THE X-RAY SPECTRAL VARIABILITY OF THE SEYFERT GALAXY NGC 3227

I.M. George ¹,², R. Mushotzky ¹, T.J. Turner ¹,², T. Yaqoob ¹,², A. Ptak ³, K. Nandra ¹,⁴, H. Netzer ⁵,

ABSTRACT

We present the results from ASCA observations of NGC 3227 performed during 1993 and 1995, along with those from a ROSAT observation performed pseudo-simultaneously with the former. We find the 0.6–10 keV continuum to be consistent with a powerlaw with a photon index $\Gamma \sim 1.6$, flatter than that typically observed in Seyfert galaxies confirming previous results. Significant Fe K-shell emission is observed during both epochs, with an equivalent width and profile typical of Seyfert 1 galaxies. The ASCA observations in 1993 reveal absorption by a screen $N_{H,z}^{\text{ion}} \sim 3 \times 10^{21}$ cm$^{-2}$ of ionized material with an X-ray ionization parameter $U_X \sim 0.01$. Both the column and ionization-state of this material are at the low end of the distribution of parameters observed for Seyfert 1 galaxies. Joint analysis of the ASCA and ROSAT data at this epoch show an additional screen of neutral material intrinsic to NGC 3227 with $N_{H,z}^{\text{neu}} \sim \text{few} \times 10^{20}$ cm$^{-2}$.

We find NGC 3227 to exhibit significant spectral variability both within and between the observations. The most likely explanation involves short-term variability in the continuum emission and longer-term variability in the column density of the ionized material. Time-resolved spectroscopy and color–color analysis indicate that the slope of the continuum steepened by $\Delta \Gamma \sim 0.1$ during a flare of duration $\sim 10^4$ s, within the 1993 observation. However we were unable to distinguish between a steepening of the ‘primary’ continuum and a change

¹Laboratory for High Energy Astrophysics, Code 660, NASA/Goddard Space Flight Center, Greenbelt, MD 20771
²Universities Space Research Association
³Present Address: Department of Physics, Carnegie Mellon University, 5000 Forbes Ave, Pittsburgh, PA 15213
⁴NAS/NRC Research Associate
⁵School of Physics and Astronomy and the Wise Observatory, The Beverly and Raymond Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel.
in the relative strengths of the power-law and a putative Compton-reflection component. The absorbing column increased by a factor of \( \sim 10 \) by the 1995 epoch, while the continuum is consistent with that observed in 1993. The 1995 data also show evidence that the warm absorber allows \( \sim 10\% \) of the nuclear emission to escape without attenuation.

We review our findings in the context of the previous results from this and similar objects and discuss the prospects of future observations.

*Subject headings:* galaxies:active – galaxies:nuclei – galaxies:Seyfert – X-rays:galaxies – galaxies:individual (NGC 3227)
1. INTRODUCTION

Recent X-ray spectra obtained by ASCA have revealed the presence of ionized material along the cylinder–of–sight in a large fraction (50–75%) of Seyfert 1 galaxies (e.g. Reynolds 1997; George et al 1998a, hereafter G98). To-date, this material has been detected primarily due to the bound-free absorption edges of O\text{vii}(739 eV) and O\text{viii}(871 eV) imprinted on the underlying X-ray continuum, although additional edges due to other ions have been detected in some objects. The depths of the absorption features (and hence accuracy to which they can be determined) vary from object-to-object, with sources having implied column densities covering a range \(N(\text{O\text{vii}} + \text{O\text{viii}}) \lesssim \text{few} \times 10^{17} \text{ cm}^{-2}\) to \(\gtrsim 10^{19} \text{ cm}^{-2}\). Both these limits on the column density most likely arise only as a result of the combination of the moderate spectral resolution of the ASCA detectors and the signal–to–ratio of most of the datasets currently available. For \(N(\text{O\text{vii}} + \text{O\text{viii}}) \lesssim 7 \times 10^{17} \text{ cm}^{-2}\), the optical depths (at the respective threshold energies) of both O\text{vii} and O\text{viii} are \(\lesssim 0.05\), making the unequivocal detection of such features extremely difficult. For \(N(\text{O\text{vii}} + \text{O\text{viii}}) \gtrsim 10^{19} \text{ cm}^{-2}\), bound-free absorption edges due to other ionized elements (most notably due to C, N, Ne K-shell and Fe L-shell transitions) become increasingly important and finally dominate the opacity if the absorbing material has ‘cosmic’ abundances, making the determination of the precise strength of the O\text{vii} and O\text{viii} edges difficult without detailed modelling. Nevertheless, even the current limits show that the column density of ionized material along the cylinder–of–sight far exceeds that of neutral material in the majority of Seyfert 1 galaxies. Assuming a standard abundance ratio of oxygen (O/H~ 9 × 10\(^{-4}\)) the observed range of \(N(\text{O\text{vii}} + \text{O\text{viii}})\) implies total hydrogen column densities for Seyfert 1 galaxies as a class covering the range \(10^{21} \lesssim N_{\text{H,z}}^{\text{ion}} \lesssim 10^{23} \text{ cm}^{-2}\). It should be stressed that these values of \(N_{\text{H,z}}^{\text{ion}}\) are lower limits since the column density of oxygen with ionization states <O\text{vii} and of fully stripped oxygen ions is unknown.

