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Towards an informed quest for accretion disc winds in quasars: the intriguing case of Ton 28

E. Nardini, E. Lusso and S. Bisogni
1INAF – Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, I-50125 Firenze, Italy
2Centre for Extragalactic Astronomy, Department of Physics, Durham University, South Road, Durham DH1 3LE, UK
3Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

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ABSTRACT
We report on the detection of a blueshifted Fe K absorption feature in two consecutive XMM-Newton observations of the luminous blue quasar Ton 28, at the 4σ cumulative significance. The rest energy of 9.2 keV implies the presence of an accretion disc wind with bulk outflow velocity of ~0.28c, while the kinetic power is most likely a few per cent of the quasar luminosity. Remarkably, Ton 28 had been specifically selected as an optimal target to reveal an ultra-fast X-ray wind based on its total luminosity ($L_{bol} > 10^{46}$ erg s$^{-1}$) and [O III] λ5007 Å equivalent width (EW $< 6$ Å), suggestive of high accretion rate and low inclination, respectively. Other peculiar optical/UV emission-line properties include narrow Hβ, strong Fe II, and blueshifted C IV. These are key parameters in the Eigenvector 1 formalism, and are frequently found in active galaxies with ongoing accretion disc winds, hinting at a common physical explanation. Provided that the effectiveness of our selection method is confirmed with similar sources, this result could represent the first step towards the characterization of black hole winds through multiwavelength indicators in the absence of high-quality X-ray spectra.

Key words: galaxies: active – quasars: individual: Ton 28 – X-rays: galaxies.
whereas Fe K absorption features in local Seyferts have marginal significance, lower blueshifts, and/or transient nature (Ponti et al. 2013; Braito et al. 2014; Marinucci et al. 2018). The latter cut leaves 145 sources. We further imposed a ROSAT detection, whose merit is twofold: providing information on the X-ray brightness, and minimizing the chance of X-ray obscuration. Of the 43 remaining sources, 36 are radio-quiet: we chose the one with the highest X-ray count rate, Ton 28.

Ton 28 is among the most luminous (Lbol $\sim 2.5 \times 10^{46}$ erg s$^{-1}$; Shen et al. 2011) non-jetted quasars at relatively low redshift ($z \simeq 0.329$), whose optical and ultraviolet (UV) spectra have been extensively examined in the literature, mainly for its nature of background beacon (e.g. Danforth et al. 2016). A portion of its SDSS spectrum is shown in Fig. 1. The Fe II emission strength is a direct consequence of our selection, given its well-known anti-correlation with [O III] (Boroson & Green 1992). In the UV, the Hubble Space Telescope spectrum exhibits an asymmetric C IV $\lambda 1549$ Å profile, blueshifted by 1120 km s$^{-1}$ at the full-width at half maximum (FWHM) centroid, which was kinematically modelled alongside the blueshifted [O III] component (680 km s$^{-1}$) as arising from the same radial outflow of conical shape, with half-opening angle of 85° and inclination of 15° (Zamanov et al. 2002). In the empirical framework designed to organize and explain the diversity of quasars known as ‘Eigenvector 1’ (see Balas et al. 2000, 2007 for details), all these optical/UV spectral properties point at the specific region of the main sequence occupied by extreme population A sources (Marziani et al. 2003), suggesting a possible route to further refine our selection criteria. By virtue of its luminosity, Ton 28 also stands out as a potential twin to PDS 456, the prototype of quasar twin (Done et al. 2012), which self-consistently combines warm and hot Comptonization from the inner accretion disc atmosphere and the X-ray corona, respectively originating the soft excess and the hard power law, and also accounts for thermal emission from the outer disc. In particular, with optxagnf, we can probe the shape of the ionizing continuum, whose convenience will become clearer later.

