A HIGHLY-IONIZED ABSORBER AS A NEW EXPLANATION FOR THE SPECTRAL CHANGES DURING DIPS FROM X-RAY BINARIES

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ABSTRACT

Until now, the spectral changes observed from persistent to dipping intervals in dipping low-mass X-ray binaries were explained by invoking progressive and partial covering of an extended emission region. Here, we propose a novel and simpler way to explain these spectral changes, which does not require any partial covering and hence any extended corona, and further has the advantage of explaining self-consistently the spectral changes in both the continuum and the narrow absorption lines that are now revealed by XMM-Newton. In $4U\,1323-62$, we detect Fe XXV and Fe XXVI absorption lines and model them for the first time by including a complete photo-ionized absorber model rather than individual Gaussian profiles. We demonstrate that the spectral changes both in the continuum and the lines can be simply modeled by variations in the properties of the ionized absorber. From persistent to dipping the photo-ionization parameter decreases while the equivalent hydrogen column density of the ionized absorber increases. In a recent work (see Díaz Trigo et al. in these proceedings), we show that our new approach can be successfully applied to all the other dipping sources that have been observed by XMM-Newton.

Key words: Accretion; accretion disks; X-ray binaries; $4U\,1323-62$.

1. INTRODUCTION

The lightcurves from dipping low-mass X-ray binaries (LMXBs) such as $4U\,1323-62$ show dips recurring at the orbital period of the system (Fig. 1 bottom). Dips are due to a structure passing through the line-of-sight at each orbital rotation. This structure is probably a thickened region of the disk related to the impact of the stream from the companion star into the disk. 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 (Fig. 1 top). 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, the "complex continuum" approach has been successfully applied to a number of dipping LMXBs including $4U\,1323-62$ (Bałucińska-Church et al. 1999). It assumes that the X-ray emission originates from two components, and the spectral changes during dips are explained by the partial and progressive covering of one of the components by a cool absorber, while the other component is rapidly and entirely covered by another cool absorber. This approach implies that the latter component comes from a point-like region such as the neutron star surface, whereas the former component comes from a very extended corona.

The improved sensitivity and spectral resolution of *Chandra* and XMM-Newton are allowing narrow absorption features from highly ionized Fe and other metals to be observed in a growing number of X-ray binaries. In particular, Fe XXV (He-like) or Fe XXVI (H-like) 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 1658−298, X 1624−490, X 1254−690, XB 1916−053 and now $4U\,1323-62$ (references in Boirin et al. 2005). These 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 then be a common feature of accreting binaries but preferentially detected in systems viewed close from the disk plane.

Here, we report the detection of Fe XXV and Fe XXVI absorption lines from the LMXB $4U\,1323-62$ and propose a new explanation for the spectral changes between persistent and dipping intervals (details in Boirin et al. 2005). We further show that this new explanation also applies to all the other bright dipping sources observed by XMM-Newton (see Díaz Trigo et al. in these proceedings and details in Díaz Trigo et al. 2005).
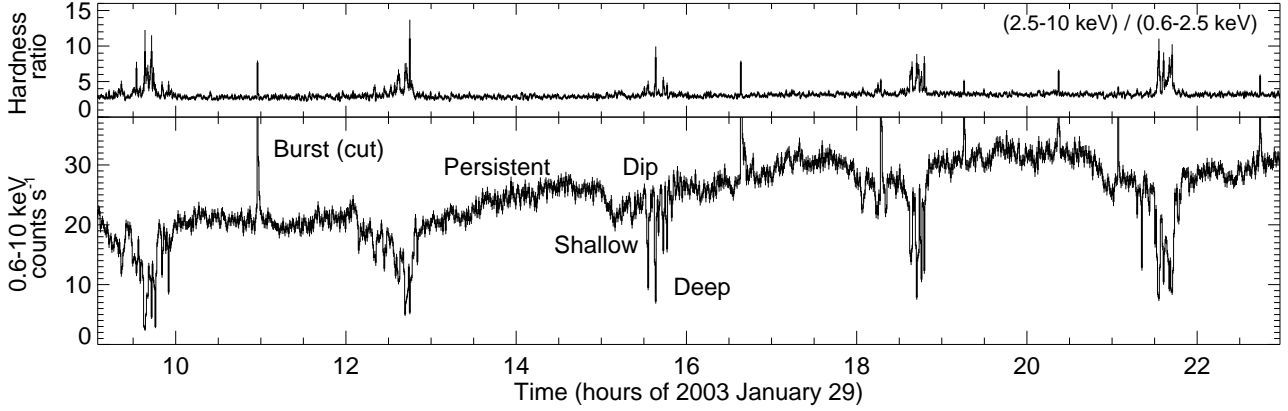
*Figure 1. 0.6–10 keV EPIC PN lightcurve of 4U 1323−62 (**bottom**). The dipping activity is associated with spectral hardening (**top**). Adapted from Boirin et al. (2005).*

