as resulting primarily from an increase in column density and a decrease in the ionization state of a highly-ionized absorber in a similar way as was done for XB 1323-619. This implies that complex spectral changes in the X-ray continua observed from the dip sources as a class can be most simply explained primarily by changes in the highly ionized absorbers present in these systems. We observe also small changes in the equivalent hydrogen column of neutral material, which may be related to the inclination of the system. Since the ionized plasma has a cylindrical geometry with a maximum column density close to the plane of the accretion disk and dipping sources are simply normal LMXBs viewed from close to the orbital plane this implies that ionized plasmas are a common feature of LMXBs.

1. Introduction

Around 10 galactic low-mass X-ray binaries (LMXBs) show periodic dips in their X-ray light curves (Fig. 1). The dips recur at the orbital period of the system and are believed to be caused by periodic obscuration by material located in a thickened outer region of the accretion disk due to its interaction with the inflowing gas stream from the companion. The presence of periodic dips and absence of eclipses from the companion indicate that dipping sources are viewed relatively close to edge-on.

The X-ray spectra of most of the dip sources become harder during dipping. However, simple photo-electric absorption by cool (neutral) material fails to explain the spectral changes from persistent to dipping intervals. Therefore more complex models have been proposed. In particular, in the "complex continuum" approach, the X-ray emission is assumed to originate from a point-like blackbody, or disk-blackbody component, together with an extended power-law component. This approach models the spectral changes during dipping intervals by the partial and progressive covering of the power-law emission from an extended source and the independent absorption of the point-like component, and has been successfully applied to a number of dipping LMXBs.

The improved sensitivity and spectral resolution of *Chandra* and XMM-Newton is allowing narrow absorption features from highly-ionized Fe and other metals to be observed from a growing number of X-ray binaries. In particular, Fe XXV or Fe XXVI 1s-2p resonant absorption lines near 7 keV were reported from the micro-quasars GRO J1655−40, GRS 1915+105 and H 1743−322, and from the neutron star systems Cir X−1, GX 13+1, MXB 1659−298, X 1624−490, XB 1254−690, XB 1916−053 and XB 1323−619 (see references in [3]). Most of the sources are known to be viewed close to edge-on (many are dippers). This indicates that the highly ionized plasma probably originates in an accretion disk atmosphere or wind, which could be a common feature of accreting binaries but preferentially detected in systems viewed close to edge-on. Boirin et al. [2] demonstrated that the changes between persistent and dipping intervals *both* in the X-ray continuum and the Fe absorption features from XB 1323−619 can be modeled as resulting primarily from an increase in column density and a decrease in the ionization state of a highly-ionized absorber. At the lower ioniza-

