Discovery of X-ray absorption lines from the low-mass X-ray binaries 4U 1916-053 and X 1254-690 with XMM-Newton

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We report the discovery of narrow X-ray absorption features from the two dipping low-mass X-ray binary 4U 1916-053 and X 1254-690 during XMM-Newton observations. The features detected are identified with resonant scattering absorption lines of highly ionized iron (Fe XXV and Fe XXVI). Resonant absorption features are now observed in a growing number of low-mass X-ray binaries (LMXBs): the two superluminal jet sources GRS 1915+105 and GRO J1655-40, the bright LMXB GX 13+1 and the four dipping sources MXB 1658-298, X 1624-490, 4U 1916-053 and X 1254-690. The early hypothesis that their origin could be related to the presence of superluminal jets is thus ruled out. Ionized absorption features may be common characteristics of accreting systems. Furthermore, their presence may depend on viewing angle, as suggested by their detection in dippers which are viewed close to the disk plane, and by the fact that GRS 1915+105, GRO J1655-40 and GX 13+1, although not dippers, are suspected to be also viewed at high inclination.

1. INTRODUCTION

1.1. 4U 1916-053 and X 1254-690

4U 1916-053 and X 1254-690 are two LMXBs showing periodic intensity dips in their X-ray light curves. The dips recur at the orbital period of the system. Dips are believed to be due to obscuration of the central X-ray source by vertical structure located at the outer edge of the accretion disk and due to the impact of the accretion flow from the companion star into the disk \cite{1}. The presence of dips in these two sources and the lack of X-ray eclipses from the companion star indicate that the system is viewed relatively close to edge-on, at an inclination angle in the range \(\sim 60\)–\(80\)\(^\circ\) \cite{2}. The period of the dips is 50 minutes in 4U 1916-053 \cite{3} and 3.88 h in X 1254-690 \cite{4}. 4U 1916-053 and X 1254-690 have been observed using a variety of X-ray instruments. In X 1254-690 the dips were not detected during all observations, but the dipping activity ceased and re-appeared several times. A likely explanation for the absence of dips during some observations is that the vertical structure in the outer region of the accretion disk had decreased in size, so that the central X-ray source could be viewed directly \cite{5}.

1.2. Narrow absorption features in X-ray binaries

Narrow absorption features from highly ionized Fe and other metals in the spectra of LMXBs were first seen from GX 13+1 using ASCA by Ueda et al. \cite{6} who detected a narrow absorption feature at 7.01 keV which they interpreted as resonant scattering of the K\(\alpha\) line from H-like Fe. XMM-Newton observations revealed an even more complex picture for GX 13+1 with narrow absorption features identified with the K\(\alpha\) and K\(\beta\) transitions of He- and H-like iron (Fe XXV and Fe XXVI) and H-like calcium (Ca XX) K\(\alpha\) detected \cite{7}. There is also evidence for the presence

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of a deep Fe XXV absorption edge at 8.83 keV and of a broad emission feature around 6.4 keV. XMM-Newton observations of the eclipsing and dipping LMXB MXB 1658-298 revealed narrow absorption features identified with O VIII Kα, Kβ, and Kγ, Ne X Kα, Fe XXV Kα, and Fe XXVI Kα together with a broad Fe emission feature at 6.47 keV \[8\]. Another LMXB dip source, X 1624-490, also displays Kα absorption lines identified with Fe XXV and Fe XXVI, as well as fainter absorption features tentatively identified with Ni XXVII Kα and Fe XXVI Kβ. A broad emission feature at 6.58 keV is also evident \[9\].

The properties of the absorption features in the 3 LMXBs show no obvious dependence on orbital phase, except during a dip from X 1624-490, where there is evidence for the presence of additional cooler material. Previously, the only X-ray binaries known to exhibit such narrow X-ray absorption lines were two superluminal-jet sources, and it had been suggested that these features are related to the jet formation mechanism. This now appears unlikely, and instead, as we discuss below, their presence is probably related to the viewing angle of the system.