2. RESULTS ON 4U 1323−62

We analyzed the 50 ks XMM-Newton observation of 4U 1323−62 performed on 2003 January 29 (Fig. 1). Bursts were excluded and one spectrum was extracted for each category of emission: persistent, shallow dipping and deep dipping. Fe XXV and Fe XXVI 1s-2p resonant absorption lines near 7 keV are clearly detected in the persistent spectrum (Fig. 2 A top), indicating that a highly-ionized disk atmosphere or wind is present in 4U 1323−62. Absorption lines are also present in the dipping spectra (Fig. 2 A middle and bottom) indicating that the structure causing the dips ("bulge" hereafter) is also ionized. However, clear spectral changes in the lines are visible from persistent to deep dipping: the strength of the Fe XXVI line decreases while that of Fe XXV increases, indicating that the bulge is less strongly ionized.

For the first time, to account for the absorption features evident near 7 keV, we include a photo-ionized absorber in the spectral model, rather than individual line profiles. We use the xabs model of SPEX, which 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. The relevant ions are automatically taken into account and their relative column densities are coupled in a physical way via a photoionization model.

We find that the persistent and dipping spectra are all well fit by a model consisting of a power-law, a blackbody and a broad Gaussian emission line, modified by absorption from neutral (abs) and ionized (xabs) material (Fig. 2 B and C). The ionized plasma has a lower ionization parameter and a larger column density during dipping. In all cases, it perfectly accounts for the narrow features near 7 keV. Remarkably, it also produces apparent continuum absorption which becomes substantial and strongly energy-dependent during dipping (compare

panels d in Fig. 2 B and C). Indeed, because the ionization is lower during dipping, there is a wider variety of ions than during persistent emission where most of the species are fully stripped of their electrons. Thus many more absorption lines and edges are expected during dipping (see Fig. 3 A). Furthermore, because the column density is larger, the edges are stronger. This explains the smooth variation of the transmission with energy (outside the sharp changes at the binding energies themselves).

By successfully fitting the dipping spectra using the persistent model, but fixing the parameters of the continuum to the persistent values, and allowing only the parameters of the absorbers (abs and xabs) to change, we actually demonstrate that the spectral changes from persistent to dipping can be modeled simply by variations in the properties of the neutral and ionized absorbers, with the ionized absorber playing the main role (Table 1). Contrary to the "complex continuum" model, the new proposed approach does not require any partial covering and hence does not require the underlying source of X-ray emission to be particularly extended in 4U 1323−62. The new explanation further presents the advantage of explaining self-consistently the spectral changes both in the continuum *and* the narrow lines.

Table 1. The column density of the neutral ($N_{\mathrm{H}}^{\mathrm{abs}}$) and ionized ($N_{\mathrm{H}}^{\mathrm{xabs}}$) absorbers and the ionization parameter $\log(\xi)$ in 4U 1323−62. During dipping, the ionized absorber has a lower ionization level and a larger column density. There is also more neutral absorber.