Figure 1. Zoom in on to the Hβ region of the SDSS spectrum of Ton 28. Best-fit model (red curve) and residuals (bottom panel) are also shown. The main emission components are plotted with different colours: Hβ in green, total [O III] $\lambda\lambda 4959,5007$ Å (narrow plus broad, blueshifted) in blue, total Fe II in orange, other lines (Hδ, Hγ, He II $\lambda 4686$ Å) in magenta. The shaded bands correspond to masked pixels. See Bisogni et al. (2017) for more details.

3 DATA ANALYSIS

The EPIC instruments were operated in Large-Window mode with medium optical filter, and the corresponding event files were reprocessed within the Science Analysis System (SAS) v16.1.0. In this Letter, we only concentrate on the EPIC/pn spectra, as the effective area of the two MOS detectors quickly falls off at high energy and does not provide enough statistics for our analysis. The source spectra were extracted from circular regions of 30° radius around the position of the target, while the background was estimated over a nearby 60° circle situated on the same chip. Single and double pixel events (patterns 0–4) were selected. Redistribution matrices and ancillary response files were generated, respectively, with rmfgen and arfgen.

The first observation (Obs. 1) was significantly affected by background flares. The standard filtering criterion, based on the fiducial acceptable threshold for the overall 10–12 keV count rate, turns out to be overly conservative in this case, entailing the rejection of about 41 per cent of the net exposure time. We have therefore followed an optimized procedure aimed at maximizing the spectral quality in the 2–8 keV band. Specifically, only the periods that cause the degradation of the signal-to-noise ratio in the energy range of interest were discarded (see Piconcelli et al. 2004 for a more detailed description of this method). This allowed us to recover a further 25 per cent of the total exposure compared to the standard cut, for a good time interval of 31.5 ks. Apart from a very minor flare, the background was low and stable for the entire span of the second observation (Obs. 2), so the full exposure of 41.4 ks is available (Table 1).

The spectral analysis has been performed with the xspec v12.9.1 fitting package. The data were binned to ensure a significance of at least 4$\sigma$ per energy channel, and the uncertainties are given at the 90 per cent confidence level ($\Delta \chi^2 = 2.71$) for the single parameter of interest, unless stated otherwise. Since the spectral variability is negligible (see below), we also created with the usual FTooltasks a merged spectrum and the relative response files, which have been used for a consistency check of our results. The photometric fluxes from the five requested Optical Monitor (OM) filters (all except UVW2) have also been retrieved for comparison with the SDSS spectrum and the X-ray emission.

Table 1. Log of the XMM–Newton observations of Ton 28.

<table>
<thead>
<tr>
<th>Obs. ID</th>
<th>Date – Time (UTC)</th>
<th>Exp. (ks)</th>
<th>Counts $^{c}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0804560101</td>
<td>2017 May 14–06:10:55</td>
<td>31.462</td>
<td>28392</td>
</tr>
<tr>
<td>0804560201</td>
<td>2017 May 15–23:37:04</td>
<td>41.369</td>
<td>35979</td>
</tr>
</tbody>
</table>

Notes. $^{a}$Exposure start. $^{b}$Net exposure. $^{c}$Net 0.3–10 keV counts.
Figure 2. EPIC/pn spectra of Ton 28 from the first (red) and the second (blue) XMM–Newton observation. A power law with $\Gamma = 1.9$, only modified by the Galactic column density at low energies, is also plotted for reference (black dotted curve). This brings out the prominent soft excess and a possible absorption feature at about 9.2 keV, as indicated by the arrow. Note that the latter feature appears to be present in both spectra, despite the markedly different background level (shaded regions) in the hard X-rays between the two observations.

Figure 3. Residuals in units of standard deviations ($\sigma$) after removing the blueshifted absorption feature from the best-fitting model at 3–10 keV (observed). Colours are as follows: red (Obs. 1), blue (Obs. 2), green (merged). The vertical line indicates the expected position of the Fe $xxvi$ Kα transition at rest. The latter identification implies an outflow velocity of $v_{\text{out}} \sim 0.25$–0.30c.

