A longer XMM–Newton look at I Zwicky 1: variability of the X-ray continuum, absorption and iron Kα line

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Accepted 2007 February 7. Received 2007 February 4; in original form 2006 October 10

ABSTRACT

We present the second XMM–Newton observation (85 ks) of the narrow-line Seyfert 1 galaxy (NLS1) I Zw 1 and describe its mean spectral and timing characteristics. On average, I Zw 1 is ∼35 per cent dimmer in 2005 than in the shorter (20 ks) 2002 observation. Between the two epochs the intrinsic absorption column density diminished, but there were also subtle changes in the continuum shape. Considering the blurred ionized reflection model, the long-term changes can be associated with a varying contribution of the power-law component relative to the total spectrum. Examination of normalized light curves indicates that the high-energy variations are quite structured and that there are delays, but only in some parts of the light curve. Interestingly, a hard X-ray lag first appears during the most distinct structure in the mean light curve, a flux dip ∼25 ks into the observation. The previously discovered broad, ionized Fe Kα line shows significant variations over the course of the 2005 observation. The amplitude of the variations is 25–45 per cent and they are unlikely due to changes in the Fe Kα-producing region, but perhaps arise from orbital motion around the black hole or obscuration in the broad iron-line-emitting region. The 2002 data are re-examined for variability of the Fe Kα line at that epoch. There is evidence of energy and flux variations that are associated with a hard X-ray flare that occurred during that observation.

Key words: galaxies: active – galaxies: nuclei – quasars: individual: I Zw 1 – X-rays: galaxies.

1 INTRODUCTION

I Zwicky 1 (I Zw 1; z = 0.0611) is considered the prototypical narrow-line Seyfert 1 galaxy (NLS1) mainly due to its distinct optical properties. At X-ray energies the active galactic nucleus (AGN) exhibits behaviour that is somewhat more modest than for typical NLS1s (e.g. Leighly 1999a,b). However, a short (20 ks) XMM–Newton observation conducted in 2002 revealed a plethora of interesting characteristics, such as: hard X-ray flaring, unresolved transition array (UTA) absorption, and possibly multiple Fe Kα emission lines (Gallo et al. 2004a, hereafter G04).

The discoveries in G04 prompted further examination with a second longer XMM–Newton observation. This is the first of three papers which describe the X-ray properties of I Zw 1 utilizing all XMM–Newton data. In this work, we present an 85 ks XMM–Newton observation and describe the mean spectral and timing characteristics of the AGN, as well as compare the data to the earlier 2002 observation. The complex ionized absorber and its long-term variability is discussed in detail in the work of Costantini et al. (2007). In addition, I Zw 1 exhibits remarkable short-term spectral variability during the 2005 observation. This is presented in Gallo et al. (2007).

2 OBSERVATIONS AND DATA REDUCTION

I Zw 1 was observed for the second time by XMM–Newton (Jansen et al. 2001) on 2005 July 18–19 during revolution 1027 (obsid 0300470101) (hereafter we will refer to this as the 2005 observation). The total duration was 85 ks, during which time all instruments were functioning normally. The EPIC pn (Strüder et al. 2001) and MOS (MOS1 and MOS2; Turner et al. 2001) cameras were
operated in small-window mode with the medium filter in place. The reflection grating spectrometers (RGS1 and RGS2; den Herder et al. 2001) also collected data during this time, as did the optical monitor (OM; Mason et al. 2001).

The observation data files from the 2002 and 2005 observations were processed to produce calibrated event lists using the XMM-Newton Science Analysis System (SAS v7.0.0). Unwanted hot, dead or flickering pixels were removed as were events due to electronic noise. Event energies were corrected for charge-transfer inefficiencies. EPIC response matrices were generated using the SAS tasks ARFGEN and RMFGEN. Light curves were extracted from these event lists to search for periods of high background flaring. Some background flaring is detected towards the end of the 2005 observation, and the data during those periods have been neglected. The total amount of good exposure time selected was 58 and 82 ks for the pn and MOS detectors, respectively. Source photons were extracted from a circular region 35 arcsec across and centred on the source. The background photons were extracted from a larger off-source region and appropriately scaled to the source-selection region. Single and double events were selected for the pn detector, and single-quadruple events were selected for the MOS. The data quality flag was set to zero (i.e. events next to a CCD edge or bad pixel were omitted). The total number of source counts collected by the pn instrument in the 0.3–10 keV range was approximately $2.75 \times 10^5$. In the 0.5–10 keV band, the MOS instruments collected about $8.4 \times 10^5$ (MOS1) and $8.9 \times 10^5$ (MOS2) source counts. Comparing the source and background spectra we found that the spectra are source dominated between 0.2–12 keV. The EPIC pn spectrum is analysed in the 0.3–10 keV band where the calibration is most certain. To avoid cross-calibration uncertainties at low energies, the MOS spectra are neglected below 0.5 keV. The 2005 spectra from all instruments show relatively good agreement in these energy bands, within known calibration uncertainties (Kirsch 2006), so they are fitted simultaneously unless stated otherwise. As the broad-band light curve is less sensitive to calibration uncertainties, the data between 0.2–12 keV are utilized.

The RGS were operated in standard Spectro + Q mode in 2005, and a total exposure of 85 ks was collected. The RGS data are used in the analysis of the ionized absorber in I Zw 1 (Costantini et al. 2007) and will not be discussed here.

During 2005, I Zw 1 was observed with the OM in fast mode through four filters ($U$, $U V W_1$, $U V W_2$ and $U V M_2$). The purpose was to examine possible optical variability. Unfortunately, the AGN was not well centred in the small, fast-mode frame and fell close to the detector edge. Consequently, optical variability could not be examined in a robust manner.