As first suggested by Halpern (1984), the material responsible for these features is generally considered to be photoionized by the intense radiation field of the nucleus. Detailed photoionization models have been successfully applied to the existing X-ray data. The location and geometry of this highly ionized material is currently unclear. It is also unclear how the material responsible for the features observed in the X-ray band is related (if at all) to the ‘associated absorbers’ (primarily resonant absorption lines due to Li-like species of C and N) commonly seen in the UV band in these objects (e.g. Crenshaw 1997) and some attempts have been made to link the two (eg. Mathur 1994; Shields & Hamann 1997). Since the UV absorption features with cores very close to zero intensity (eg. Crenshaw, Maran, Mushotzky 1998) are seen imprinted on broad emission lines, this places the bulk of the UV-absorber outside the broad emission line region (BELR).
It is becoming increasingly clear that a single screen of ionized gas in photoionization equilibrium may be too simple a model. First, the column density of the ionized gas has sometimes been seen to vary by large factors on relatively long timescales (e.g. MCG-6-30-15, Fabian et al 1994; NGC 3783 George et al 1998b), in fact the first paper proposing the presence of absorption by ionized material in an active galaxy, the QSO MR2251-178, made this suggestion based on the variable column density (Halpern 1984). Second, differential variability between the depths of the O\textsubscript{vii} and O\textsubscript{viii} edges has been seen in some objects on timescales $\sim 10^4$ s (e.g. MCG-6-30-15, Reynolds et al 1995, Otani et al 1996; NGC 4051, Guainazzi et al 1996). Third, a number of sources have revealed spectroscopic evidence for one or more screens of ionized gas (e.g. NGC 3516, Kriss et al 1996; NGC 3783, George et al 1998b, see also those objects with a '1 keV deficit’ in G98). Such observations are providing our first insights into the location, physical conditions and kinematics of the material in the vicinity of the X-ray source.

The nucleus of the Sb galaxy NGC 3227 ($z = 0.003$) is heavily reddened (see Komossa & Fink 1997, thereafter K97, and references therein), which is at least partially responsible for its classification historically as both a Seyfert 2 (Huchra & Burg 1992) and Seyfert 1.5 (Osterbrock & Martel 1993) from spectroscopy of the optical emission lines. Evidence for substantial amounts of neutral material within the galaxy is also provided by the detection of HI (Mundell et al 1995a) and OH (Rickard, Bania & Turner 1982) absorption, along with CO (e.g. Rigopoulou et al 1997 and references therein) and H\textsubscript{2}CO (tentatively; Baan, Haschick & Uglesich 1993) emission. The host galaxy appears to be interacting with a nearby companion, NGC 3226 (eg. Arp 1966). The radio, [O\textsubscript{iii}] and H\textalpha emission reveal asymmetrical physical conditions on the opposing sides of the nucleus and a misalignment between the collimation of the radio emitting plasma and that of the photoionizing continuum (e.g. Mundell et al 1995b; González Delgado & Pérez 1997). Spatially–resolved spectroscopy of the circumnuclear regions have revealed evidence that the BELR (and hence perhaps the ‘nucleus’ itself) is off-set from the center of rotation by $\sim$250 pc (Mediavilla & Arribas 1993; Arribas & Mediavilla 1994).

In the X-ray band, NGC 3227 was first detected in the Ariel-V sky-survey and has been observed subsequently by all major X-ray instruments (e.g. Malizia et al 1997 and references therein). Of particular note are the results from the EXOSAT observations, which revealed differential variability between the soft and medium X-ray bands (Turner & Pounds 1989), and the Ginga observations which suggested an asymmetric profile for the Fe K$\alpha$ emission line (Pounds et al 1989; George, Nandra & Fabian 1990) and evidence for an Fe K-shell absorption edge (Nandra & Pounds 1994). ROSAT and ASCA observations of NGC 3227 in 1993 have revealed the presence of ionized material within the cylinder–of–sight (e.g. Ptak et al 1994; K97; Reynolds 1997; G98). The values derived from $N_{H,z}^{ion}$ and $U_X$ are some of
the lowest yet reliably measured in a Seyfert galaxy, which may be related to the relatively low luminosity of the source ($\sim 10^{42}$ erg s$^{-1}$ in the 0.1–10 keV band). The $N_{H,\text{ion}}$ is similar to that necessary to give rise to the reddening observed in the optical and UV bands if the ionized material contains embedded dust with a gas-to-dust ratio and composition similar to that seen in our Galaxy (K97; G98).

Here, for the first time, we present the results from the analysis of an ASCA observation of NGC 3227 performed in 1995 May. We also describe the results from a re-analysis of an earlier ASCA observation carried out in 1993 May, along with those from a contemporaneous ROSAT observation. The observations are described in §2, and the preliminary data reduction and temporal analysis in §3. We show that NGC 3227 exhibits significant energy-dependent variations both within and between the two epochs. In §4 we consider the time-averaged spectra at each epoch in order to parameterize the significant change in the observed continuum and between 1993 and 1995, and to parameterize the Fe K emission evident during both epochs. We present a more detailed analysis of the energy-dependent variability within each observation in §5 using both an X-ray color analysis and time-resolved spectral analysis. In §6 we review our findings in the context of the previous results from this and similar objects and briefly discuss the prospects in the future, and in §7 present our conclusions.