Table 2. Best-fitting absorption line parameters when modelled with a Gaussian profile against the local power-law continuum. $F$ is the flux over the observed 3–10 keV band, while $\Delta \chi^2$ is the statistical improvement after the inclusion of the line (for the loss of two degrees of freedom). The line’s rest energy is frozen ($f$), and its rest EW is $-340 (\pm 160)$ eV (tied, 90 per cent confidence).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Obs. 1</th>
<th>Obs. 2</th>
<th>Tied</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{abs}}$ (keV)</td>
<td>6.97(f)</td>
<td>6.97(f)</td>
<td>6.97(f)</td>
</tr>
<tr>
<td>$v_{\text{out}}/c$</td>
<td>$0.29^{+0.03}_{-0.04}$</td>
<td>$0.25^{+0.04}_{-0.03}$</td>
<td>$0.25^{+0.04}_{-0.03}$</td>
</tr>
<tr>
<td>$A_{\text{abs}} (10^{-6} \text{s}^{-1} \text{cm}^{-2})$</td>
<td>$-1.7^{+0.1}_{-0.2}$</td>
<td>$-1.0^{+0.3}_{-0.5}$</td>
<td>$-1.2^{+0.5}_{-0.6}$</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>1.95$^{+0.25}_{-0.20}$</td>
<td>1.81$^{+0.20}_{-0.19}$</td>
<td>1.88$^{+0.15}_{-0.16}$</td>
</tr>
<tr>
<td>$F (10^{-13} \text{erg s}^{-1} \text{cm}^{-2})$</td>
<td>$3.7^{+1.0}_{-1.2}$</td>
<td>$3.6^{+0.4}_{-0.2}$</td>
<td>$3.7^{+0.4}_{-0.1}$</td>
</tr>
<tr>
<td>$\chi^2/\nu$</td>
<td>44.0/38</td>
<td>63.3/58</td>
<td>111.6/102</td>
</tr>
<tr>
<td>$\Delta \chi^2$</td>
<td>$-7.6$</td>
<td>$-12.9$</td>
<td>$-19.5$</td>
</tr>
<tr>
<td>$F$-test probability</td>
<td>0.9514</td>
<td>0.9954</td>
<td>0.9997</td>
</tr>
</tbody>
</table>

Irrespective of the broad-band interpretation, negative residuals remain in both spectra at about 6.9 keV (9.2 keV in the rest-frame; Fig. 3). To better examine the properties of this possible absorption feature, we focused on the 3–10 keV band, following the common practice of modelling the local continuum only (e.g. Tombesi et al. 2010). The spectra from Obs. 1 and Obs. 2 were fitted separately, yielding remarkably consistent results in spite of their different quality. The continuum and line parameters are listed in Table 2. For a provisional identification with the Fe $xxvi$ Kα at 6.97 keV, the implied outflow velocity is of the order of $v_{\text{out}} \sim 0.25$–0.30c. When all the parameters are tied between the two observations, the improvement in the joint fit statistics is $\Delta \chi^2 = -19.5$ for the loss of two degrees of freedom. According to an $F$-test, the line detection is genuine with a probability of 99.97 per cent, or $3.7 \sigma$.

The lack of any obvious $K\alpha$ emission feature from neutral iron at 6.4 keV can be explained in the context of the X-ray Baldwin effect (Iwasawa & Taniguchi 1993). However, any model accepts a narrow line with rest EW of $\sim 140 (\pm 80)$ eV, centred on an energy that does not formally correspond to any major transition, $E = 6.86^{+0.09}_{-0.11}$ keV. We tentatively rule out any residual calibration inaccuracy after the Change Transfer Inefficiency correction, as this would also affect the range around the gold M edge, and much more severely (see, e.g. Nardini et al. 2016). Unless moderate velocity shifts are involved, the line could then be a superposition of fluorescent $K\alpha$ lines from Fe $xxv$–$xxvi$, confirming the existence of highly ionized gas in the nuclear regions of Ton 28. Interestingly, also the absorption feature at 9.2 keV is most likely a blend of the same transitions (see below). While this leaves room for speculation (i.e. reflection off the wind), we do not discuss the emission line any further in this work.