### 3 2005 X-RAY LIGHT CURVES

During the 20 ks 2002 observation I Zw 1 exhibited a modest X-ray flare, which lasted a total of ~5 ks (G04). Notably the flare appeared to be quite hard, concentrated in the 3–12 keV band, thus inducing spectral variability. Aside from this lone event the light curve was relatively quiet in comparison to many NLS1.

The 2005 light curve appears more active, especially variable with, on average, larger amplitudes than observed in 2002 (Fig. 1). Perhaps the most interesting event in the light curve is the sharp drop about 25 ks into the observation. There is spectral variability related to the light curve, and this is discussed at length in Gallo et al. (2007). Here, we will focus on the flux variations.

Light curves were created in three EPIC pn energy bands: 0.2–0.7, 2–3 and 3–12 keV. Using the light curves in 1000-s bins, each of the high-energy light curves was cross-correlated (following Edelson & Krolik 1988) with the 0.2–0.7 keV band to search for possible lags (positive delay means hard band lags the soft band). All of the cross-correlation functions (CCFs) were asymmetric towards positive lags (Fig. 2). As will be demonstrated in the spectral analysis, the softest band is the region where both the power-law component and the soft excess component influence the spectrum. Both higher bands are dominated by the power-law component alone.

There are a few AGNs where time delays as a function of Fourier frequency (see Nowak et al. 1999 and references therein for details) have been determined (see Papadakis, Nandra & Kazanas 2001, for the first reported detection in an AGN). If there were a single delay between the light curves in the various energy bands, then the time delay between all of the Fourier frequencies would be the same. In contrast, what is typically observed is that as the frequency of the...
Fourier components decreases, the delays increase. Furthermore, as the energy band separation between two light curves increases, the delays, at the same frequency, also increase (e.g. see Arévalo et al. 2006 for a recent discussion).

In the case of I Zw 1, we cannot estimate time-lags as a function of frequency due to limited signal in the hard-band light curve. However, the CCFs are consistent with what we observe in other AGNs and NLS1. The CCFs show broad humps around zero time-lag with an asymmetry towards positive lags, but not a single, distinct delay. This is consistent with the hypothesis that in I Zw 1, just like in other Seyferts, the sine and cosine functions in the hard-band light curves are delayed with respect to those in the soft-band light curves, but the delay is not the same for all of them: the delays increase with decreasing frequency and increased separation between the energy bands.

Of interest may be the particularly small values measured in the CCFs (0.5–0.7). We examine this further by directly comparing light curves in each energy band normalized to their respective mean (Fig. 3). Most obvious in the comparison between the 0.2–0.7 and 3–12 keV band is the significance of the delay between ~25–52 ks (vertical dashed lines in Fig. 3). In particular, the delay seemingly begins at the onset of the sharp dip in the light curve. If we calculate the CCF in this time regime alone we see a clear dominant lag at ~1 ks (Fig. 4). However, as Fig. 3 demonstrates, the lag is not always present. Sometimes there are no delays, and at other times the light curves show different behaviour and even anticorrelations (e.g. ~20–25 ks and >75 ks into the observation). All of these factors contribute to the small value of the CCF peaks. Similar behaviour was seen in the NLS1 IRAS 13224–3809 (Gallo et al. 2004b) where the authors suggested possible alternating lags between high- and low-energy bands (i.e. sometimes hard band lags and other times it leads).

4 2005 SPECTRAL MODELLING

The source spectra were grouped such that each bin contained at least 20 counts (typically more). Spectral fitting was performed using XSPEC v11.3.0 (Arnaud 1996). All parameters are reported in the rest frame of the source unless specified otherwise. The quoted errors on the model parameters correspond to a 90 per cent confidence level for one interesting parameter (i.e. a $\Delta \chi^2 = 2.7$ criterion). A value for the Galactic column density towards I Zw 1 of $5.07 \times 10^{20}$ cm$^{-2}$ (Elvis, Lockman & Wilkes 1989) is adopted in all of the spectral fits. $K$-corrected luminosities are calculated using a Hubble constant of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and a standard flat cosmology with $\Omega_M = 0.3$ and $\Omega_{\Lambda} = 0.7$.

In the analysis of the 2002 data, G04 were able to fit the spectra with various phenomenological models, but could not distinguish a superior one. While they were able to establish that a second, soft component was a necessary part of the continuum they were unable to determine whether the soft excess was curved (e.g. blackbody-like) or flat (power-law-like).

4.1 The 2–10 keV spectra

As was done for the 2002 data (G04), we built-up a broad-band spectral model for the 2005 observation utilizing all the EPIC data. Fitting the 2–10 keV EPIC spectra with a single power law (each instrument having free photon index ($\Gamma$) and normalization to accommodate existing cross-calibration uncertainties) resulted in a satisfactory model ($\chi^2$/d.o.f. = 1.03/1090). Adding a Gaussian profile to this continuum, with a common energy ($E$) and width ($\sigma$) among all three instruments was a significant improvement ($\Delta \chi^2 = 59.5$ for five free additional parameters). The best-fitting line parameters were $E = 6.70 \pm 0.14$ keV, $\sigma = 523^{+276}_{-157}$ eV and $EW_{9.0} = 265^{+105}_{-32}$, $EW_{11.0} = 220^{+130}_{-49}$, $EW_{13.0} = 239^{+191}_{-79}$ eV. G04 introduced the possibility of multiple line features in the Fe Kα region of the 2002 spectrum, including an intrinsically narrow 6.4 keV line. No such line is present in the 2005 spectrum. A narrow, neutral line is completely insignificant in the pn spectrum and any such feature in the MOS has an $EW < 27$ eV.

