An absorption event in the X-ray light curve of NGC 3227

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Accepted 2003 April 30. Received 2003 April 24; in original form 2002 October 16

ABSTRACT
We have monitored the Seyfert galaxy NGC 3227 with the Rossi X-ray Timing Explorer (RXTE) since 1999 January. During late 2000 and early 2001 we observed an unusual hardening of the 2–10 keV X-ray spectrum which lasted several months. The spectral hardening was not accompanied by any correlated variation in flux above 8 keV. We therefore interpret the spectral change as transient absorption by a gas cloud of column density $2.6 \times 10^{23} \text{cm}^{-2}$ crossing the line of sight to the X-ray source. A spectrum obtained by XMM–Newton during an early phase of the hard-spectrum event confirms the obscuration model and shows that the absorbing cloud is only weakly ionized. The XMM–Newton spectrum also shows that $\sim 10$ per cent of the X-ray flux is not obscured, but this unabsorbed component is not significantly variable and may be scattered radiation from a large-scale scattering medium. Applying the spectral constraints on the cloud ionization parameter and assuming that the cloud follows a Keplerian orbit, we constrain the location of the cloud to be $R \sim 10–100$ light-days from the central X-ray source, and its density to be $n_H \sim 10^8 \text{cm}^{-3}$, implying that we have witnessed the eclipse of the X-ray source by a broad line region cloud.

Key words: galaxies: individual: NGC 3227 – galaxies: Seyferts – X-rays: galaxies.

1 INTRODUCTION
The presence of broad, permitted lines in the optical spectra of type 1 active galactic nuclei (AGN) indicates the presence of dense ($n_H > 10^6 \text{cm}^{-3}$), relatively low-ionization gas close to the central engine (e.g. Peterson 1997; Krolik 1999). The covering factor of the ‘broad line region’ (or BLR) is estimated from line equivalent widths to be around 10 per cent, while the strengths of low-ionization and Balmer lines imply column densities $N_H > 10^{23} \text{cm}^{-2}$ (see Peterson 1997; Krolik 1999, for reviews). ‘Reverberation mapping’ measurements of time-delays in the response of optical lines to changes in the optical continuum indicate that the BLR lies within a few light-weeks of the continuum source (e.g. Peterson et al. 1998; Kaspi et al. 2000).

It is perhaps surprising that clear-cut evidence for the low-ionization BLR clouds in type 1 AGN has not previously emerged in the X-ray band. The soft X-ray band (<2 keV) is particularly sensitive to absorption by gas along the line of sight to the central X-ray source. Numerous studies using missions sensitive to the soft X-ray band (e.g. ROSAT, ASCA, BeppoSAX and, most recently, the grating instruments on Chandra and XMM–Newton) have shown the presence of absorption due to more highly ionized gas (the ‘warm absorber’) along the line of sight in many Seyfert 1s, but the precise location of this gas is still fairly uncertain (e.g. M{\^e}Hardy et al. 1995; George et al. 1998a; Netzer et al. 2002; Schurch & Warwick 2002). Column density variations of cold X-ray absorbing gas have been reported on time-scales of months–years in both type 1 and type 2 Seyferts (Malizia et al. 1997; Risaliti, Elvis & Nicastro 2002). If such variations are due to clouds crossing the line of sight with Keplerian velocities, the obscuring clouds may lie within or not much beyond the BLR. Unfortunately, due to the sparse temporal sampling of X-ray spectra of AGN available with most X-ray missions, it is difficult to put these apparent absorption changes into context, and assess if they really are caused by the motion of dense absorbing clouds across the line of sight to the X-ray source.