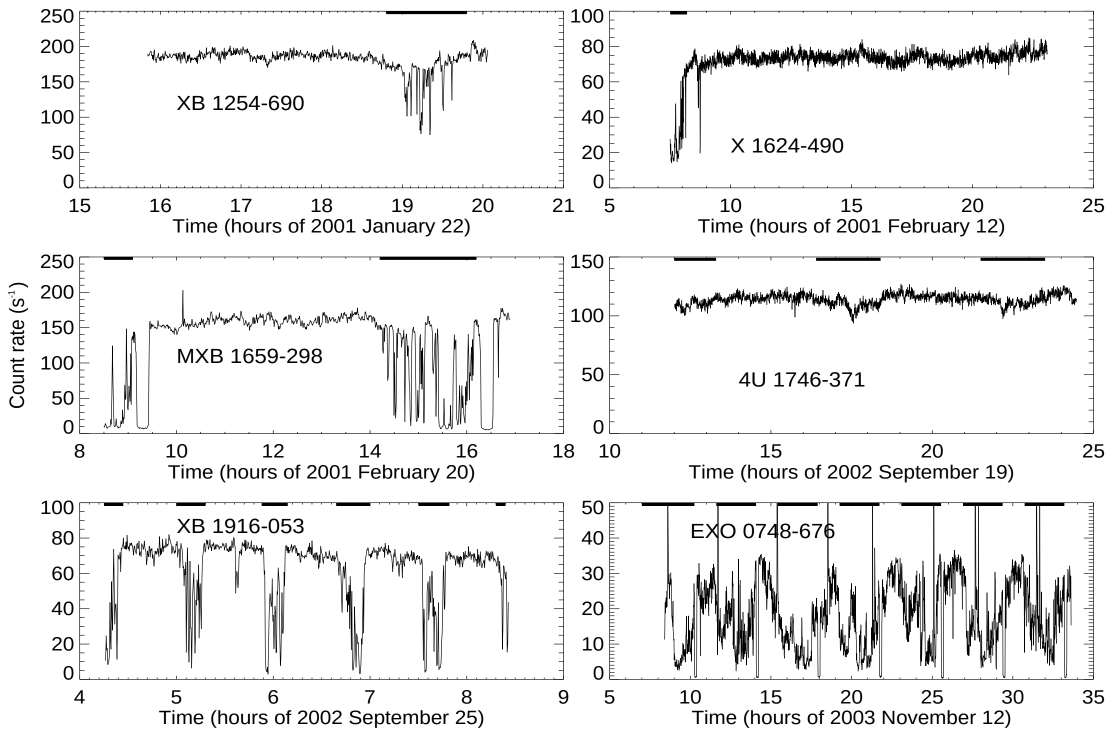

Figure 1. EPIC pn 0.6–10 keV lightcurves of the LMXBs analyzed in this work. The thick horizontal lines mark the intervals used to extract dip spectra.

tion levels seen during dips, lower-Z abundant ions such as H-like Ne, Si, and S and intermediate ionization states of Fe are present and their absorption features blend together at CCD energy resolution. This and the appearance of strong edges from the same ions result in an apparent change in the continuum, which is consistent with that actually observed during dips.

Here we demonstrate that the model applied to XB 1323−619 [2] explains the spectral changes, *both* in the continuum and in the narrow absorption features, between persistent and dipping intervals of all the bright dipping LMXBs observed by XMM-Newton. Details may be found in [3].

2. Data analysis and results

We re-analysed all the XMM-Newton observations of bright dipping LMXBs in a similar way as it was done for XB 1323−619. Their EPIC pn 0.6-10 keV lightcurves are shown in Fig. 1. We fit the spectra of all the sources with a continuum consisting of a power-law, and a blackbody components modified by absorption from neutral material (the `abs*(bb+pl)` model in SPEX). For each source we fit simultaneously all the EPIC pn spectra of the persistent and dipping intervals with the continuum parameters tied together, while we allowed to vary all the other parameters. We included Gaussian emission profiles when emission features were evident near 1 keV and/or 6 keV. To account for the absorption features around 7 keV we included absorption from a photo-ionized plasma (`xabs`) in the spectral model. The `xabs` model treats the absorption by a thin slab composed of different ions, located between the ionizing source and the observer. The processes considered are the continuum and the line absorption by the ions and scattering out of the line-of-sight by the free electrons in the slab. All relevant ions are automatically taken into account. We are able to account for the complex

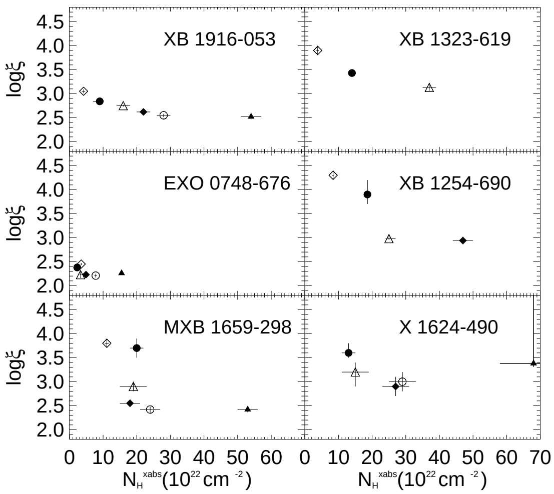

Figure 2. Evolution of $\log(\xi)$ and $N_{\rm H}^{\rm xabs}$ for the LMXBs studied in this paper. Empty diamonds, filled circles, empty triangles, filled diamonds, empty circles and filled triangles indicate the persistent and Dip 1 to Dip 5 intervals, respectively.

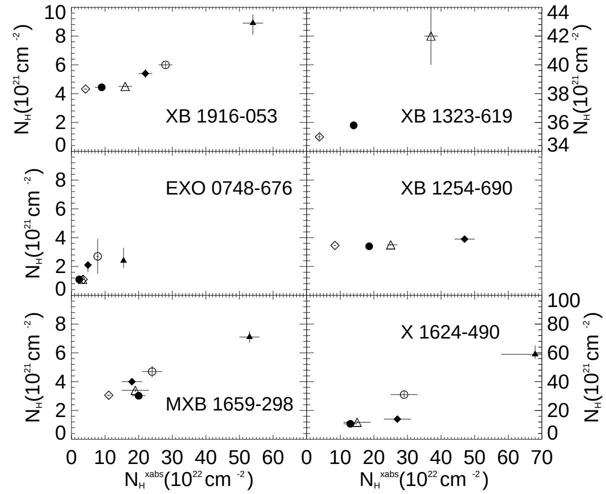

Figure 3. Evolution of $\rm N_H$ and $N_{\rm H}^{\rm xabs}$ for the LMXBs studied in this paper. Empty diamonds, filled circles, empty triangles, filled diamonds, empty circles and filled triangles indicate the persistent and Dip 1 to Dip 5 intervals, respectively.