A comparable improvement ($\Delta \chi^2 = 38.0$ for five free additional parameters) can be achieved if a disc line profile (Fabian et al. 1989) rather than a Gaussian profile is used for the broad residuals. In this case the best-fitting energy and inner disc radius are $E = 6.55^{+0.35}_{-0.10}$ keV and $R_{in} = 6$–26 gravitational radii, respectively. The disc inclination ($i$) is fixed at 50°, to remain consistent with our finding in Section 6.1. Leaving the parameter free to vary does not enhance the fit statistics, nor does it affect the best-fitting line energy. The line strength is $EW \approx 200$ eV in each spectrum. For simplicity, we adopt the Gaussian profile.

![Figure 3](https://example.com/figure3.png)  
**Figure 3.** Light curves in the 0.2–0.7 keV (black dots) and 3–12 keV bands normalized to their respective means. A hard band lag is apparent in between ~25–52 ks (marked by the vertical dashed lines). The start time corresponds to the beginning of the pn exposure.

![Figure 4](https://example.com/figure4.png)  
**Figure 4.** The CCF when cross-correlating the 0.2–0.7 and 3–12 keV light curves between 25–55 ks only. A hard band lag appears more dominant in this time band and peaks at ~1 ks.
4.2 Simple broad-band models

Extrapolating the 2–10 keV fit to 0.3 keV in the pn and 0.5 keV in the two MOS left a gradual rise in the residuals that is typically associated with the soft excess.

The entire 2005 0.3–10 keV band was modelled with various continuum models. Through repeated effort we found it necessary to include in all models an additional neutral absorber at the redshift of the source, as well as a low-energy (≤650 eV) absorption edge that mimics the more complicated ionized absorption.

As with the 2002 observation, the 2005 data show that a second continuum component is required to fit the spectrum of I Zw 1 (see Table 1). According to an F-test, the addition of a second continuum component (i.e. two additional parameters) to a single power law is highly significant (F-test probability ≤ 10^{-17}). Also like the 2002 observation, a single superior model does not stand out. However, there are similarities among all the models in Table 1. One may notice that the second component is not highly curved. Even in the case of the blackbody plus power-law model, the high temperature of the blackbody component will give it a flatter appearance in the EPIC bandpass.

Of interest is that there is detectable diminishing of the intrinsic column density in I Zw 1 since 2002. The exact change depends on what continuum model is assumed, but appears to be at least on the 50 per cent level.

The residuals from the blackbody plus power-law fit are shown in Fig. 5. Notable in Fig. 5 are the positive residuals, which remain in the fit above ~8 keV. These residuals are apparent in all broad-band fits to the 2005 data (see also Fig. 7 and the lower panel of Fig. 8), with the exception of the double power-law model. The most likely cause is the significant spectral variability exhibited by I Zw 1 in 2005 (Gallo et al. 2007). Gallo et al. suggest that the power-law photon index could be changing during the 2005 observation, which would explain the difficulty in fitting the average spectrum with a single power law. The reason that the residuals are minimal in the

| Model                  | \(\chi^2/\text{d.o.f.} \) | \( N_{\text{H}} \times 10^{20} \text{ cm}^{-2} \) | Continuum | Edge | Partial absorber |
|------------------------|---------------------------|------------------------|-----------|------|-----------------|
| Single power law       | 1.13/1628                 | 0.71^{+0.23}_{-0.20}  | \( \Gamma_{\text{p}} = 2.37 \pm 0.01 \) | \( E = 644^{+9}_{-10} \) | \( \tau = 0.15 \pm 0.02 \) |
| Single power law       | 1.08/1629                 | 1.62^{+0.28}_{-0.31}  | \( \Gamma_{\text{p}} = 2.43 \pm 0.06 \) | \( E = 648^{+6}_{-7} \) | \( \tau = 0.19 \pm 0.02 \) |
| with partial covering  |                          |                        | \( \Gamma_{\text{p}} = 2.35 \pm 0.01 \) | \( E = 648^{+6}_{-7} \) | \( N_{\text{H}_{\text{pc}}} = 31.5^{+7.6}_{-14.1} \) |
| Broken power law       | 1.08/1626                 | 2.13^{+0.31}_{-0.38}  | \( \Gamma_{\text{p}} = 2.48 \pm 0.03 \) | \( E = 648^{+6}_{-7} \) | \( \tau = 0.20 \pm 0.02 \) |
| Blackbody plus power law | 1.08/1626             | <0.20                  | \( kT = 216 \pm 12 \) | \( E = 651^{+7}_{-9} \) | \( \tau = 0.20 \pm 0.02 \) |
| Double power law       | 1.04/1626                 | 3.2^{+0.69}_{-0.27}   | \( \Gamma_{1} = 2.6^{+0.05}_{-0.04} \) | \( E = 652^{+6}_{-7} \) | \( \tau = 0.18 \pm 0.02 \) |
double power-law model could simply be that the second power law does not begin to dominate the spectrum until rather high energies (~5.5 keV in the pn spectrum).

Based on the blackbody plus power-law model, the average 0.3–10 keV flux during 2005, corrected for Galactic absorption, is \( \sim 1.4 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \). The luminosities in the 0.3–10 and 2–10 keV bands are 1.28 \( \times \) 10^{44} erg s\(^{-1}\) and 0.43 \( \times \) 10^{44} erg s\(^{-1}\), respectively. I Zw 1 is \( \sim 35 \) per cent dimmer than it was in 2002. For comparison, the estimated 2–10 keV luminosity during the ASCA observation was 0.53 \( \times \) 10^{44} erg s\(^{-1}\) (Leighly 1999b).