2. THE OBSERVATIONS

The new ASCA observation of NGC 3227 reported here was carried out over the period 1995 May 15–16, we have also performed a re-analysis of the ASCA observation from 1993 May 08–09, described previously in Ptak et al (1994), Reynolds (1997), Nandra et al (1997a,b), and G98. Here we utilize raw data from the Rev2 processing along with new screening criteria and the latest calibration files. These changes result in slightly different values for some parameters compared to the results published previously. Details on the ASCA satellite, its instrumentation and performance can be found in Makishima et al. (1996) and references therein.

The ROSAT observation of NGC 3227 reported here was performed over the period 1993 May 08-19 with the PSPC in the focal plane. The results from this observation have been reported previously by K97 and are included again here to enable us to compare the results to the contemporaneous ASCA data. Our analysis differs slightly from that used by K97 since we make use of a different analysis package (FTOOLS) and include the latest

---

6hence raw data from the same processing configuration (6.4.2) is used for all the datasets
spatial and temporal gain corrections for the data. Details on the ROSAT satellite, its instrumentation and performance can be found in Briel et al. (1994) and references therein. The full observing log is given in Table 1.

3. DATA SCREENING & PRELIMINARY ANALYSIS

3.1. Data Screening

The unscreened ASCA event files containing data collected in FAINT and BRIGHT data modes were combined, as were data obtained during all three telemetry modes. These data were then screened using the ascascreen/xselect script (v0.39) within the FTOOLS package (v4.0). The screening criteria used were as given in Nandra et al (1997a), with the exception that the elevation angle above the Earth’s limb was > 20° for the SIS0 data obtained in 1993, and that the CCD pixel threshold was < 50 and < 100 for the 1993 and 1995 data (respectively). The original pulse-height assignment for each event was converted to a pulse-invariant (PI) scale using sispi (v1.1). In the case of the GIS data (only) 'hard particle flares' were rejected using the so-called HO2 count rate, and standard 'rise-time' rejection criteria employed. These criteria resulted in effective exposure times of ∼ 30 ks and ∼ 39 ks in each SIS and GIS (respectively) during the 1993 observations, and ∼ 34 ks and ∼ 37 ks during the 1995 observations.

The cleaned ROSAT event file, produced using the standard screening criteria provided by SASS (v7.9), was extracted from the HEASARC archive. The latest corrections were then applied for the spatial and temporal variations in the gain of the PSPC (see Snowden et al 1995) using pcsasscor (v1.1.0), pctcor (v1.1.0) and pcecor (v1.2.0). The effective exposure amounted to 19.5 ks spread over an 11 day period.

3.2. Image Extraction

Images were extracted for each instrument during each observation. In all cases, a bright source was detected with an X-ray centroid consistent with the optical position of NGC 3227 to within the uncertainty in the positional accuracy of the attitude reconstruction of the respective satellite.

As has been previously noted by Radecke (1997), a number of serendipitous sources are evident within the central 20 arcmin of the field-of-view of the ROSAT PSPC. All are relatively weak (with count rates in the 0.2–2.0 keV band a factor ≲ 3% of that
from NGC 3227). Only one of the serendipitous sources (which we tentatively identify as NGC 3226, with a count rate of $\sim 1.5 \times 10^{-2}$ ct s$^{-1}$ in the 0.2–2.0 keV band) lies close enough to affect the analysis of the PSPC data from NGC 3227, and this has been excluded from the regions used to extract the source and background data. No serendipitous sources were detected in the ASCA images. Given the weakness of NGC 3226 and all other sources in the immediate vicinity, we consider it unlikely they contaminate significantly the analysis of the ASCA data from NGC 3227.

Extraction cells were defined for the subsequent temporal and spectral analysis. In the case of the ASCA SIS data, a circular extraction cell of radius $\sim 3.2$ arcmin was centered on NGC 3227. In the case of the 1995 observations, the image of NGC 3227 was centered close to the standard position on the default CCD chip of each SIS. The source region lies completely within the active region of the chip, and from the point-spread function (psf) of the XRT/SIS instrument, contains $\sim 84\%$ of the total source counts. However, in the 1993 observation all four chips were active on each SIS and NGC 3227 was centered on the default CCD chip, but within $\sim 1.8$ arcmin of the corner of the chip closest to the intersection of the 2 $\times$ 2 CCD array. In principle, the data collected by all 4 chips can be combined. However, given the differences between the various CCDs comprising each SIS detector, here we choose to analyse only the photons falling on the nominal, better-calibrated CCD of each SIS. Thus the extraction cells used were circles, but excluding all regions beyond the active area of the nominal chip. From the psf, we estimate these cells included $\sim 61\%$ and $\sim 45\%$ of the total source counts for SIS0 and SIS1 respectively. An extraction cell was defined to provide an estimate of the background for each SIS detector which consisted of the whole of the nominal CCD chip excluding a circular region of $\sim 4.3$ arcmin centered on the source.

For GIS data, the source region was circular of radius $\sim 5.2$ arcmin centered on NGC 3227. Given the larger field-of-view of the GIS instrument, such a region lies completely on the detector at both epochs. From the psf of the XRT/GIS instrument the region contains $\sim 89\%$ of the total source counts. An annulus, centered on the source and covering $\sim 5.2$–9.8 arcmin was used to provide an estimate of the background. Given their larger field-of-view, these regions were fully located on the active area of the GIS detectors during both observations. All fluxes and luminosities quoted below (not count rates) have been corrected for the fraction of the source photons falling outside the source extraction cells and for the contamination of source counts in the background extraction cells.