changes in the 0.6-10 keV continuum and absorption lines during dips from the LMXBs studied here (with the exception of 4U 1746−371 where the dips are very shallow) by large increases in the column density, $N_{\rm H}^{\rm xabs}$, and decreases in the amount of ionization, ξ, of a highly-ionized absorber (see Table 1), together with much smaller increases in the $\rm N_H$ of a neutral absorber (for X 1624−490 the increase in the column densities of the neutral and ionized absorbers are comparable). For all the sources, the strongest absorption lines in the persistent spectra are the Fe XXV and Fe XXVI 1s-2p transitions except for XB 1254−690, where the absorber is the most highly ionized with $\log(\xi)= 4.2 \pm 0.2$ and only the Lyα and β Fe XXVI absorption features are evident. EXO 0748−676 and 4U 1746−371 do not exhibit strong absorption lines. Our analysis indicates that the EXO 0748−676 absorber is significantly less ionized than in the other LMXBs studied with $\log(\xi) = 2.45 \pm 0.02$. This could indicate that the source is continuously dipping. In contrast, for 4U 1746−371 the non-detection of a Fe XXV absorption feature and the evidence of one from Fe XXVI indicate a highly-ionized absorber, similar to the one in XB 1254−690.

A similar evolution of decreasing ξ and increasing $N_{\rm H}^{\rm xabs}$ is observed for all sources, being the evolution stronger from persistent to Dip 2 stages than between dips (see Fig. 2). For EXO 0748−676, the evolution of the highly-ionized absorber is unusually small compared to the other sources. This could be explained if EXO 0748−676 were in a continuous dipping state (see above). Figure 3 shows the evolution of $\rm N_H$, with respect to the ionized absorber, $N_{\rm H}^{\rm xabs}$, from persistent to deepest dip intervals for each source. XB 1254−690 shows a particularly small increase in $\rm N_H$ compared to other sources. This may indicate that we are viewing XB 1254−690 at an inclination angle such that the line of sight is not obscured by additional neutral material at any orbital phase and the dips result only from additional obscuration by the ionized absorber. The source may be being viewed relatively far from the plane of the accretion disk and only the ionized absorber significantly intercepts the line of sight. This special geometry and small changes in the size of the ionized absorber may explain the remarkable complete occasional disappearance of dipping activity from this source [4,1]. If this picture is correct, the

Table 1
The persistent (Dip 1 for X 1624−490) values of N_H (col. 2), N_H^{xabs} (col. 6) and $\log(\xi)$ (col. 8) and the changes in N_H (col. 3) and N_H^{xabs} (col. 7) from persistent to the deepest dip intervals observed for each source. N_{Hgal} is the averaged interstellar value for the 0°5 region in the sky containing the source. $\Delta N_H/(N_{Hpers}\text{-}N_{Hgal})$ is the relative change in N_H local to the source from persistent to the deepest dip interval. Col. 9 shows the value of $\log(\xi)$ during the deepest dip for each source. N_H for EXO 0748−676 is constrained to be $\geq 1.1 \times 10^{21}$ atom cm^{-2}. All values of N_H, N_H^{xabs} and their changes are expressed in units of 10^{22} atom cm^{-2}.