5 A COMPARISON OF THE 2002 AND 2005 SPECTRA

5.1 Summary of the 2002 observation

The 0.2–10 keV spectrum of I Zw 1 has long been known to differ from those of other NLS1. It possesses a rather weak soft excess and is modified by intrinsic neutral and ionized absorption. The 2002 observation of I Zw 1 (G04) was rather typical of what had been seen previously (e.g. Leighly 1999a,b).

There were several simple continuum models (e.g. blackbody plus power law, broken power laws, multiple blackbodies plus power law) that when modified by intrinsic ionized absorption (an absorption-edge), neutral absorption (absorption column density) and a Fe K\( \alpha \) emission line, fit the EPIC spectra adequately in 2002. None of these continuum models stood out as superior. Since the 2002 data were reprocessed with the newest calibration we refit the simple models to the newly processed data and find comparable results. The one modification was in the intrinsic absorption column density, which was slightly lower with the new calibration \( (N_H = 4.5 \pm 0.5 \times 10^{20} \text{ cm}^{-2}) \) as opposed to \( N_H = 10.0 \pm 0.1 \times 10^{20} \text{ cm}^{-2} \).

A particularly interesting spectral result from the 2002 observation was the possible presence of multiple iron lines. In addition to a broad and ionized line, the spectrum also required a narrow, unresolved emission line at 6.4 keV. The most obvious interpretation adopted by G04 was that this feature was produced in distant unresolved material such as the torus, but an alternative interpretation is offered in Section 8.4.2.

5.2 Spectral changes since 2002

The 2005 spectrum does appear substantially different from the 2002 observation. The broad-band parameters between 2002 and 2005 can be depicted by extrapolating the best-fitting 2–10 keV power law to both spectra down to lower energies (Fig. 6).

The 2005 observation shows a much softer spectrum, a suggestion that the level of absorption may have changed since 2002. The best-fitting power law in the 2–10 keV band is slightly flatter in 2005 \( (\Gamma = 2.15 \pm 0.02 \text{ compared to } \Gamma = 2.28 \pm 0.03 \text{ in 2002}) \), which likely also contributes to the apparently stronger soft excess at that epoch. The inset in Fig. 6 shows the residuals in the Fe K\( \alpha \) band. As with previous observations, the iron line appears broad and ionized. The agreement in the appearance of the iron line at both epochs is good.

We applied the blackbody plus power-law model from 2002 to the 2005 data to examine consistency between the two epochs. Simply rescaling the model was unacceptable \( (\chi^2_{\nu}/\text{d.o.f.} = 5.7/846) \). Allowing the level of neutral absorption to vary freely significantly improves the fit quality \( (\chi^2_{\nu}/\text{d.o.f.} = 1.27/845) \) indicating that the column density of the neutral absorber has dropped in 2005 to \( N_H \approx 1.4 \times 10^{20} \text{ cm}^{-2} \). Allowing the low-energy absorption edge to vary in energy and depth is a further improvement \( (\Delta \chi^2 = 36.2 \text{ for two additional free parameters}) \). The overall fit is not acceptable \( (\chi^2_{\nu}/\text{d.o.f.} = 1.23/843) \) and demonstrates that subtle changes in the intrinsic continuum shape since 2002 may be appropriate.

If rather we consider a constant absorber and allow only the continuum parameters to vary, we obtain a worse fit \( (\chi^2_{\nu}/\text{d.o.f.} = 1.35/843) \). Indeed variable absorbers seem necessary and are supported by the RGS data (Costantini et al. 2007).

6 A REFLECTION INTERPRETATION FOR I Zw 1

6.1 The 2005 observation

The spectrum of I Zw 1 is power law dominated, but there is the necessity for a small contribution from a soft component below ~2 keV. The ionized disc reflection model (Ross & Fabian 2005) blurred by relativistic effects has had relatively good success in duplicating the appearance of the soft excess (e.g. Crummy et al. 2006).

All the EPIC spectra were fitted with the blurred reflection plus power-law model. As in the previous fits, we included an intrinsic neutral absorption component and an absorption edge as a pseudo-ionized absorber. Since the model is complex, to simplify the fitting process the normalizations of the MOS spectra were linked to the pn spectrum and only a constant scalefactor was used to correct for possible flux offsets between instruments. The incident spectrum for the reflection component was linked to that of the power-law component.

The fit quality is not as satisfactory as some of the simple models \( (\chi^2_{\nu}/\text{d.o.f.} = 1.10/1627) \), but it does have the advantage of offering a physical explanation for the origin of the soft excess and broad Fe K\( \alpha \) line. Fit parameters are shown in Table 2, and the model along with fit residuals are presented in Fig. 7. The fraction of reflected-total flux in the 0.3–10 keV range (corrected for Galactic and source absorption) is \( \sim 0.30 \). Drawing conclusions from the fit parameters should probably be done with caution given the complexity of the low-energy absorption. However, it is likely that the disc inner radius is not extremely small \( (R_g = 5.0^{+0.2}_{-0.1} \text{ g}) \) and the emissivity profile is not very steep \( (\alpha = 2.48_{-0.03}^{+0.30}) \). Both points suggest that
Table 2. The blurred reflection and power-law model (with absorption) applied to the 2005 EPIC spectra ($\chi^2$/d.o.f. = 1.10/1627). The absorption parameters are as defined in Table 1. The blurring parameters are the emissivity index ($\alpha$); inner ($R_{in}$) and outer ($R_{out}$) disc radius in gravitational radii ($r_g = GM/c^2$); and disc inclination ($i$). The iron abundance and ionization parameter ($\xi = 4F \nu^{-1}$, where $F$ is the total incident flux and $\nu$ is the hydrogen number density) of the reflector are also given.