Here we report the discovery of narrow X-ray absorption features from highly ionized Fe in the XMM-Newton spectra of 4U 1916-053 and X 1254-690. Detailed reports on these discoveries may be found in \[10\] and \[11\] respectively.

2. OBSERVATIONS & RESULTS

4U 1916-053 was observed by XMM-Newton \[12\] for 5 h on 2002 September 25. X 1254-690 was observed for 4 h on 2001 January 25, and for 7 h one year later on 2002 February 7. We report results obtained with the EPIC pn camera \[13\] in the 0.5–10 keV energy band.

2.1. X-ray light curves

Fig. 1 shows the EPIC pn light curves of 4U 1916-053 on 2002 September (top), X 1254-690 on 2001 January (middle), and X 1254-690 again on 2002 February (bottom). The upper panels show the hardness ratio (counts in the 2.5–10 keV band divided by counts in the 0.5–2.5 keV band). The binning time is 20 s in every panel.

![Figure 1. The 0.5–10 keV EPIC pn background subtracted light curves of 4U 1916-053 on 2002 September (top), X 1254-690 on 2001 January (middle), and X 1254-690 again on 2002 February (bottom). The upper panels show the hardness ratio (counts in the 2.5–10 keV band divided by counts in the 0.5–2.5 keV band). The binning time is 20 s in every panel.](image-url)
nearly two orbital periods of the system. Such a cessation and re-appearance of the dipping activity has already been observed [11,15]. The persistent intensity of X 1254-690 is \( \sim 185 \text{ counts s}^{-1} \) and \( \sim 175 \text{ counts s}^{-1} \) during the 2001 and 2002 observations, respectively.

### 2.2. X-ray spectra

#### 2.2.1. Persistent emission

Persistent-emission spectra were extracted from the 4U 1916-053, the X 1254-690 2001 and 2002 observations by selecting non-dipping intervals. The overall continua were modeled using absorbed multicolor disk-blackbody and power-law components. The spectra fit with such models are shown in Fig. 2 (upper panels). The spectrum of X 1254-690 during the 2002 observation is not shown, as it is very similar to the 2001 observation one.

Examination of the residuals (middle panels of Fig. 2) reveals broad structure around 1 keV. This structure is well modeled by an edge at 1.8 keV and \( \sim 1 \text{ keV} \) structure in 4U 1916-053. These absorption features in 4U 1916-053 and X 1254-690.

Examination of the remaining fit residuals shows several deep negative residuals around 7 keV (Fig. 3). These were modeled by Gaussian absorption lines whose properties (the line energy, \( E_{\text{line}} \), the width, \( \sigma \), and the equivalent width, \( EW \)) are given in Table 1 and whose significance was checked to be higher than 3\( \sigma \) using F-tests. This is the first detection of such absorption features in 4U 1916-053 and X 1254-690. The measured energy of the Gaussian lines are consistent with Fe XXV K\( \alpha \) and Fe XXVI K\( \alpha \) transitions in the case of X 1254-690. In addition to these clearly detected lines, in the case of 4U 1916-053, there is marginal evidence for three other absorption features at 7.82 keV, 8.29 keV, and 2.67 keV at energies consistent with Ni XXVII K\( \alpha \), Fe XXVI K\( \beta \) and S XXVI transitions, respectively.

In order to investigate whether the properties of the absorption features depend on orbital

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**Table 1**

Properties of the absorption Gaussian lines detected in 4U 1916-053 and X 1254-690. The underlying continuum models include a disk-blackbody, a power-law and an edge or a Gaussian emission feature near 1 keV.