In this Letter, we present a study of the long-term X-ray spectral variability of the Seyfert 1.5 galaxy NGC 3227, using data from a monitoring campaign carried out by the Rossi X-ray Timing Explorer (RXTE). A previous study of spectral variability in NGC 3227 showed evidence of an order of magnitude increase in the cold/low-ionization column (from $\sim 10^{21}$ to $\sim 10^{22} \text{cm}^{-2}$) between ASCA observations obtained in 1993 and 1995 (George et al. 1998b). Using data from our monitoring campaign, we show that in 2000/2001 NGC 3227 underwent an unusual event lasting $\sim 3$ months, during which the spectrum became exceptionally hard. The symmetry of this event suggests it is due to absorption by a high column density cloud ($N_H \sim 3 \times 10^{23} \text{cm}^{-2}$) moving across the line of sight to the X-ray source. This interpretation is confirmed by an XMM–Newton observation obtained serendipitously, early in the event, which shows that the cloud is not substantially ionized. We...
Analysis System (SAS V5.3) we produced EPIC MOS and PN spectra we added all spectra within weekly intervals. Each of these weekly of the detector gain and the changing numbers of detectors used.

In order to increase the signal-to-noise ratio of the PCA spectra, we added all spectra within weekly intervals. Each of these weekly spectra was fitted in XSPEC 11.0.1 with a model consisting of a power law, a Gaussian emission line and the Wisconsin absorption model. The energy range used for spectral fitting was restricted to 2–12 keV. Because the data were extracted from varying combinations of PCUs and the detector gain was changed on several occasions during the time-span of the monitoring campaign, simple count rate light curves cannot be used to measure the variability of the source. We therefore calculated model fluxes from the spectral fits in the bands 2–10 and 8–10 keV in order to obtain detector independent light curves over the full time-range of the monitoring campaign.

NGC 3227 was observed by XMM–Newton on 2000 November 28–29. We retrieved the EPIC and RGS pipeline products from the XMM science data archive (XSA). Using the XMM Science Analysis System (SAS v5.3) we produced EPIC MOS and PN spectra for NGC 3227. The extraction radius was 30 arcsec and only events in single and double patterns with FLAG = 0 were selected.

3 A TRANSIENT ABSORPTION EVENT

3.1 RXTE monitoring

During the first quarter of the year 2001, transient hardening of the 2–12 keV spectrum was observed. The event lasted for about 100 d and peaked around MJD 51 950. Due to the limited spectral resolution and signal-to-noise ratio of the spectra, the spectral fits alone cannot distinguish whether the hardening is caused by intrinsic slope variation or by additional absorption. When we fit the weekly binned spectra with the power law + Gaussian line model and the absorbing column density set to the galactic value of $N_H = 2.2 \times 10^{20}$ cm$^{-2}$, we find a flattening of the photon index to $\Gamma \sim 0$, harder than so far observed in any AGN X-ray spectrum (see Fig. 1).

We now consider the two simplest possibilities: that the transient hardening is caused by a change in the primary continuum shape, or that it is caused by obscuration by a cloud of large column density. As the hard-spectrum event occurs during a period when the source long-term X-ray flux is quite low, and the X-ray spectra of a number of Seyfert 1s are known to become harder at low fluxes (e.g. Uttley et al. 1999; Vaughan & Edelson 2001; Lamer et al. 2003), we first test whether the spectral shape is simply correlated with flux. If this hypothesis is true, we would expect the relation between photon index and flux to be the same both within the 100-d hard-spectrum event and at other times. Specifically, we need to measure photon index versus 8–10 keV flux (i.e. where absorption effects are minimal), in order to remove any spurious correlation produced by varying absorption, which would naturally cause the flux in softer bands (which are absorbed) to correlate with the fitted photon index. Fig. 2 shows the photon indices of the weekly binned spectra plotted against the 8–10 keV flux. We find that the ‘normal’ spectral variability of NGC 3227 is very similar to that found in other Seyfert galaxies. At low flux levels the spectral index steepens rapidly with increasing flux; at higher flux levels the increase of the spectral slope levels off and saturates at $\Gamma \sim 2.0$. Similar flux–slope relations have been found in NGC 4051 (Lamer et al. 2002) and MCG-6-30-15 (Shih, Iwasawa & Fabian 2002). On the other hand, the data points from the 2001 event clearly fall outside the normal range in the flux–index plane. The indices are much harder and do not strongly correlate with changes in the 8–10 keV flux.