| Model component | Fit parameter |
|-----------------|--------------|
| Absorption      | $N_{H1} = 1.05^{+0.07}_{-0.13} \times 10^{20}$ cm$^{-2}$ |
| (neutral and ionized) | $E = 638^{+7}_{-9}$ eV |
| $\tau$          | $0.30 \pm 0.01$ |
| Power law       | $\Gamma = 2.24 \pm 0.01$ |
| Blurring        | $\alpha = 2.48^{+0.36}_{-0.31}$ |
| $R_{in}$        | $5.0^{+2.5}_{-1.6}$ $r_g$ |
| $R_{out}$       | $200 r_g$ (fixed) |
| $i$             | $51^\circ \pm 2^\circ$ |
| Reflector       | $Fe = 1.1 \pm 0.1$ solar |
|                 | $\xi = 3060^{+107}_{-106}$ erg cm$^{-1}$ s$^{-1}$ |

The advantage of this model is that it can account for the iron emission and soft excess in a self-consistent manner. Moreover, as will be discussed in Gallo et al. (2007), this reflection scenario can potentially explain some of the complicated spectral variability exhibited by I Zw 1.

6.2 Simultaneous fit to the 2002 and 2005 data

Based on the investigation in Section 5.2, most of the spectral differences between 2002 and 2005 can be associated with changes in the level of absorption. However, there do appear to be subtle changes in the shape of the continuum as well. As I Zw 1 was nearly twice as bright in 2002, in terms of the blurred reflection model the reflection component does not necessarily originate from the innermost confines around the black hole as is suggested for many NLS1.

The advantage of this model is that it can account for the iron emission and soft excess in a self-consistent manner. Moreover, as will be discussed in Gallo et al. (2007), this reflection scenario can potentially explain some of the complicated spectral variability exhibited by I Zw 1.

The data from both epochs were fitted simultaneously to examine consistency in the reflection scenario. For simplicity, many parameters were fixed to the best-fitting 2005 values (see Table 3). The primary parameters that were left free for each data set were the power law and absorption parameters, and the normalization of the reflection component. The iron abundance and disc inclination were linked between the two spectra as large changes in these parameters would not be expected over 3 yr. A reasonable fit can be achieved ($\chi^2$/d.o.f. = 1.06/1480) in this manner (see Fig. 8 and Table 3).

As is seen in Table 3 there is no strong indication for a change in the shape of the direct power-law component between 2002 and 2005. In addition, most of the blurring and reflection parameters have been fixed. The most notable changes are in the amount of absorption (as noted in previous fits and by Costantini et al. 2007),

| Model component | 2002 | 2005 |
|-----------------|------|------|
| Absorption      | $N_{H1} = 4.38^{+0.20}_{-0.19}$ cm$^{-2}$ | $2.28^{+0.14}_{-0.17} \times 10^{20}$ cm$^{-2}$ |
| Power law       | $E = 623 \pm 10$ eV | $634^{+11}_{-6}$ eV |
| Blurring        | $\alpha = 2.48^f$ | $2.48^f$ |
| $R_{in}$        | $5.0^f$ | $5.0^f$ $r_g$ |
| $R_{out}$       | $200^f$ | $200^f$ $r_g$ |
| $i$             | $58 \pm 3$ | $58 \pm 3$ |
| Reflector       | $Fe = 1.10 \pm 0.13$ | $1.10 \pm 0.13$ solar |
| $\xi$           | $3060^f$ | $3060^f$ erg cm$^{-1}$ s$^{-1}$ |
| $R$             | $0.27 \pm 0.04$ | $0.45 \pm 0.04$ |
| $F_R$           | $0.22 \pm 0.03$ | $0.31 \pm 0.03$ |

Figure 7. Top panel: the best-fitting blurred reflection model (only the pn model is shown for clarity). The reflection (red, dash–dotted curve) and power-law (blue, dashed curve) components, which make up the combined fit (black, solid curve) are presented. Bottom panel: the residuals of the model to the EPIC spectra. Symbols are as defined in Fig. 5.

Figure 8. Residuals from a self-consistent power law plus blurred reflection model fitted simultaneously to the pn data from 2002 (top panel) and 2005 (bottom panel).
the reflection fraction ($R$, fraction of reflected emission to power-law emission in the 0.3–10 keV band), and in the level at which the reflection component contributes to the total 0.3–10 keV spectrum ($F_R = 0.22 \pm 0.03$ in 2002 and $0.31 \pm 0.03$ in 2005).

7 IRON-LINE VARIABILITY

7.1 Fe Kα variability during the 2005 observation

In the analysis of G04 there were indications that the broad feature in the 2002 observation was composed of multiple (at least two) narrower emission lines. In the 2005 observation, the residuals can be fit by a single Gaussian profile. Based on the width of the line ($\sigma = 523^{+175}_{-125}$ eV) in the EPIC spectra, the line-emitting region is between 12–66 $r_g$. Similar distance estimates come from the disc line fit and the blurred reflection model. Given the long observation and proximity of the line emitting region makes it plausible to search for line variability.