	Persistent	Shallow dip	Deep dip
$N_{\mathrm{H}}^{\mathrm{abs}}$	3.50 ± 0.02	3.58 ± 0.03	4.2 ± 0.2
$N_{\mathrm{H}}^{\mathrm{xabs}}$	3.8 ± 0.4	14 ± 1	37 ± 2
$\log(\xi)$	3.9 ± 0.1	3.43 ± 0.08	3.13 ± 0.07

$N_{\mathrm{H}}^{\mathrm{abs}}$ and $N_{\mathrm{H}}^{\mathrm{xabs}}$ are in 10^{22} cm^{-2} and ξ in erg cm s^{-1}.
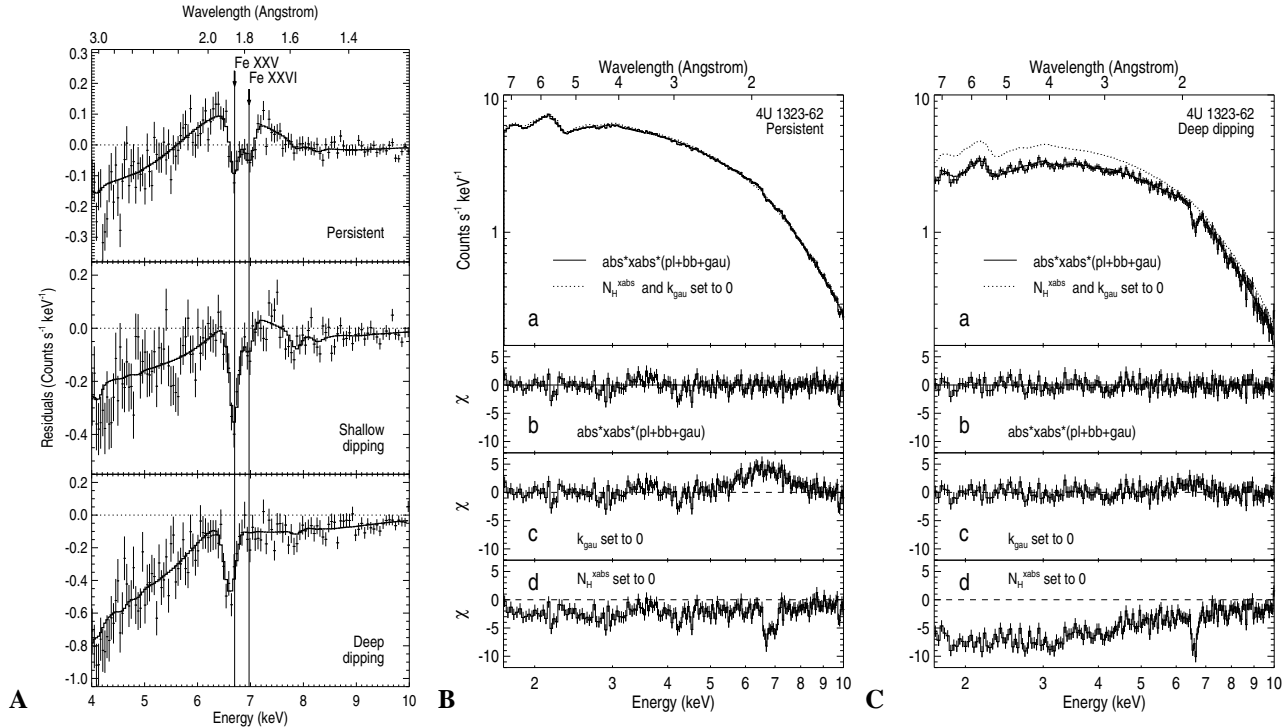
Figure 2. EPIC PN results on 4U 1323−62 from Boirin et al. (2005). **A)** 4–10 keV spectral residuals showing the Fe XXV and Fe XXVI absorption lines during persistent (**top**) and shallow (**middle**) emission. During deep dipping (**bottom**), the Fe XXVI line is not present anymore: the absorber is less strongly ionized. **B) a)** Persistent spectrum fit with a model consisting of a power-law (pl), a