|              | Persistent Emission |
|--------------|---------------------|
|              | 4U 1916-053 2001 Jan. | X 1254-690 2002 Feb. |
| **Fe XXV K\( \alpha \)** absorption Gaussian | | |
| \( E_{\text{line}} \) (keV) | 6.65 \( \pm 0.05 \) | 6.95 \( \pm 0.04 \) | 6.96 \( \pm 0.04 \) |
| \( \sigma \) (eV) | <100 | <120 | <95 |
| \( EW \) (eV) | \( -30 \pm 12 \) | \( -27 \pm 8 \) | \( -21 \pm 8 \) |
| **Fe XXVI K\( \alpha \)** absorption Gaussian | | |
| \( E_{\text{line}} \) (keV) | 8.29 \( \pm 0.05 \) | 8.16 \( \pm 0.06 \) |
| \( \sigma \) (eV) | <170 | <80 |
| \( EW \) (eV) | \(-17 \pm 9 \) | \(-16 \pm 9 \) |

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**Table 2**

Properties of the Fe XXVI K\( \alpha \) absorption Gaussian line detected in 3 individual segments of persistent emission during the 2001 observation of X 1254-690.

| X 1254-690 Persistent emission (2001 Jan.) | Segment 1 | Segment 2 | Segment 3 |
|------------------------------------------|----------|----------|----------|
| Phase range | 0.12-0.35 | 0.35-0.59 | 0.59-0.82 |
| **Fe XXVI K\( \alpha \)** absorption Gaussian | | |
| \( E_{\text{line}} \) (keV) | 6.93 \( \pm 0.09 \) | 6.95 \( \pm 0.03 \) | 6.97 \( \pm 0.04 \) |
| \( \sigma \) (eV) | <185 | <140 | <126 |
| \( EW \) (eV) | \(-22 \pm 15 \) | \(-21 \pm 11 \) | \(-31 \pm 14 \) |
phase, the persistent emission interval of the 2001 observation of X 1254-690 was divided into three intervals of \( \sim 3220 \) s. To estimate the phases covered by these intervals, we use a period of 3.88 h and the time 19.25 h of 2001 January 22, corresponding to the apparent dip center, as an arbitrary reference for phase 0. The same continuum model as the one used for the total persistent spectrum was fit to the 3 individual spectra. The Fe \( \alpha \) absorption feature is clearly evident, but the Fe \( \alpha \) absorption feature is not significantly detected. The properties of the Fe \( \alpha \) absorption features in the 3 segments are given in Table 2. They are all consistent with those obtained from the total persistent spectrum. Thus, there does not appear to be any obvious dependence of the Fe \( \alpha \) absorption feature properties on orbital phase during the persistent emission.

2.2.2. Dipping emission

In order to investigate the properties of eventual absorption features during the dipping intervals, three spectra were extracted during the dipping emission of 4U 1916-053, based on intensity selection criteria. Events corresponding to a background-subtracted pn count rate in the range 40–60, 20–40 and 0–20 s\(^{-1}\) (see Fig. 1) were extracted to form “shallow”, “intermediate” and “deep” dipping spectra, respectively. The same continuum model as the one used for the total persistent spectrum was fit to the 3 individual dipping spectra with all the parameters fixed except the normalizations and the absorbing column density, which were allowed to vary in order to account for the spectral variations of the continuum during dipping. This models the overall continuum shape reasonably well. Furthermore, an absorption feature at \( \sim 6.7 \) keV is also detected in each intensity-selected spectrum. Its energy is consistent with a Fe \( \alpha \) transition, as in the persistent spectrum. The deep dipping spectrum also shows a second absorption feature at \( \sim 8.35 \) keV. Its energy is roughly consistent with a Fe \( \beta \) transition. However, this identification is inconsistent with the absence of the Fe \( \alpha \) line in the spectrum. Thus, the interpretation of the feature at 8.35 keV is unclear.

| Table 3 |
|---|
| Properties of the absorption Gaussian lines detected in the three intensity-selected dipping spectra (shallow, intermediate and deep) of 4U 1916-053. |

| 4U 1916-053 Dipping emission |
|---|
| **Shallow** | **Inter.** | **Deep** |
| Fe \( \alpha \) absorption Gaussian |
| \( E_{\text{line}} \) (keV) | 6.70 ± 0.05 | 6.67 ± 0.06 | 6.59 ± 0.05 |
| \( \sigma \) (eV) | <110 | 160 ± 60 | <173 |
| \( EW \) (eV) | -74 ± 20 | -164 ± 44 | -119 ± 45 |
| Second absorption Gaussian |
| \( E_{\text{line}} \) (keV) | 8.35 ± 0.05 |
| \( \sigma \) (eV) | <144 |
| \( EW \) (eV) | -120 ± 50 |