The mean pn spectrum was divided into 17 segments, each of 5 ks. The exposure in each segment was $\sim 3.5$ ks, taking account of the lifetime of the pn camera in small window mode. The average number of source counts in the 5.0–7.2 keV band was slightly more than 300. The counts were grouped into spectra such that each bin contained at least 20 counts. For each 5-ks spectrum the continuum was determined by fitting the 4–10 keV band with a power law, while excluding the 5–7.2 keV range. The omitted band was replaced and the spectrum was rebinned into channels of 250 eV. Excess counts above the continuum in each 250 eV bin were recorded. From this information an excess residual image was created as illustrated in Iwasawa et al. (2004; and in preparation). The result is analogous to modelling each spectrum with a power law plus Gaussian profile and measuring the flux in the Gaussian component. The advantage of creating an excess residual image is that we can circumvent the limitations of working in the Poisson regime, thus making trends in the variations of the line flux more visible.

The resulting image from the 2005 observation is shown in Fig. 9 and clearly indicates that the broad-line flux is variable. Most notably, the line flux diminishes significantly 45–60 ks from the start of the observation.

To create a light curve from the image, the excess counts between 5.8–6.7 keV were accumulated. Uncertainties on the light-curve data points were estimated from Monte Carlo simulations of the excess residual image. One thousand images were created in an identical manner as done for I Zw 1. The spectra from which the images were derived were simulated for identical conditions as the 2005 observation, assuming a power law plus stationary Gaussian profile. The uncertainty in the observed light curve was taken to be the s.d. in the excess counts resulting from the simulated images. Details of the process including caveats are discussed in Iwasawa, Miniutti & Fabian (2004).

The Fe Kα light curve shows clear variability (Fig. 10) with a constant fit being unacceptable ($\chi^2 = 2.45$). The fractional variability amplitude ($F_{\text{var}}$, using uncertainties derived in Edelson et al. 2002) is $34.8 \pm 9.7$ per cent.

A light curve of the 6–10 keV continuum was generated based on the power-law fits used to derive the Fe Kα light curve. The uncertainties in the 6–10 keV flux were assumed to be the same as the uncertainty in the corresponding count rate. The continuum light curve, normalized to its average flux, is shown in Fig. 11 with the broad-line flux light curve (Fig. 10), normalized to its average flux, overplotted as a dashed curve. Interestingly, the curves appear to be anticorrelated in some parts of the light curve. Cross-correlating the broad-line and 6–10 keV continuum light curves indicates a weak correlation with the broad-line light curve lagging the continuum fluctuations by $\sim 15$ ks (lower panel, Fig. 11).

The fractional variability in the 6–10 keV continuum is $F_{\text{var}} = 20.8 \pm 4.0$ per cent, less than the $F_{\text{var}}$ in the Fe Kα line. Statistically, the amplitude of the continuum variations is consistent with the Fe Kα variations within about 2σ. However, the difference is likely larger since the uncertainties on $F_{\text{var}}$ are conservatively underestimated (Edelson et al. 2002).

7.2 Revisiting the Fe Kα variability in 2002

In fitting the spectra in various segments of the 2002 observation, G04 found little evidence of intensity variations in the broad-line. We take advantage of the excess-residual technique to re-examine the broad-line variability in the 2002 observation. An excess-residual image has been created for the 2002 pn observation.
in a nearly identical manner as was done for the 2005 observation. The only difference is that the time resolution is slightly better during 2002 because the mean spectrum was divided into six segments of 3.6 ks each (rather than 5 ks). This can be done without degrading the data quality because the I Zw 1 was brighter in 2002 and because the observation was conducted in large-window mode, which has a CCD lifetime of ~95 per cent; therefore the actual exposure in each segment of the 2002 observation is almost the same as the exposure in each segment of the 2005 data.

The 2002 excess-residual image is shown in Fig. 12. The broad-line is dominant in the 6.0–6.5 keV range, but there is also apparent brightening that occurs in the 5.5–6.0 keV band between 10–15 ks. This is of particular interest because the continuum light curve shows a hard X-ray flare that peaks during this time interval (see G04).

Light curves were extracted from the excess-residual image in the 6.0–6.5 keV (blue line) and 5.5–6.0 keV (red line) bands. They were then normalized to their respective means and plotted with the normalized 2002 3–12 keV continuum light curve (Fig. 13). As the observation was so short uncertainties in the residual-image light curves were not derived in a robust manner as was done for the 2005 data. We also note that propagation of Poisson uncertainties in each data bin yields very large error bars (on the order of 100 per cent), therefore we are only illustrating a trend in Fig. 13.

The light curves suggest that the variations are more intense in the 5.5–6.0 keV line than in the 6.0–6.5 keV line. There also is no obvious connection between the 6.0–6.5 keV line light curve and that of the continuum. On the other hand, the 5.5–6.0 keV variations appear to be well correlated with the high-energy continuum variations and, despite the unknown size of the true error bars in the 5.5–6.0 keV line light curve, the trend is obvious.
8 DISCUSSION

8.1 I Zw 1: a not so prototypical NLS1 in X-rays?

The strong Fe ii emission in the optical spectrum of I Zw 1 was noted a half century ago (Sargent 1968), and given the intensity and narrowness of the lines the AGN became a laboratory for Fe ii studies (e.g. Phillips 1976, 1977, 1978; Boroson & Green 1992; Laor et al. 1997; Vestergaard & Wilkes 2001). Its narrow Balmer lines were also noted fairly early on (e.g. Oke & Lauer 1979).

When a formal definition of the NLS1 class was established (Osterbrock & Pogge 1985), based on optical spectral properties, it was realized that I Zw 1 was already the best-studied member of this class of AGNs, likely leading to its labelling as the prototype NLS1. However, some X-ray properties are also characteristic of NLS1s and I Zw 1 does not exhibit all these qualities to noticeable levels. In fact, in some instances I Zw 1 even displays behaviour that is atypical of the class. For example, I Zw 1 is observed through a column density intrinsic to the AGN. This is unusual for NLS1s (e.g. Boller, Brandt & Fink 1996), but also for type 1 AGNs in general.