blackbody (bb) and a broad Gaussian emission line (gau), modified by absorption from neutral (abs) and ionized (xabs) material. **b)** Flat residuals from the above model indicating that the fit is good. **c)** Residuals showing the contribution of the Gaussian emission line at 6.6 keV (by setting its normalization, k_{gau}, to 0). **d)** Residuals showing the contribution of the ionized absorber (by setting $N_{\mathrm{H}}^{\mathrm{xabs}}$ to 0). It perfectly accounts for the narrow Fe XXV and Fe XXVI absorption lines. **C)** Same as **B** but for the deep dipping intervals. The ionized absorber does not only produce the line near 7 keV, but also energy-dependent absorption throughout the spectrum (panel **d**).
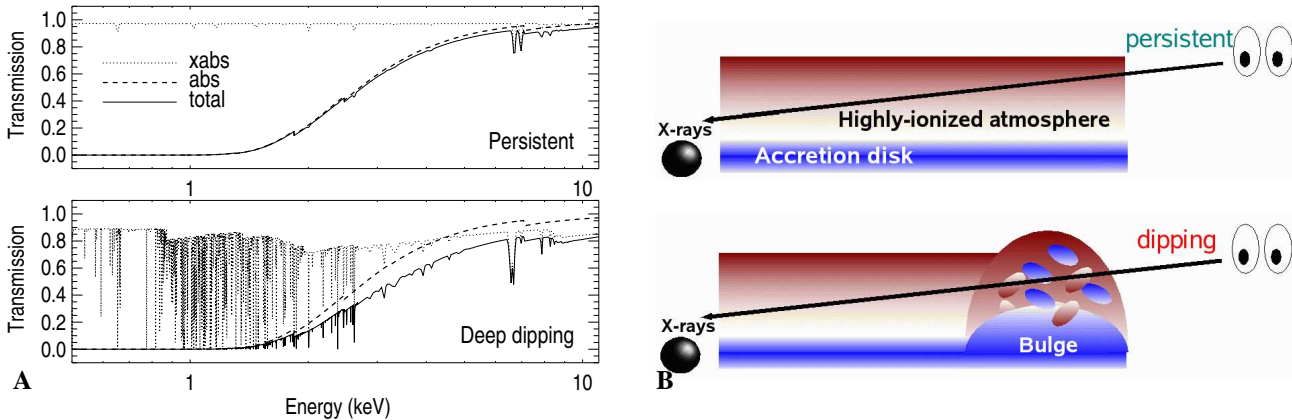