3. DISCUSSION

We have reported the discovery of several narrow absorption lines consistent with Fe \( \alpha \) or Fe \( \beta \) transitions in the persistent emission spectra of the two dipping LMXBs 4U 1916-053 and X 1254-690. There is no evidence for orbital dependence of the properties of the lines during the persistent emission of X 1254-690. An Fe \( \alpha \) absorption feature is also detected during intensity-selected dipping spectra of 4U 1916-053, as in the persistent spectrum. The detection of these lines indicate the presence of a highly ionized plasma within these sources.

Narrow X-ray absorption lines were first detected from the superluminal-jet sources GRO J1655-40 [10,17] and GRS 1915+105 [18,19]. ASCA observations of GRO J1655-40 revealed the presence of absorption features due to Fe \( \alpha \) and Fe \( \beta \) which did not show any obvious dependence of their \( EWs \) on orbital phase. GRO J1655-40 has been observed to undergo deep absorption dips [20] consistent with observing the source at an inclination angle, \( \iota \), of 60°–75° [2]. An inclination of 69.5±0.3° is independently attributed to GRO J1655-40 from optical observations by [21]. ASCA observations of GRS 1915+105 revealed, in addition, absorption features due to Ca \( \alpha \), Ni \( \alpha \) and Ni \( \alpha \). A recent Chandra HETGS observation of this source revealed ab-
Figure 2. The upper panels show the EPIC pn spectra of the persistent emission of 4U 1916-053 (left) and of X 1254-690 during the 2001 observation, and the best-fit disk-blackbody and power-law continuum models. The residuals (middle panels) reveal the presence of a broad feature centered around 1 keV, together with several narrow absorption features around 7 keV. The lower panels show the residuals when these features are included in the spectral model.

Figure 3. Zoom of the residuals around 7 keV for 4U 1916-053 (left) and X 1254-690 (right) when the best-fit models discussed in the text are fit to the pn spectra of the persistent emission and the normalisations of the narrow absorption features are set to zero.
sorption edges of Fe, Si, Mg, and S, as well as resonant absorption features from Fe XXV and Fe XXVI and possibly Ca XX [19]. An inclination of \( \sim 70^\circ \) is attributed to GRS 1915+105, assuming that the jets are perpendicular to the accretion disk [22]. Until recently, it was possible that these absorption features were peculiar to superluminal-jet sources and related in some way to the jet formation mechanism. With the discovery of narrow absorption features from the LMXBs GX 13+1 [6], MXB 1658-298 [8], X 1624-490 [9], and now from 4U 1916-053 and X 1254-690, this appears not to be the case. As proposed by Kotani et al. [18], ionized absorption features may be common characteristics of disk accreting systems. However, it is interesting to note that 3 of the above 4 LMXBs are dipping sources. These are systems that are viewed from directions close to the plane of their accretion disks with \( i \sim 60\text{--}80^\circ \) [2]. This suggests that inclination angle is important in determining the strength of these absorption features, which implies that the absorbing material is distributed in a cylindrical, rather than a spherical geometry, around the compact object. The azimuthal symmetry is implied by the lack of any evident orbital dependence of these features, neither during the persistent emission, nor during the dipping emission.

The conclusions about the X-ray absorption features discovered in LMXBs may be summarized as follows:

- The absorption features are caused by highly ionized ions (iron or other metals).
- The early hypothesis of their origin being related to superluminal jets is ruled out.
- Highly ionized plasmas are probably common characteristics of disk accreting systems.
- Absorption features are preferably observed in systems viewed at high inclination.
- The highly ionized absorbing material is probably distributed in a flat cylindrical geometry around the compact object.

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