In the case of outflows, where a line’s energy is clearly not known in advance, a mere $F$-test is not appropriate to establish the reliability of a feature, as spurious detections can emerge at any energy (e.g. Protassov et al. 2002). Hence, in order to corroborate our find-
ings, we also resorted to Monte Carlo simulations. For simplicity, at this stage, we made use of the merged spectrum, grouped to a significance of 6σ per energy bin. Here, the addition of a Gaussian absorption profile to the power-law continuum brings an improvement of Δχ² = −17.3 for the loss of two degrees of freedom1 (see Fig. 3). We neglected the emission line and assumed as null hypothesis a featureless power law, with photon index and normalization as derived from the best fit over the 3–10 keV band. Following Miniutti & Fabian (2006), we ran a preliminary simulation with the fakeit command within XSPEC to generate a spectrum with the same exposure (72.8 ks), background, and response of the real data. We performed a first fit to obtain a refined input model, taking into account the effects of photon statistics on the null hypothesis itself, and proceeded with the proper simulation. After applying a self-consistent 6σ binning, the resulting spectrum was fitted with a power law, and the reference χ² value was recorded. We subsequently scanned the 7–10 keV rest-frame energy band in steps of 0.1 keV for the presence of a line, allowing for both negative and positive amplitudes. The minimum χ² returned by the line scan was stored for comparison with the reference value. The whole procedure was repeated for 10 000 times. In only nine cases (eight in absorption, one in emission) the statistical improvement afforded by a spurious line is Δχ² < −17.3, thus setting the confidence level of our detection to 99.91 per cent, or 3.3σ. This is still a rather conservative estimate, as the coincidence of residuals at the same energy in two different spectra, although individually less significant (Fig. 3), is not considered; moreover, the false positives in the simulations are all confined below 8.5 keV, boosting the reliability of a feature at 9.2 keV even further.

4 DISCUSSION AND CONCLUSIONS

Based on our past experience and extensive simulations, a safe (i.e., >3σ) detection of an unresolved Fe K wind signature with vout ∼ 0.1c and EW = −100 eV in the EPIC/pn spectrum of a local AGN requires a 2–10 keV flux approaching 10⁻¹² erg s⁻¹ cm⁻² and at least 2000 net counts at 5–10 keV, for a power-law continuum of Γ = 2. The exceptional strength of its soft excess (whose value, corrected for Galactic absorption, exceeds 1.2 adopting the definition of Vasudevan et al. 2013) implies that the hard X-ray flux of Ton 28 is considerably lower than expected from the ROSAT count rate, falling below the above reference threshold by a factor of two (cf., Table 2). The same applies to the number of 5–10 keV counts available, which is just above 800 from Obs. 1 and Obs. 2 combined. None the less, the sizeable rest EW of −340 (±160) eV and the cosmological redshift of the source (which virtually offsets the more substantial blueshift of the line) proved to be instrumental in stretching the standard limits of detectability. Indeed, the evidence for a highly ionized, mildly relativistic BH wind in Ton 28 appears to be rather robust, as it does not simply rely on the shear statistical improvement in the spectral fits after the inclusion of the absorption line, but it is also supported independently by Monte Carlo simulations and by the presence of the feature in two observations with strikingly different background intensities, when any other line-like residual due to photon noise is cancelled out in the merged spectrum.