Figure 3. **A)** Transmission of the ionized (dotted line) and neutral absorbers (dashed line), and the total transmission (thick line) during persistent (**top**) and deep dipping (**bottom**) intervals of 4U 1323−62 (adapted from Boirin et al. 2005). During persistent segments, the ionized plasma transmits all the photons except those with an energy matching the Fe XXV and Fe XXVI transitions, while during deep dipping, the transmission is affected by lines and edges from many ions and becomes strongly energy-dependent. The neutral absorption is larger during dipping than during persistent states, indicating that part of the neutral absorber is located in the binary rather than in the interstellar medium, at least during dipping. **B)** These results suggest that a highly-ionized atmosphere is present above the accretion disk and seen in absorption during persistent segments (**top**). During dipping (**bottom**), the bulge passes through the line-of-sight. It's denser, a bit less ionized and probably contains clumps of neutral material.
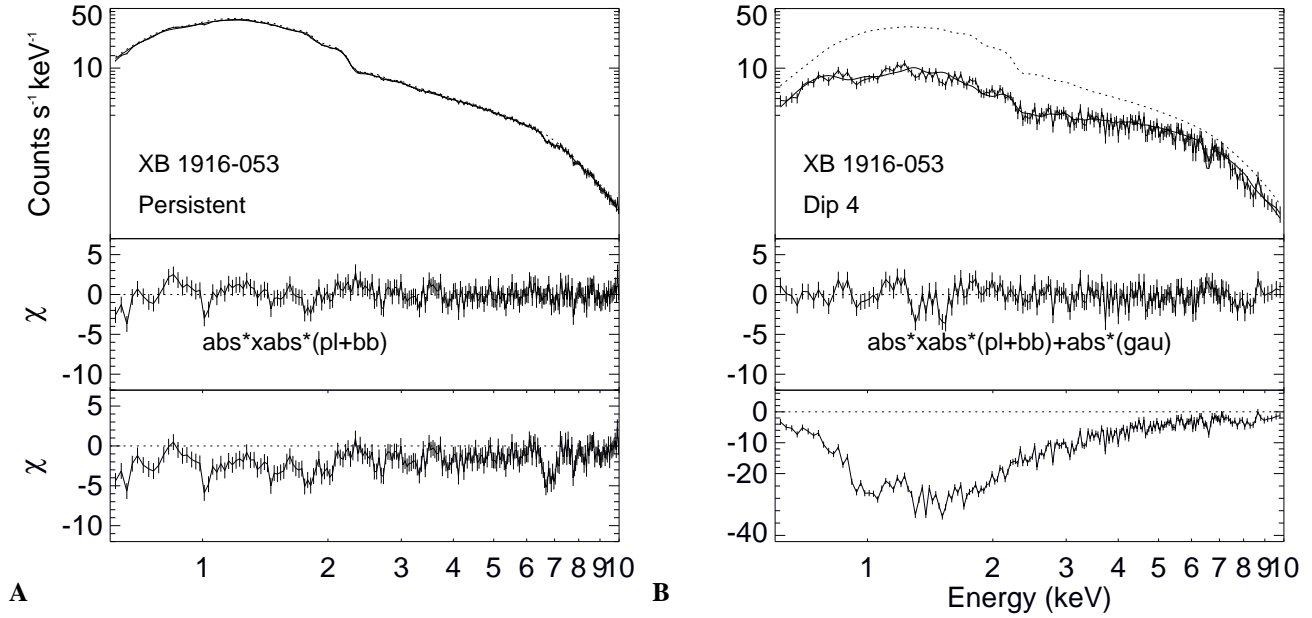
Figure 4. EPIC PN persistent (**left**) and dipping (**right**) spectra of XB 1916−053 fit using a photo-ionized absorber model (from Díaz Trigo et al. 2005). The flat residuals in the **middle** panel indicate that the fits are good. The contribution of the ionized absorber is shown in the **bottom** panel (by setting $N_{\mathrm{H}}^{\mathrm{xabs}}$ to 0). During persistent intervals, it produces mainly the narrow absorption lines near 7 keV, while during dipping, it also produces strong energy-dependent absorption throughout the spectrum.
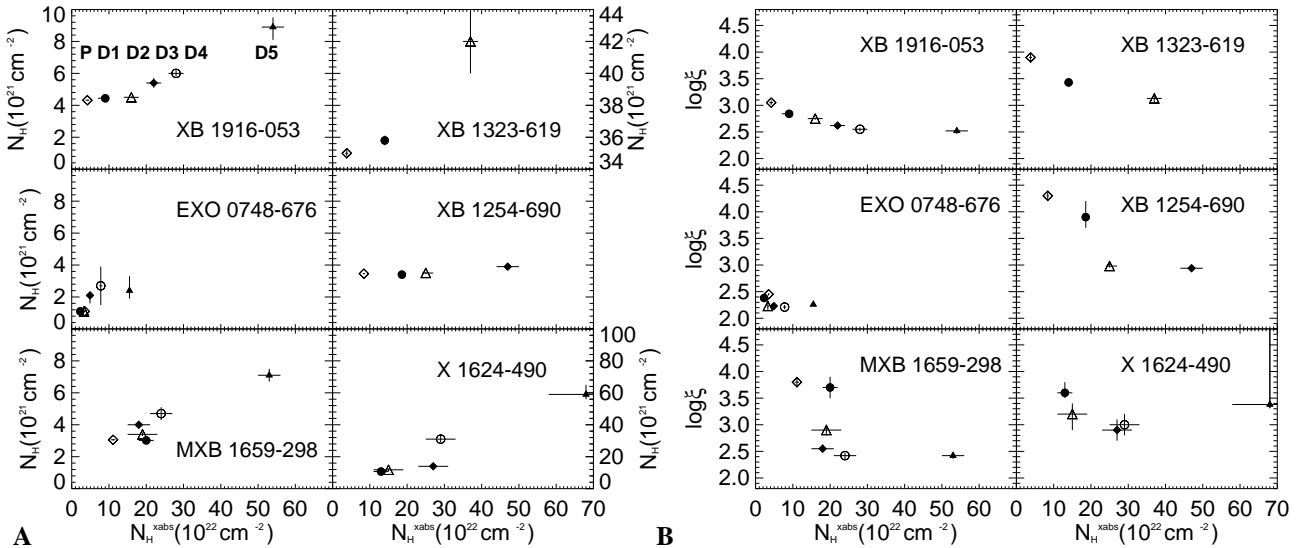