In the case of the ROSAT PSPC data, the source region was circular of radius $\sim H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$ assumed throughout.
\(~ 2.3 \text{ arcmin} \) and the background region an annulus covering radii \(~ 2.3-4.1 \text{ arcmin} \), both regions centered on NGC 3227 (a circle, radius \(~ 0.7 \text{ arcmin} \) centered on NGC 3226 was excluded from both). From the psf of the XRT/PSPC instrument the source region contains \(~ 98\% \) of the total source counts.

### 3.3. Basic Temporal Analysis

Light curves were constructed for the source and background regions for several different energy ranges. To increase the signal-to-noise ratio, the light curves from SIS0 and SIS1 and from GIS2 and GIS3 were combined and then rebinned on a variety of timescales.

In Fig. 1 we show the light curves for the SIS (0.5–10 keV), GIS (2–10 keV), and PSPC (0.2–2.0 keV) with a bin size of 128 s. Variability is apparent in the ASCA light curves both within the individual observations and between the epochs. Although only \(~ 2.3 \text{ ks} \) of the ROSAT pointing were made during the 1993 ASCA observations, variability in the PSPC count rate is apparent during this period and during the remainder of the ROSAT observation. The full PSPC light curve is shown by K97, and the dynamic range exhibited by the PSPC count rate during the whole ROSAT observation indicated by the dotted box in Fig. 1.

In Fig. 2 we show the light curves for the SIS using a bin size of 512 s using the bands XM\(_1\): 0.5–1.2 keV, XM\(_2\): 1.5–3.5 keV, and XM\(_3\): 4.0–10.0 keV (Netzer, Turner & George 1994). The count rate decreased in all three bands between the 1993 and 1995 observations with the amplitude increasing towards lower energies. Clearly the source underwent a significant change in the shape of the observed spectrum between the two epochs.

In Table 2 we list the normalized ‘excess variance’, \(\sigma_{\text{rms}}^2\), of each ASCA light curve using the prescription\(^8\) given in Nandra et al (1997a). The values of \(\sigma_{\text{rms}}^2\) show statistically significant variability (at > 95\% confidence) in the XM\(_1\) and XM\(_2\) bands during 1993 and in the XM\(_2\) band during 1995. There is an indication that \(\sigma_{\text{rms}}^2\) decreases towards higher energies when the whole of the 1993 dataset in considered, but (as will be discussed in \(\S 4\)) \(\sigma_{\text{rms}}^2\) is independent of energy when the ‘outburst’ is excluded. In the case of the 1995 observations, \(\sigma_{\text{rms}}^2\) is significantly lower in the XM\(_1\) band indicating the process responsible for the variability is not stationary. We also note that \(\sigma_{\text{rms}}^2(\text{XM}\_2) > \sigma_{\text{rms}}^2(\text{XM}\_3)\) during the 1995 observations.

\(^8\)We note there is a typographical error in the expression for the error on \(\sigma_{\text{rms}}^2\) given in Nandra et al (1997a) whereby the expression within the summation should be squared.
3.4. Spectral Analysis Technique

Source and background spectra were extracted from the cleaned event list of each detector using the extraction cells described in §3.2. For the SIS datasets, redistribution matrices generated using sisrmg (v0.8) were used. For the GIS datasets the redistribution matrices released on 1995 Mar 06 (generated by gisres v4.0) were used. Ancillary response files were generated for all the ASCA detectors using ascaarf (v2.72). In the case of the PSPC data, the standard response file pspcb_gain2_256.rsp was used.

In all cases described below, the spectral analysis is performed on the data from all instruments simultaneously, with different relative normalizations to account for (small) uncertainties in the determination of their effective areas. (The correction for the relative fractions of the source counts falling outside the source regions is applied within the ancillary response files.) Data from the SIS below 0.6 keV were excluded from the spectral analysis as it is commonly accepted that there are significant uncertainties associated with the calibration of the XRT/SIS system below this energy. Whilst the SIS calibration is suspect at these energies, we do make use of the fact that it is considered unlikely to be in error by > 20% (see below). The individual spectra were grouped such as to contain a minimum of 20 counts per new bin, and hence allowing $\chi^2$ minimization techniques to be employed within the XSPEC (v10.00) spectral analysis package.

We have adopted spectral models consisting of an underlying power-law continuum (of photon index $\Gamma$) absorbed by a screen of neutral material at zero redshift. In all cases the column density of this material, identified as being due to absorption within our galaxy, was fixed at $N_{H,0}^{gal} = 2.1 \times 10^{20}$ cm$^{-2}$ as derived from 21 cm measurements towards NGC 3227 (Murphy et al. 1996; these authors estimate an uncertainty $\lesssim 10^{19}$ cm$^{-2}$). All the spectral models also contain additional screens of neutral and/or ionized material fully- or partially-covering the cylinder–of–sight to NGC 3227. With the small redshift of NGC 3227, ASCA is unable to distinguish absorption at $z = 0$ from that at the redshift of the source. Nevertheless, here we assume that these additional screens are intrinsic to NGC 3227.