The soft excess emission above the underlying steep power law is weak in I Zw 1 compared to most NLS1s, and not because of the relatively high intrinsic absorption (e.g. Leighly 1999b; Tanaka, Boller & Gallo 2005). Even the clear detection of a broad Fe Kα emission line in I Zw 1 seems unusual given that NLS1s appear not to show broad emission lines so obviously (e.g. Fabian et al. 2002, 2004; Guainazzi, Bianchi & Dovciak 2006). The identification of I Zw 1 as the prototype NLS1 originated due to its well-studied optical properties, but it now lingers mainly as a historic perspective. It can even be argued that some of its X-ray properties are atypical of the norm.

8.2 Time-lags

The average CCFs calculated in Section 3 show a tendency for positive lags (hard band following soft band). This phenomenon has been observed in other AGNs (e.g. Arévalo et al. 2006 and references therein) and Galactic black holes (e.g. McClintock & Remillard 2005). However the origin of the lags is not certain.

In a simple corona with a uniform temperature and optical depth, variations can result from fluctuations in the intensity of the seed photons. Variations of this nature should produce fixed delays between low- and high-energy bands, resulting in a common time delay for all Fourier components. We do not estimate time-lags as a function of frequency in I Zw 1; however the broad, asymmetric CCFs suggest that we do not have a single, well defined delay between the various energy bands. Examination of normalized light curves in different energy bands further supports this. A time-lag is only seen in parts of the light curves. In fact, at times the light curves are not correlated, or are actually anticorrelated.

Lags are seen in Cyg X-1, which can be attributed to spectral evolution in magnetic flares as they detach from the accretion disc (e.g. Poutanen & Fabian 1999). Another possibility is that the lags are manifested by material that propagates towards the black hole from regions of soft X-ray emission to regions of hard X-ray emission (e.g. Böttcher & Liang 1999; Kotov, Churazov & Gilfanov 2001).

Based on the observation of another NLS1, IRAS 13224+3809, Gallo et al. (2004b) claimed a lag that alternated (sometimes hard band followed other times it led), with possible dependency on the average flux of the source. There is likely similar behaviour here as the first notable lag coincides with a sharp flux dip in the light curve about 25 ks into the observation.

8.3 Diminished neutral absorption since 2002

Significant variations in the low-energy spectra of some Seyfert 1 galaxies have been previously observed and interpreted as changes in the low-energy continuum component (e.g. Page et al. 2002; Starling et al. 2004). In the case of I Zw 1, this does not appear to be the most straightforward explanation. There is detectable diminishing of the intrinsic column density in I Zw 1 since 2002. The exact change depends on what continuum model is assumed, but appears to be at least on the 50 per cent level.

Changes in the neutral column density have been reported in several type 2 (i.e. absorbed) AGNs (e.g. Risaliti, Elvis & Nicastro 2002), but to the best of our knowledge not in a NLS1. I Zw 1 is a merging and starburst system so there are several sources of absorption that exist in the galaxy and could feasibly change (e.g. due to bulk motion or dissipation of an absorbing component) over the span of a few years, which separates the two observations.

8.4 Origin of the Fe Kα variability

8.4.1 Flux variations in the 2005 observation

The broad Fe Kα line in I Zw 1 shows remarkable short-term variability. Understanding the origin of this variability is challenging.

Fig. 11 suggests that the emission line and continuum variations could be correlated if we consider the iron-line fluctuations to lag the continuum by 10–12 ks. Such a delay would place the iron-line emitting region at approximately 180 r_g in I Zw 1. The distance is too large to account for the width of the iron feature which based on various spectral fits (e.g. Gaussian profile, disc line profile, blurred ionized reflector), originates within about 60 r_g. A second problem is that the amplitude of the variations appears to be larger in the Fe Kα line than in the 6–10 keV continuum that would be producing it. Even if we assume that the amplitudes of the variations are identical, it would be unlikely that all of the incident continuum will be reprocessed by the iron producing region and then emitted back into our line of sight.

Another possibility is that the variations are a result of some extrinsic effect rather than intrinsic changes in the line-emitting region. For example, motion within the accretion disc could account for some of the flux changes (e.g. Iwasawa et al. 2004). In this case, one would expect energy modulation in the excess residual map, which are not present in Fig. 9. However, the strength of the modulations is dependent on the distance of the line-emitting region from the black hole and the disc inclination. It could be that in I Zw 1 this combination of parameters does not generate observable modulations.

In a speculative approach, we fit the Fe Kα line light curve (Fig. 10) with a sine curve. The fit was statistically good (χ^2_r = 1.02) and the implied period was 49.1 ks. If the 49.1 ks corresponds to the orbital period of the emitting region around the black hole, then we can estimate the distance (e.g. following Bardeen, Press & Teukolsky 1972) to be ~25 r_g. This distance is consistent with that estimated from the width of the broad Fe Kα line in the spectral models, but it is not clear why only the line-emitting region is affected in this manner and not the continuum.

Finally, the Fe Kα variations could be due to variations in some optically thick absorber in the line-emitting region. Such obscuring
material could be created from instabilities in the accretion disc of highly inhomogeneous flows (e.g. Merloni et al. 2006).