Having ruled out simple, flux-correlated variability as the source of the hard-spectrum event, we next consider the possibility that it is caused by transient obscuration by a large column of gas. The apparent symmetry of the event supports this possibility, suggesting...
that a symmetric (i.e. spherical) cloud passed in front of the X-ray source. From the flux of hard X-rays and the normal flux–index relation in NGC 3227 (Fig. 2) we estimate an intrinsic photon index of $\Gamma = 1.6$ during the absorption event. We repeated the model fitting with the power law + Gaussian line model with the photon index fixed at $\Gamma = 1.6$ and the absorption column density left free to vary. Fig. 3 shows the resulting column density for the assumption of a neutral absorber. We fitted the profile of column density changes with two simple models, a uniform sphere and a $\beta$-model of the form $N_H = N_{H,\max}/(1 + (r/R)^\beta)$ (see Fig. 3). The $\beta$-model gave a much better fit (reduced $\chi^2 \simeq 0.98$ versus $\chi^2 \simeq 1.85$ for the uniform sphere model), for a $\beta$ index of $\approx 0.5$, suggesting that the cloud density is not uniform but increases towards the centre. The column density peaks at $N_H \sim 2.6 \times 10^{20}$ cm$^{-2}$. However, based on the RXTE data alone, we cannot absolutely discount the possibility that the hard-spectrum event is caused by very unusual circumstances.

3.2 The XMM–Newton spectrum

NGC 3227 was observed by XMM–Newton around MJD 51877, during an early phase of the hard spectrum event (see Fig. 3). We performed joint model fitting on the EPIC MOS1, MOS2 and PN spectra. The hard bands ($>2$ keV) can be modelled by a strongly absorbed ($N_H \sim 5 \times 10^{22}$ cm$^{-2}$) power law spectrum and a narrow Fe K$_\alpha$ fluorescence line. The absorbing column density is consistent with the value measured by RXTE at the same time (see Fig. 3). In the soft range below 1 keV an unabsorbed power law spectrum dominates (see below and Fig. 4).

Table 1. XMM EPIC spectral fits.

| Model | $N_{H,1}$ $10^{20}$ cm$^{-2}$ | Unabsorbed component | Absorbed component | $\xi$ | $\chi^2$ (dof) |
|-------|----------------|---------------------|---------------------|------|---------------|
|       |                   | $\Gamma_1$ | $10^{-4}$ | $10^{20}$ cm$^{-2}$ | $\Gamma_2$ | $10^{-4}$ | $10^{20}$ cm$^{-2}$ | $\nu$ | $\chi^2$ (dof) |
| (i) 1 powl | $0.0^{+0.2}_{-0.0}$ | 1.45 $\pm$ 0.02 | 1.62 $\pm$ 0.03 | 632 $\pm$ 9 | 1.45 $\pm$ 0.02 | 17.4 $\pm$ 1.0 | - | 1707 (1565) |
| (ii) 2 powl | 1.4 $\pm$ 0.4 | 1.71 $\pm$ 0.06 | 1.64 $\pm$ 0.05 | 527 $\pm$ 16 | 1.28 $\pm$ 0.03 | 13.0 $\pm$ 1.3 | - | 1673 (1564) |
| (iii) warm abs. | 1.6 $\pm$ 0.5 | 1.74 $\pm$ 0.06 | 1.64 $\pm$ 0.06 | 576 $\pm$ 33 | 1.29 $\pm$ 0.03 | 13.4 $\pm$ 1.4 | $10^{+1.5}_{-0.6}$ | 1650 (1562) |
| (iv) warm abs. + refl. | 1.5 $\pm$ 0.4 | 1.72 $\pm$ 0.05 | 1.64 $\pm$ 0.05 | 708 $\pm$ 35 | 1.72 $\pm$ 0.05 | 22.5 $\pm$ 2.2 | $0.3^{+0.8}_{-0.3}$ | 1647 (1562) |

Using XSPEC, we fitted four different partial covering models to the XMM EPIC spectra:

(i) Single power law model with partial absorption: $\text{WABS}[\text{POWL} + \text{ZWABS}(\text{POWL} + \text{ZGAUSS})]$, with the two power-law components having identical slopes.