3.5. Models of the Photoionized Gas

Models including a photoionized absorber have been suggested previously to offer the most viable explanation for features observed in this and other Seyfert 1 galaxies. The photoionization code ION (version ION96) was used to calculate the physical state of a slab of gas when illuminated by an ionizing continuum (Netzer 1993, 1996). As in G98,
below 200 eV we assume an illuminating continuum typical of AGN of the luminosity of NGC 3227 (the 'weak IR' case of Netzer 1996), solar abundances and a density of \( n = 10^{11} \text{ cm}^{-3} \). (Models with densities as low as \( 10^8 \text{ cm}^{-3} \) give indistinguishable results.)

At energies >200 eV the ionizing continuum was assumed to be a powerlaw, and series of models were calculated assuming different X-ray spectral indices. Following Netzer (1996) and G98, the dimensionless 'X-ray ionization parameter', \( U_X \) (defined in G98, eqn. 1), is used to parameterize the intensity of the ionizing continuum in the 0.1–10 keV band. The conversion factors between \( U_X \) and ionization parameters defined over the entire photoionizing continuum (>13.6 eV) for various spectral forms can be found in G98.

4. ANALYSIS OF THE TIME-AVERAGED SPECTRA

Despite the variability exhibited by NGC 3227 at both epochs (Figs. 1 & 2), it is useful to first consider the time-averaged spectra observed during each observation. Spectra were therefore extracted using the extraction cells described in §3.2 for the whole duration of each observation. A strong emission line is present in the spectrum of NGC 3227 during both observations as a result of iron K-shell fluorescence. The best-fitting parameters of such a line are dependent upon the form of the underlying continuum, which itself is highly correlated with the absorption present in the soft X-ray band. Thus in §4.1.1 we exclude the 5–7 keV band (source frame) from our analysis and concentrate first on the form of the continuum and the nature of the absorber. The characteristics of the emission line and its possible effect on the properties of the continuum and absorption are then considered in §4.2.

4.1. Analysis excluding the Iron K-shell Region

4.1.1. The 1993 Observations

We first consider a model (hereafter model A) in which a single powerlaw continuum is absorbed by the Galactic column density \( N_{\text{H},0}^{\text{gal}} \) and an additional screen of neutral material \( (N_{H,z}^{\text{neu}} \text{ at } z = 0.003) \). A statistically acceptable fit for the 1993 ASCA data is obtained using model A, with a \( \chi^2 \)-statistic, \( \chi^2 = 1200 \) for 1126 degrees-of-freedom (dof) and best-fitting parameters listed in Table 3 (Fit 1). However, the extrapolation of this model below 0.6 keV gives rise to an increase in the \( \chi^2 \)-statistic, \( \Delta \chi^2_{0.6} = 43 \) for \( \Delta N_{0.6} = 12 \) additional data points (hence \( \Delta \chi^2_{0.6}/\Delta N_{0.6} = 3.6 \)), and a mean data/model ratio in the 0.4–0.6 keV band of
Thus we reject model A as an adequate description of the time-averaged ASCA spectrum during 1993. The inadequacy of model A in the soft X-ray band is confirmed by a joint analysis of the ASCA and ROSAT data (Table 3, Fit 2). From the mean data/model ratios plotted in the lower panel of Fig. 3a it can be seen that model A underpredicts the number of counts observed \( \lesssim 0.6 \) keV.

The excess of counts compared to model A could be considered evidence for either a steepening of the continuum and/or an additional emission component in the soft X-ray spectrum of NGC 3227. Indeed such components (with 2 or more additional free parameters) can be invoked to improve the quality of the extrapolation \(<0.6 \) keV. However, superior fits also can be obtained with one additional free parameter, \( U_X \), the ionization state of the gas intrinsic to NGC 3227. Hereafter we refer to this as model B. This model gives \( \chi^2 = 1122 \) for 1125 dof when applied to the 1993 ASCA data alone (Table 3, Fit 4). Not only does model B provide a superior description of the ASCA data all energies \( >0.6 \) keV, it also extrapolates in an acceptable manner to energies \( <0.6 \) keV (with \( \Delta \chi^2_{0.6}/\Delta N_{0.6} = 1.7 \) and \( R_{0.6} = 0.9 \)). Model B also offers an acceptable solution to a joint analysis of the ASCA and ROSAT data (Table 3, Fit 5), although it does appear to slightly overpredict the PSPC count rate. (Fig. 3b).

A vast improvement is achieved in the goodness–of-fit to the joint ASCA–ROSAT data if a screen of neutral material \( (N_{\text{H},z}^\text{neu} \simeq 3.6 \times 10^{20} \) cm\(^{-1}\) ) is added to model B \( (\Delta \chi^2 = 52) \). Hereafter this is referred to as model C. The best-fitting parameters of this joint ASCA–ROSAT analysis (Table 3, Fit 8) are consistent with those obtained from an analysis of the ASCA data alone (Table 3, Fit 7), and are shown along with the mean data/model ratios in Fig. 3c. As can be seen from Fig. 3c, there is a deficit of PSPC counts compared to such a model in the 0.4–0.6 keV band. No such deficit is seen in the ASCA data. Given the remaining uncertainties in the cross-calibration of the two satellites and that the source exhibits large-amplitude variability on short timescales (coupled with only a small fraction of the ROSAT data having been obtained during the ASCA observation), we consider model C to provide a remarkably good description of the overall, time-averaged spectrum during the 1993 observations. The luminosity of the underlying continuum (corrected for all absorption) over the 0.1–10 keV band is \( L_{0.1–10} = (1.65 \pm 0.08) \times 10^{42} \) erg s\(^{-1}\), and that

\[ R_{0.6} = 2.3. \]