We can therefore attempt to gain more insights into the physical properties of this X-ray wind. With this aim, it is necessary to properly account for absorption by photoionized gas, as the outflow velocity itself depends on the identification of the ionic species and transition involved. We first reverted to the full 0.3–10 keV spectra, using a phenomenological continuum model of the form $zbody + bknpower$ to overcome the limitations of optxagnf and accurately reproduce the hard X-ray slope. The marginal differences between Obs. 1 and Obs. 2 are ascribed to a 7–10 keV rest-frame, which the fit is indeed very good, with χ²/ν = 788.8/823 before allowing for the wind. Incidentally, the blackbody has a temperature $kT = 116 (±3)$ eV, while the power law breaks from $Γ \simeq 2.5$ to 1.8 around 4.3 keV (rest-frame). We then created a suitable absorption grid with xstar (Kallman & Bautista 2001), adopting as ionizing continuum the broad-band SED shape derived from the optxagnf model with free $M_{BH}$, coarsely sampled by 10 logarithmically spaced points between 1 eV and 100 keV and normalized to a 1–1000 Rydberg luminosity of $10^{46}$ erg s⁻¹. Column density and ionization parameter (defined as $ξ = L_{\text{InR²}}$, in units of erg cm⁻¹ s⁻¹) turn out to be largely degenerate (Fig. 4, left-hand panel). Even so, for solar iron abundance the best nominal $N_H$ hits the hard limit imposed in our grid ($2 \times 10^{24}$ cm⁻²). We thus opted for moderate iron overabundance ($Z_{Fe} = 0.3$), which might even be more appropriate for the innermost regions of an object like Ton 28 (e.g. Hamann & Ferland 1999). The fits are poorly sensitive to turbulent velocity, which was fixed to 5000 km s⁻¹. The application of such a grid delivers a final $χ^2/ν = 768.9/820 (Δχ^2 = −19.9)$, confirming the high statistical significance of the accretion disc wind.2

We note that this exercise does not yet provide sufficiently tight constraints on the absorber to determine the energetics of the wind, as the mass outflow rate depends on quantities that are either highly uncertain (column density, iron abundance) or completely unknown (covering factor, radial location). Only the outflow velocity is pinpointed with fairly good precision to $v_{\text{out}} = 0.28_{-0.02}^{+0.03}$ c (Fig. 4, right-hand panel).

1 We note that this value is not sensitive to the spectral grouping. If 5σ bins were adopted instead, we would still get $Δχ^2 = −17.0$.

2 Given the $ξ - N_H$ degeneracy, only two degrees of freedom are effectively lost. The improvement corresponding to an $N_H$ fixed to 5 × 10²³ cm⁻², for instance, is $Δχ^2 = −19.7$, equivalent to 4σ.
hand panel). Fe XXVI is in fact the dominant species over most of the relevant ionization range. For the best-fitting value of log $\xi \approx 5.5$, the 9.2-keV feature is actually a blend of the K$\alpha$ lines from Fe XXVI and Fe XXV, with an approximate intensity ratio of 7 : 5. For reference, the relative weight is unity at log $\xi \approx 5.2$, while traces of Fe XXV are found up to log $\xi \approx 7$. Capitalizing on the measure of the outflow velocity, we can still infer a conservative figure of the narrow H$\beta$ emission, the relative weight is unity at log $\xi \approx 10$. Despite the large uncertainties, it seems then likely that the ultra-fast X-ray wind in Ton 28 meets the minimum requirements for AGN feedback to work (e.g. Hopkins & Elvis 2010).

While blind searches and occasional detections have already suggested that the appearance of blueshifted Fe K absorption is a prevalent phenomenon among AGN, the case of Ton 28 is brought to the next level by the very way our target had been selected. In a sense, this result could be regarded as the first step towards an informed discovery of ultra-fast X-ray winds, and the indirect identification of objects that are currently undergoing such a phase. Our selection was indeed quite straightforward, simply requiring high bolometric luminosity and low [O III] EW, which can be plainly translated into high Eddington ratio and low inclination, respectively. The latter lends phenomenon among AGN, the case of Ton 28 is brought to the fore. For our best estimate on X-ray data reduction. SB is supported by NASA through an award no. AR7-18013X issued by the Chandra X-ray Observatory Center, operated by the Smithsonian Astrophysical Observatory Center, operated by the Smithsonian Astrophysical Observatory for and on behalf of NASA under contract NAS8-03060. SB was also partially supported by grant HST-AR-13240.009.

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