(ii) Double power law model: $\text{WABS}[\text{POWL1} + \text{ZWABS}(\text{POWL2} + \text{ZGAUSS})]$, both power-law indices are free to vary.

(iii) Double power law model with warm absorber as partial coverer: $\text{WABS}[\text{POWL1} + \text{ABSORI(POWL2 + ZGAUSS})]$.

(iv) Single power law with Compton reflection and warm absorber: $\text{WABS}[\text{POWL} + \text{ABSORI(HREFL(POWL))} + \text{ZGAUSS})]$.

The results of the spectral fitting are summarized in Table 1, and the double power law + warm absorber model is shown in Fig. 4. In all of the four models a narrow iron K$_\alpha$ fluorescence line with rest frame energy 6.4 keV and equivalent width $\sim 240$ eV is required. The neutral, unredshifted absorption in all four models is consistent with the Galactic value ($2.2 \times 10^{20}$ cm$^{-2}$). From model (iii), we find that constraints on $N_H$ and the ionization parameter, $\xi$, of the absorbing gas suggest that the obscuring cloud is not neutral, but ionized, albeit with a low ionization parameter (see Fig. 5).

Note that the absorbed power-law component is rather hard ($\Gamma \sim 1.3$), as expected due to the low 8–10 keV flux ($2.2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$) measured during the XMM–Newton observation (see Fig. 2 for comparison with the ‘normal’ photon index–flux relation). The unabsorbed power-law component in the soft range has a normalization of about 10 per cent of the absorbed power-law component. The best-fitting parameters of models (ii) and (iii) (also see Fig. 4) also show that the unabsorbed component is intrinsically softer than the absorbed component. There are three possible reasons...
for this finding as follows. (1) We see two components emitted from different regions of the AGN, e.g. the softer, unabsorbed power law arises from a more extended emitting region, which is not completely obscured by the cloud while the inner, hard X-ray emitting region is obscured. (2) The absorbed and unabsorbed components are intrinsically identical, but have a steeper slope in the soft range below \( \sim 1\) keV. This could be due to a soft excess or a hard reflection spectrum at higher energies. The reflection spectrum (model iv) fits the data well with a rather high ratio (3.2 \( \pm \) 0.6) of reflection covered to escape component. The large reflected fraction may be due to the low flux state during the time of the XMM observations. (3) The slope of the underlying power law spectrum is highly variable, and therefore the slope of the scattered and delayed component differs from the slope of the absorbed, nuclear component.

We produced XMM EPIC light curves for both the unabsorbed component in the 0.2–1 keV range and for the absorbed component at 2–10 keV (Fig. 6). While the absorbed emission is clearly variable, no significant variability is found in the soft component (a constant model yields \( \chi^2 = 36.7\) for 33 d.o.f.). We therefore conclude that the two components are emitted in different regions of the AGN. As the soft power-law component does not show any intraday variability, it could arise from a relatively large volume, and might represent radiation scattered from an extended, ionized medium.

We note that, since submission of this paper the 2000 November XMM–Newton observation of NGC 3227 has also been published by Gondoin et al. (2003). They fit a slightly different model to us, we refer readers to Gondoin et al. for a full discussion of their model.

4 PHYSICAL CONSTRAINTS ON THE ABSORBING MATTER

Assuming that the hard-spectrum event is caused by the passage of an absorbing cloud along the line of sight to the X-ray source, we can place lower limits on the distance of the cloud from the source and its density by making a few basic assumptions.