As noted in §3.4, the calibration of the XRT/SIS system below 0.6 keV remains somewhat suspect (hence our exclusion of data \( <0.6 \) keV during our spectral analysis). However, it is unlikely that the uncertainties are of an amplitude sufficient to provide a viable explanation of the values of \( \Delta \chi^2_{0.6}/\Delta N_{0.6} \) and \( R_{0.6} \) obtained here. We adopt the criteria used in G98 whereby we consider a model to extrapolate to SIS energies \( <0.6 \) keV in an acceptable manner if either \( \Delta \chi^2_{0.6}/\Delta N_{0.6} < 2.0 \) or \( R_{0.6} \) lies in the range \( 0.8 \leq R_{0.6} \leq 1.2 \). Recent results from the cross-calibration of the ASCA SIS and BeppoSAX LECS instrument show such criteria to be reasonable (Orr et al 1998).
over the 0.5–2 keV band is \( L_{0.5–2} = (0.43 \pm 0.02) \times 10^{42} \text{ erg s}^{-1} \).

### 4.1.2. The 1995 Observations

Neither model A nor B provide an acceptable description of the time-averaged \( \text{ASCA} \) spectrum obtained in 1995 (Table 3, Fits 3 & 6). Model C does provide a formally acceptable fit with \( \chi^2 = 1064 \) for 1001 dof (Table 3, Fit 9), but does not extrapolate in an acceptable manner below 0.6 keV (\( \Delta \chi^2_{0.6}/\Delta N_{0.6} = 2.1 \) and \( \overline{\chi^2}_{0.6} = 1.4 \)) and gives rise to systematic residuals in the data/model ratios (Fig. 3d). Nevertheless, it is clear from the increases in \( N_{\text{neu}H,z} \), \( N_{\text{ion}H,z} \) and \( U_X \) that NGC 3227 underwent a profound spectral change between 1993 and 1995.

From further analysis of this dataset, the simplest acceptable model is if we allow some fraction, \( D_f \), of the underlying continuum to escape without suffering attenuation by the ionized material, whilst the remainder \( (1 – D_f) \) travels through an ionized column density \( N_{\text{ion}H,z} \). We assume all the photons observed also travel through additional, complete screens of neutral material \( (N_{\text{neu}H,z} \text{ and } N_{\text{gal}H}) \). Hereafter we refer to this model as model D. Model D provides an acceptable fit to the data with \( \chi^2 = 983 \) for 1000 dof (Table 3, Fit 12). Furthermore, this model leads to no notable systematics in the mean data/model ratio and extrapolates in an acceptable manner \(< 0.6 \text{ keV} \) (Fig. 3e). The current data only allow an upper limit \( (U_X \lesssim 0.06) \) to be placed in the ionization parameter. For the best-fitting values of \( N_{\text{ion}H,z} \) and \( D_f \), constraints on lower values of \( U_X \) rely upon extremely subtle changes in the form of the observed spectrum in the 1–3 keV band, and the data are formally consistent with \( U_X = 0 \) (i.e. neutral material). The luminosity of the underlying continuum (corrected for all absorption) is \( L_{0.1–10} = (1.91 \pm 0.10) \times 10^{42} \text{ erg s}^{-1} \), over the 0.1–10 keV band, and \( L_{0.5–2} = (0.48 \pm 0.03) \times 10^{42} \text{ erg s}^{-1} \) over the 0.5–2 keV band.

For completeness, Table 3 also lists the best-fitting values when model D is applied to the \( \text{ASCA} \) data (Fit 10) and the joint \( \text{ASCA–ROSAT} \) data (Fit 11) obtained in 1993. In neither case do we find a requirement for partial-covering of the ionized gas, although the allowed range in \( D_f \) encompasses that found for the 1995 dataset.

### 4.2. Analysis of the Iron K-shell Region

As can be seen from Fig. 3, the spectrum of NGC 3227 contains an Fe K\( \alpha \) fluorescence line in the 5–7 keV band at both epochs. We have repeated the spectral analysis (using the \( \text{ASCA} \) data only) including the data within this band. Only crude estimates of the
line intensity and profile are possible with the current data due to the small number of line photons detected (summing all four detectors only $\sim 300$ Fe K$\alpha$ photons were detected during the 1993 observations, and $\sim 400$ photons during the 1995 observations). We assume a continuum given by model C (§4.1) and have added spectral components to model the Fe emission. In all cases we include the Fe K$\beta$ emission with the same profile as the K$\alpha$ component, but at 0.113 its intensity (e.g. Kikoin 1976).