Figure 5. Main properties of the ionized and neutral absorbers in the dipping binaries where the photo-ionization absorber model was tested (from Díaz Trigo et al. 2005). Each symbol represents a different intensity stage of the source, from the persistent level, P, to the deepest dipping level, D5, as indicated in the top left panel. **A)** Column density of the neutral absorber, N_{H}, (including local and interstellar material) versus column density of the local ionized absorber, $N_{\mathrm{H}}^{\mathrm{xabs}}$. In all the sources, the amount of both neutral and ionized material in the line-of-sight increases from persistent to deep dipping stages. **B)** Ionization parameter, ξ, versus column density, $N_{\mathrm{H}}^{\mathrm{xabs}}$, of the ionized absorber. In all the sources, the ionization parameter decreases from persistent to deep dipping while $N_{\mathrm{H}}^{\mathrm{xabs}}$ increases.

3. RESULTS ON OTHER DIPPING SOURCES

To test the new proposed explanation for the spectral changes, Díaz Trigo et al. (2005) analyzed the EPIC PN data of all the bright dipping binaries observed by XMM-Newton: XB 1916−053, EXO 0748−676, X 1254−690, 4U 1746−371, MXB 1658−298 and X 1624−490 (see Díaz Trigo et al. in these proceedings). For each source (except 4U 1746−371 whose dips were too shallow for the analysis to be carried out), the persistent and dipping spectra were fit together with the parameters of the underlying continuum emission tied together, and the parameters of the absorbers (one neutral, abs, and one photo-ionized, xabs) left free to vary. Good fits were obtained for each source (see the case of XB 1916−053 in Fig. 4). Thus, the changes in the properties of a neutral and of an ionized absorber in the line-of-sight can account for the spectral changes in the continuum and in the narrow features of all the dipping sources that could be tested so far. From persistent to deep dipping, the amount of neutral absorber increases (Fig. 5 A), corresponding to an increase by a factor ~ 2 in the amount of the local material. At the same time, the column density of the ionized absorber is found to increase by a factor of 4 to 12 (Fig. 5 A) while its ionization parameter decreases (Fig. 5 B). The changes in this ionized material clearly play the main role in explaining the overall energy-dependent spectral changes observed in the dipping sources (see the bottom panel of Fig. 4 A and B showing the contribution of the ionized absorber).

4. CONCLUSIONS AND PROSPECTS

Modeling the spectral changes between persistent and dipping intervals is a powerful means of learning about the bulge and the accretion disk in all the X-ray binaries. Until now, these spectral changes were modeled by invoking absorption of a point-like emission region by a neutral absorber, together with progressive and partial covering of an extended emission region by another neutral absorber. We propose a novel and simpler explanation invoking a neutral absorber and a photo-ionized absorber. It was successfully applied to all the bright dipping sources that could be tested to date: 4U 1323−62, XB 1916−053, EXO 0748−676, X 1254−690, MXB 1658−298 and X 1624−490. No partial covering was needed, indicating that none of the underlying X-ray sources requires to be particularly extended. The new approach has the strong advantage of explaining self-consistently the spectral changes both in the continuum and in the narrow absorption lines that have been revealed by XMM-Newton.

These results suggest a geometry for X-ray binaries such as drawn in Fig. 3 B. A highly-ionized plasma is present above the accretion disk. If the binary is viewed relatively close to edge-on, the ionized plasma lies in our line-of-sight toward 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 in the persistent spectrum of 4U 1323−62. 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 during dipping. Contrary to the complex continuum approach, our modeling of the dipping spectra 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. If the ionized absorber is present at the radius of the bulge, its layers could be shifted to higher altitudes. This could explain the differences observed between persistent and dipping intervals in a given source, and the differences in the absorbers properties observed from source to source, as a function of inclination. 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.

Here are some of the key issues that we would like to address thanks to future detailed X-ray observations of the dipping sources:

- constraints on the distribution of the ionized material: inner and outer radii, height, density gradient, ionization gradient, composition, velocity (static atmosphere versus out-flowing wind);

- response of the ionized material to changes in the underlying source luminosity or spectral energy distribution;

- dependence of the properties of the ionized material on the system parameters such as the disk size or inclination;

- role of the reflection (back-scattering) of X-rays onto the ionized and neutral materials.

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