For simplicity, we shall assume a cloud of uniform density and ionization parameter, following a circular orbit around the X-ray source. Although our assumption that the cloud has a uniform density is almost certainly not true (see Fig. 3), the discrepancy in \( N_H \) profiles between the \( \beta \)-model and uniform sphere model is typically only a factor of a few. Therefore we do not expect any significant (i.e. order of magnitude) error in our estimates of cloud parameters to result from this simplifying assumption. The ionization parameter \( \xi \) is given by

\[
\xi = \frac{L_{\text{ion}}}{n_H R^2},
\]

where \( L_{\text{ion}} \) is the ionizing luminosity in the range from 13.6 eV to 13.6 keV, \( n_H \) is the hydrogen number density of the gas and \( R \) is its distance from the ionizing source. The diameter of the cloud is given by \( N_H/n_H \), so that the velocity of the cloud across the line of sight is \( v_\text{cloud} = N_H/(n_H t_\text{cross}) \) (where \( t_\text{cross} \) is the crossing time of the cloud across the line of sight). Assuming a circular orbit of radius \( R \) around the central black hole of mass \( M_{BH} \), we can obtain an expression for the hydrogen number density:

\[
n_H = \frac{N_H}{t_\text{cross}} \sqrt{\frac{R}{GM_{BH}}}.
\]

where \( G \) is the gravitational constant. Finally, we can combine equations (1) and (2) and rearrange to obtain \( R \):

\[
R \approx 4 \times 10^{16} M_{\odot}^{1/5} \left( \frac{L_{\text{ion}} t_\text{days}}{N_H^{2/5}} \right)^{2/5} \text{cm},
\]

where \( L_{\text{ion}} = L_{\text{ion}}/10^{42} \text{ erg s}^{-1} \), \( t_\text{days} \) is the crossing time in days, \( M_{\odot} = M_{BH}/10^7 \text{ M}_{\odot} \) and \( N_{22} = N_H/10^{22} \text{ cm}^{-2} \). We next take the conservative 99 per cent confidence limits imposed on ionization parameter by the XMM–Newton spectrum of \( \xi = 0.1–30 \) (see Fig. 5), a cloud maximum column density of \( N_H = 1.87 \times 10^{22} \text{ cm}^{-2} \) and crossing time of 62 d (the best-fitting uniform sphere parameters). The best estimate of black hole mass from reverberation mapping is \( M_{BH} = 5 \times 10^7 \text{ M}_{\odot} \) (Wandel, Peterson & Malkan 1999), and we estimate \( L_{\text{ion}} = 10^{42} \text{ erg s}^{-1} (H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \text{, using the observed flux during the event and assuming a typical continuum photon index } \Gamma = 1.6) \). Combining these values in equation (3), we calculate that \( R \) lies in the range 9–86 light-days. Using these limits in equation (2), we find a corresponding range of possible densities, \( n_H \sim 0.7–2.0 \times 10^6 \text{ cm}^{-3} \), so that the cloud must be of order a light-day in diameter or less. Note that these estimates are not strongly dependent on the central black hole mass, to which no strong lower limit can be set in NGC 3227 (Wandel et al. 1999). A factor of 10 reduction in black hole mass will only reduce the lower and upper limits on \( R \) by 37 per cent and increase \( n_H \) by 250 per cent.

5 DISCUSSION

We now consider how the physical constraints we can place on the properties of the eclipsing cloud in NGC 3227 compare with...
the constraints expected for gas in various regions of the AGN. Most obviously, the location of the cloud (roughly 10-100 light-days from the central X-ray source) is consistent with an origin in the BLR of NGC 3227, the size of which is estimated from optical reverberation studies to be between 10-20 light-days (Salamanca et al. 1994; Winge et al. 1995; Wandell et al. 1999), although note that because these estimates refer to the region of the BLR which emits most of the Balmer lines, the full extent of the BLR may be significantly larger. Similarly, the density we estimate for the cloud is also consistent with the lower limit on densities of BLR clouds estimated from optical line ratios (e.g. see Krolik 1999, for discussion) and rules out an origin in the lower density, more distant, narrow line region (NLR) or large-scale molecular torus envisioned by the standard unification model. This last constraint is particularly strong, as even in the absence of any lower bound on ionization parameter, the density of the cloud can only increase with assumed orbital radius, due to the well constrained total column density and the strong dynamical constraint on cloud size imposed by the cloud crossing time.