4.2.1. Gaussian Line Profiles

First we consider simple Gaussian line profiles, with a centroid at a rest-frame energy $E_z(K\alpha)$ for the K$\alpha$ component, width $\sigma$, and intensity $I(K\alpha)$. Such a model provides an acceptable fit to the data at both epochs, giving $\chi^2/dof = 1359/1399$ and $\chi^2/dof = 1205/1261$ for the 1993 and 1995 observations respectively. In both cases the 90% confidence range (for the three interesting parameters associated with the Fe emission) for the centroid energy is $6.23 \lesssim E_z(K\alpha) \lesssim 6.45$ keV and consistent with all ionization states from Fei (6.4 keV) to FeXVIII. The width of the line is constrained to lie in the range $0.0 \leq \sigma \lesssim 250$ eV (at 90% confidence). The intensity of Fe emission was similar during both epochs ($I(K\alpha) = 4.1^{+2.6}_{-1.1} \times 10^{-5}$ photon cm$^{-2}$ s$^{-1}$ and $5.8^{+3.1}_{-1.3} \times 10^{-5}$ photon cm$^{-2}$ s$^{-1}$ for the 1993 and 1995 observations respectively). As evident from Fig. 3, the observed continuum at $\sim 6.4$ keV is also similar ($\sim 3 \times 10^{-4}$ photon cm$^{-2}$ s$^{-1}$ keV$^{-1}$), giving equivalent widths in the range $100 \lesssim EW(K\alpha) \lesssim 250$ eV at both epochs. The best-fitting value of the other parameters ($\Gamma$, $N_{H,z}^{\text{neu}}$, $N_{H,z}^{\text{ion}}$, $U_X$ and $D_f$) were consistent with the values found in §4.1.

We have also included a spectral component to a model any ‘Compton-reflection’ of the underlying continuum. The reflected continuum is a flat spectral component (e.g. see George & Fabian 1991). Given the sensitivity and bandpass of ASCA and the signal–to–noise ratio of the NGC 3227 data, such a component is unlikely to be unambiguously detected but its presence can affect the observed continuum $\gtrsim 6$ keV. We assuming this reflecting material has a planar geometry, is neutral, subtends a solid angle $\Omega_R$ at the continuum source, and is observed face-on. For simplicity we only include the continuum reflected by such material (any fluorescent Fe emission from the reflector will parameterized as part of the Fe emission already included in our model). The addition of a reflection component does not lead to a significant improvement of the goodness–of–fit. At both epochs $R = F(\Omega_R/2\pi) \lesssim 2$ (at 90% confidence), where $F$ is a scaling factor to account for any enhancement of the flux seen by the reflector compared to that seen by the observer. For comparison to the results presented in §5.2.1, we note that fixing $R = 1$, the index of the ’primary’ continuum increases (by $\Delta \Gamma \simeq 0.1$) to $\Gamma \simeq 1.70$ and $\simeq 1.64$ during the 1993 and 1995 observations.
The best-fitting values of the other parameters \((N_{neu}^{H,z}, N_{H,z}^{ion}, U_X, \text{and } D_f)\) were consistent with the values found in §4.1.

### 4.2.2. Relativistic Line Profiles

We considered so-called 'diskline' profiles for the Fe emission. Following the parameterization of Fabian et al (1989), these profiles are generated assuming a planar geometry where the inclination of our cylinder–of–sight with respect to the normal to the plane is given by \(i\), and in which the line emissivity, \(q\), is proportional to radius \(r^{-q}\) over the range \(R_i < r < R_o\), and zero elsewhere. Kinematic and general relativistic effects are included assuming the emitting material is in Keplarian motion around a Schwarzschild black hole. As is common with ASCA data with this signal–to-noise ratio, we cannot constrain all the parameters of the diskline component simultaneously so we have fixed \(R_i\) at the innermost stable orbit of a Schwarzschild black hole (ie. \(R_i = 6r_g\), where \(r_g = GM/c^2\) is the gravitational radius of a black hole of mass \(M\)) and \(R_o = 10^3r_g\). We have also restricted \(q\) to lie in the range \(0 \leq q \leq 3\) appropriate if the Fe emission is the result of X-ray illumination of the disk.

A diskline profile offers a superior description of the data (at > 99% confidence for the 1995 data using the \(F\)-test) compared to the Gaussian profiles discussed in §4.2.1, with \(\chi^2/dof = 1355/1398\) and 1193/1259 for the 1993 and 1995 observations respectively. At both epochs the best-fitting value of \(E_z(K\alpha) \simeq 6.5\) keV, but with 90% confidence limits (for the four interesting parameters associated with the Fe emission) covering the range 6.4 keV (corresponding to Fe–XII) to \(\sim 6.6\) keV (corresponding to FeXXIV). The index of the emissivity, \(q\), could not be well constrained by the 1993 observations (\(0 \leq q \leq 2.4\)), but was better determined by the 1995 observations to lie in the range \(1.9 \leq q \leq 2.4\). In both cases, the inclination was found to be \(i \leq 30\) degrees at 90% confidence. The intensity of Fe emission assuming such a profile is \(I(K\alpha) = 4.7_{-1.8}^{+2.1} \times 10^{-5}\) photon cm\(^{-2}\) s\(^{-1}\) (100 \(\leq EW(K\alpha) \leq 230\) eV) and \(9.0_{-2.9}^{+3.1} \times 10^{-5}\) photon cm\(^{-2}\) s\(^{-1}\) (200 \(\leq EW(K\alpha) \leq 400\) eV) for the 1993 and 1995 observations respectively.

Again we find no significant improvement of the goodness–of–fit at either epoch, when a Compton-reflection component is included in the model, with \(\mathcal{R} \leq 1.2\) (at 90% confidence) during both epochs. Again for comparison of the results presented in §5.2.1, we find that fixing \(\mathcal{R} = 1\), the index of the ‘primary’ continuum increases to \(\Gamma \simeq 1.70\) at both epochs, whilst the best-fitting values of the other parameters \((N_{neu}^{H,z}, N_{H,z}^{ion}, U_X, \text{and } D_f)\) were consistent with the values found in §4.1.
5. TIME-RESOLVED ANALYSIS

In §4 we found that adequate descriptions of the time-averaged spectra could be obtained at both epochs. Here, given the rapid variability of the source (Figs. 1 & 2) we investigate the variations within each observation in order to explore the origin of the variations. First, in §5.1 we present an analysis of the X-ray colors, and in §5.2 spectral analysis of selected temporal ranges.