8.4.2 Energy and flux variations in the 2002 observation

The most impressive feature in the 2002 continuum light curve of I Zw 1 was a modest X-ray flare concentrated in the 3–12 keV band. The 6.0–6.5 keV line emission is not particularly variable and demonstrates no connection to the continuum variations. This behaviour is typical of other results (e.g. Iwasawa et al. 2004). However, the 5.5–6.0 keV line emission exhibits more intense variations which mimic the continuum light curve. In particular, the peak intensity in the 5.5–6.0 keV line light curve corresponds well with the peak of the hard X-ray flare.

Due to limited data, examination of time-resolved spectra during 2002 do not yield significant results. The likely correlation between the continuum and 5.5–6.0 keV line light curve suggests that this is emission due to Fe Kα, which is produced in a spot on the accretion disc that is illuminated by the X-ray flare (i.e. perhaps corotating with the disc). The 6.0–6.5 keV line emission is representative of the average broad-line emission, which is produced at distances of ~35rg as suggested by its width. The 5.5–6.0 keV line emission and hard X-ray flare are generated closer to the black hole where Doppler and gravitational effects are more intense than the region where the 6.0–6.5 keV emission line is produced (i.e. <35rg).

It is worth noting that the low-energy emission could be related to the narrow 6.4 keV (6 keV observed frame) emission feature that was identified in the 2002 spectrum by G04. Since the feature was not detected in the 2005 spectrum its origin could be connected to the transient 5.5–6.0 keV line (perhaps the blue wing of this line), which is produced during the X-ray flare.

The combination of a hard X-ray flare, and redshifted and broadened Fe Kα emission line has been seen in a very similar object, Nab 0205+024 (Gallo et al. 2004c). However, due to limited data, time-resolved spectral modelling did not yield information about possible line variability. Re-examination of the Nab 0205+024 data making use of excess residual imaging may be fruitful.

8.5 Physical models for I Zw 1

The level of absorption (neutral and ionized) appears to have changed between the two epochs. However, even after considering this there does seem to be some subtle change in the intrinsic continuum shape.

It is of interest to compare the changes in the context of a physical model such as reflection and light bending. In terms of the blurred reflection model, most of the intrinsic changes can be understood as arising from different relative contributions of the two continuum components. At both epochs (and historically), I Zw 1 appears to be in a power-law-dominated state – the soft excess is notably weak in this object.

If the power-law component is a compact isotropic emitting source located above the black hole, as depicted in the light-bending scenario (e.g. Miniutti & Fabian 2004), then the changes in the continuum shape are largely motivated by the proximity of this source to the black hole. In the higher flux 2002 observation, the contribution from the reflection component was less, and hence the soft excess was weaker. The AGN was brighter and in a power-law-dominated state. In 2005, I Zw 1 was dimmer and the reflection component (i.e. the soft excess) was stronger.

This is almost certainly a simplified description of the true situation. One would expect other spectral changes to occur as the power-law component varies its distance from the black hole. For example, with increasing distance the photon index should harden (i.e. if due to Comptonization), ionization parameter may decrease as the accretion disc is less illuminated, and R in will probably increase.

As the 0.3–10 keV spectrum of I Zw 1 is dominated by one component and subject to ionized absorption, it would not be surprising if other physical models provided adequate fits. Broad-band absorption models, like the blurred absorption models (e.g. Gierlinski & Done 2004), have not been examined here, but could likely duplicate the spectrum of I Zw 1. It may be possible to break this degeneracy by examining the spectral variability, which is complex in I Zw 1 and is somewhat unlike what is seen in other NLS1 (Gallo et al. 2007).

9 CONCLUSIONS

In this work, we presented an 85 ks XMM–Newton observation and described the mean spectral and timing characteristics of the AGN, as well as compared the data to a previous, shorter XMM–Newton observation from 2002. The complex ionized absorber is discussed in detail in the work of Costamante et al. (2007). The remarkable spectral variability is presented in Gallo et al. (2007). The main findings from this work are the following.

(i) I Zw 1 is ~35 per cent dimmer in 2005 than it was in 2002. Between the two epochs the level of neutral column density intrinsic to I Zw 1 changed, as well as the ionized absorber. In addition, subtle changes in the continuum shape are apparent. If modelled with the blurred reflection model, the long-term continuum changes can be understood as arising from different relative contributions of the two continuum components (i.e. direct power law and ionized reflection).

(ii) Variability is prevalent in all X-ray bands. The most distinct structure in the mean light curve is a flux dip ~25 ks into the observation. Average CCFs show a tendency for positive lags meaning soft band changes lead harder bands. However, examination of normalized light curves indicates that the high-energy variations are quite structured and lags are only apparent in some parts of the light curve. Interestingly, the hard X-ray lag first appears at the onset of the flux dip in the light curve. This possible alternating lag has been proposed for another NLS1 (IRAS 13224–3809, Gallo et al. 2004b) and it is not consistent with Comptonization from a single corona with a uniform temperature and optical depth, and variable seed photons.

(iii) The broad ionized Fe Kα line shows significant variations over the course of the 2005 observation, which are not clearly due to intrinsic changes in the Fe Kα-producing region. Other, viewer-perspective effects, such as orbital motion or absorption in the broad iron-line-emitting region, could be invoked to describe the variability.

(iv) The broad-line variability during 2002 is re-examined here. There is evidence suggesting that a relativistically broadened Fe Kα line is produced as a result of a hard X-ray flare illuminating the inner regions (i.e. <35rg) of the accretion disc.

ACKNOWLEDGMENTS

The XMM–Newton project is an ESA Science Mission with instruments and contributions directly funded by ESA Member States and the USA (NASA). The XMM–Newton project is supported by the Bundesministerium für Wirtschaft und Technologie/Deutsches...
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