By the same token, the cloud cannot be very dense, as according to our equation (2), the density scales only with the square root of distance from the central X-ray source, so if the assumed density were significantly larger than 10^{11} cm^{-3} the cloud would be located much further from the X-ray source than is consistent with any known component of the AGN (the same reasoning can be used to strongly constrain cloud size). Our strong constraint on cloud density is in conflict with the estimate of much denser BLR clouds (n_{H} \sim 10^{11} cm^{-3}) in the luminous Seyfert 1 NGC 5548, by Ferland et al. (1992), who required a large hydrogen number density to prevent the clouds becoming too heavily ionized in the high radiation density environment implied by the relatively small BLR size estimated from reverberation mapping. However, we note that although NGC 3227 has a similar sized BLR to NGC 5548 (e.g. see Peterson et al. 2002), it has a much lower X-ray luminosity (10^{42} erg s^{-1} versus 5 \times 10^{43} erg s^{-1}), so that the radiation density in the BLR of NGC 3227 is likely to be much lower than in NGC 5548. In fact, if for comparison, we convert from our ionization parameter \xi to the equivalent formulation U used by Ferland et al. (1992) (e.g. see George et al. 1998a, for conversion factors), we find U < 0.1 in NGC 3227, consistent with the value estimated for NGC 5548 and the BLR in other AGN (see Ferland et al. 1992; Peterson 1997, and references therein).

The size inferred for the eclipsing cloud is quite large, implying that only of order ~100 clouds are required to produce the ~10 per cent covering fraction estimated for the BLR (Peterson 1997; Krolik 1999). This smaller number of clouds conflicts with the large number (>10^4) required to produce the smooth broad line profiles observed in type 1 AGN (e.g. Atwood, Baldwin & Carswell 1982), assuming that the cloud intrinsic linewidths are small, thermal widths only. This latter assumption might be relaxed if the cloud linewidths are intrinsically broadened, e.g. if the clouds are dynamically unstable, which might be expected given the large cloud size. Note also that our cloud size estimates can be used to constrain the size of the primary X-ray emitting region to be less than ~1 light-day, or around 170 Schwartzschild radii for a 5 \times 10^7 M_{\odot} black hole (assuming the primary X-ray emitting region is totally covered, as suggested by the lack of variability in the unabsorbed spectral component).

When considering the implications of these results for models of the BLR in AGN in general, one must bear in mind the caveat that strong observational selection effects almost certainly exist in any detection of BLR clouds by X-ray absorption. For example, eclipses of the X-ray emitting region by much smaller clouds, of the higher densities envisaged by Ferland et al. (1992), would only be noticeable if the X-ray emitting region was itself very compact (smaller than hundreds of light-seconds or less than one Schwartzschild radius for a 5 \times 10^7 M_{\odot} black hole). Furthermore, the duration of such events would be much shorter than the observed ~100 d (perhaps only a few thousand seconds), so would only be detectable with continuous monitoring, which we do not have. Therefore we cannot rule out the existence of such small clouds in NGC 3227. Other selection effects may also be at work. For example, the relatively low radiation density in the BLR of NGC 3227 may permit the existence of large, relatively low-density clouds which might not exist in other AGN. The presence of such clouds may also account for the smaller amplitude column-density variations reported in NGC 3227 by George et al. (1999b). Alternatively, the fact that column variations are apparently common in NGC 3227 might be explained if the BLR has a planar geometry and we are viewing the X-ray source through the BLR plane. Even taking into account the above caveats, our results imply that a population of large BLR clouds exists in at least some AGN. Taking the estimate of much smaller, higher density clouds in NGC 5548 (Ferland et al. 1992) at face value, it seems that BLR cloud densities and sizes in different AGN must span at least a three order-of-magnitude range.

ACKNOWLEDGMENTS

We would like to thank Hagai Netzer and Brad Peterson for helpful discussions.

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