LMXB	N_{Hpers}	ΔN_H	N_{Hgal}	$\Delta N_H/(N_{Hpers}\text{-}N_{Hgal})$	$N_H^{xabs}{}_{pers}$	ΔN_H^{xabs}	$\log(\xi)_{pers}$	$\log(\xi)_{dip}$	Dip depth
XB 1916−053	0.432 ± 0.002	0.46 ± 0.07	0.27	2.8 ± 0.4	4.2 ± 0.5	50 ± 3	3.05 ± 0.04	$2.52^{+0.02}_{-0.06}$	80%
XB 1323−619[a]	3.50 ± 0.02	0.7 ± 0.2	1.57	0.4 ± 0.1	3.8 ± 0.4	33 ± 2	3.9 ± 0.1	3.13 ± 0.07	75%
EXO 0748−676	0.11	$0.13^{+0.09}_{-0.05}$	0.11	∞	3.5 ± 0.2	12.0 ± 0.5	2.45 ± 0.02	2.26 ± 0.03	>85%
XB 1254−690	0.346 ± 0.002	0.04 ± 0.01	0.31	1.0 ± 0.3	8.4 ± 0.3	39 ± 3	4.3 ± 0.1	2.94 ± 0.05	50%
MXB 1659−298	0.306 ± 0.003	0.40 ± 0.04	0.19	3.5 ± 0.4	11.1 ± 0.6	42 ± 3	3.8 ± 0.1	$2.42^{+0.02}_{-0.06}$	>85%
X 1624−490[b]	10.7 ± 0.5	48^{+6}_{-3}	2.22	$5.7^{+0.7}_{-0.4}$	13 ± 2	55 ± 9	3.6 ± 0.2	≥3.3	80%

[a] Values for XB 1323−619 are derived from the spectral fits in [2].
[b] The changes for X 1624−490 are calculated between the Dip 1 and Dip 5 stages.

large changes in N_H observed from X 1624−490 during dips would indicate that we are viewing this source very close to the plane of the accretion disk. The eclipsing binaries EXO 0748−676 and MXB 1659−298 (together with the non-eclipsing system X 1624−490) show the largest change in N_H. This suggests that the size of the change in N_H may be related to the inclination angle. Thus we would be seeing X 1624−490 and XB 1254−690 very close to, and relatively far from, the planes of the accretion disks.

3. Conclusions

Modeling the spectral changes between persistent and dipping intervals is a powerful means of learning about the bulge and the accretion disk in all X-ray binaries. We have demonstrated that the complex changes in the 0.6–10 keV continuum and absorption lines during dips from most of the LMXBs studied may be self-consistently understood as resulting from large increases in N_H^{xabs} and decreases in ξ of a highly-ionized absorber, together with much smaller increases in the N_H of a neutral absorber. These changes are similar to those found for XB 1323−619 [2]. We do not need to invoke unusual abundances or partial coverage of an extended emission region to account for these changes.

These results suggest a geometry for the X-ray binaries such that the highly-ionized plasma is situated above the accretion disk. The absence of emission features in the spectra indicates that the photoionized plasma is mostly equatorial. When the binary is viewed relatively close to edge-on the plasma lies in our line-of-sight towards the X-rays emitted in the vicinity of the compact object, and signatures of the plasma appear in the spectrum, such as the Fe XXV and Fe XXVI absorption lines. This is the case of the dipping LMXBs studied here. At the azimuth where the stream of material from the companion star impacts the disk, there is material projected at higher altitudes above the disk. This bulge or thickened part of the disk passes through our line of sight at the dipping phase. Contrary to the complex continuum approach, our modeling indicates that this material is ionized (but less than the plasma seen during persistent intervals). It probably contains clumps of neutral material.

The precise distribution of the ionized absorber is unknown. Possibly, from the surface of the disk to higher altitudes, the density of the ionized material decreases and hence its ionization parameter increases. In any case, the geometry inferred from the dipping sources should be valid for all the other accreting binaries which only differ from the dipping ones in being viewed further away from the disk plane. This makes the dipping sources among the best targets to improve our understanding of the disk structure and of the accretion process. Long observations of dipping LMXBs will provide insight into the phase-distribution of the plasma, the inner and outer radii, height, density gradient, composition and velocity of the ionized material. Further, for variable sources, we can study the response of the ionized material to changes in the underlying source luminosity or spectral energy distribution. A large sample of sources will provide insight in the dependance of the properties of the ionized material on the system parameters such as the disk size or inclination.

In particular, even if the photo-ionized model provides an explanation for the origin of the spectral changes during dips, there are many questions still unresolved. Some examples are the frequent appearance and disappearance of dips in the dipping source XB 1254−690, recently observed also in XB 1916−053, or the apparent energy independent dips from 4U 1746−371, unlike those of the majority of LMXBs.

REFERENCES

1. Boirin, L. and Parmar, A., 2003, A&A, 407, 1079
2. Boirin L., Méndez M., Díaz Trigo M., Parmar A. N. and Kaastra J. S. 2005, A&A, 436, 195
3. Díaz Trigo M., Parmar A. N., Boirin L., Méndez M. and Kaastra J. S. 2006, A&A, 445, 179
4. Smale, A. P., Church, M. J. and Bałucińska-Church, M., ApJ, 581, 1286

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