5.1. X-ray Color Analysis

In §3.3 it was found that the amplitude of the variability exhibited within the three spectral bands XM$_1$, XM$_2$ and XM$_3$ was different both within and between the 1993 and 1995 observations (Table 2). In Fig. 4 we show the ratio of the XM$_1$ to XM$_3$ and XM$_2$ to XM$_3$ count rates (hereafter referred to as the XM$_1$/XM$_3$ and XM$_2$/XM$_3$ colors) as a function of time, along with the total SIS count rate (from Fig 1) for reference. As expected from Fig. 2, both the XM$_1$/XM$_3$ and XM$_2$/XM$_3$ colors are variable during the 1993 observations (at > 99% confidence). This variability appears correlated with the total SIS count rate in the sense that the source is softer when brighter (Fig. 4). Significant variability is also exhibited in the XM$_1$/XM$_3$ (at ∼ 95% confidence) and XM$_2$/XM$_3$ (at ∼ 99% confidence) bands during the 1995 observations, though clearly of a lower amplitude than those seen in 1993. Given the smaller amplitude of the variation in the total SIS count rate during 1995, it is unclear whether any correlation between the color and intensity exists during this epoch.

In Fig. 5 we show these data on the XM$_1$/XM$_3$–XM$_2$/XM$_3$ plane. Also shown are the predictions for various theoretical spectra after being folded through the spectral response of the XRT/SIS instrument. As suggested by Netzer et al (1994), color–color diagrams of this type can be useful in comparing the color variations observed with those predicted assuming different scenarios. In both panels of Fig. 5 the filled circle indicates the location of the best-fitting model for the time-averaged spectrum described in §4. The two straight, solid lines show the loci of simple power laws absorbed only by a screen of neutral material. Line A is for the case where the power law is attenuated by a column density of $N_{\text{gal}}^{H,0} = 2.1 \times 10^{20}$ cm$^{-2}$, whilst line B shows the effect where an additional screen of neutral material with a column density $N_{\text{neu}}^{H,z} = 3.6 \times 10^{20}$ cm$^{-2}$ (as found from the ASCA/ROSAT joint analysis during 1993) also attenuates the spectrum. Both lines are shown from $\Gamma = 1.0$ (highest value of XM$_1$/XM$_3$) to $\Gamma = 2.0$ (lowest value of XM$_1$/XM$_3$).
5.1.1. The 1993 observations

The simplest scenario is that the spectral variability arises solely from changes in the ionization state of a single screen in response to changes in continuum flux. However, even large changes in flux will give only small changes in the XM$_1$ count rate for a column $N_{H,z}^{ion} \sim 10^{21}$ cm$^{-2}$ of ionized material in equilibrium (e.g. see Netzer et al 1994). For such a column (and $\Gamma \sim 1.6$) variations in $U_X$ from $10^{-3}$ to 10 (i.e. a factor of $10^4$ in the intensity of the illuminating continuum) only change XM$_1$/XM$_3$ from $\sim 1.3$ to $\sim 2.4$ and XM$_2$/XM$_3$ from $\sim 2.9$ to $\sim 3.2$. Of course detailed predictions of the behaviour of the gas depend on whether it has reached ionization equilibrium following a change in continuum intensity. The timescales required to reach equilibrium will be further discussed in §6.3.2. For simplicity, in the following we assume the ionized material is in equilibrium.

Large changes in the XM$_1$/XM$_3$ and XM$_2$/XM$_3$ colors can be obtained through variations in $N_{H,z}^{ion}$. In Fig. 5a), line C shows the locus of variations in $N_{H,z}^{ion}$ (only) from $N_{H,z}^{ion} = 0$ (where line C intersects line B) to $N_{H,z}^{ion} \sim 20 \times 10^{21}$ cm$^{-2}$. The dotted region marked D delineates the area on the color–color diagram in which both $N_{H,z}^{ion}$ and $U_X$ are allowed to vary by a factor 0.25–4 from the mean value. Clearly variations of reasonable amplitude in neither $N_{H,z}^{ion}$ alone, nor $N_{H,z}^{ion}$ and $U_X$ can be the sole explanation of the observed variability.

The parallelogram marked E in Fig. 5a) delineates the region on the color–color diagram covering a factor 0.25–4 from the mean value of $U_X$ and spectral index in the range $1.3 \leq \Gamma \leq 2.0$, with $N_{H,z}^{ion}$ fixed at the mean value. The observed colors are in much better agreement with this region. Thus we suggest that the dominant cause of the variations in the XM$_1$/XM$_3$ and XM$_2$/XM$_3$ colors observed during 1993 is variations in the underlying spectral index. As evident from Fig. 4, the XM$_1$/XM$_3$ and XM$_2$/XM$_3$ colors are both highest during the temporal range 1993(t3) suggesting the largest variation in the underlying spectral index occurred during this period. Indeed as found in §3.3, the excess variance ($\sigma_{rms}^2$) is a strong function of energy when all the data from this epoch are considered, with $\sigma_{rms}^2$(XM$_1$)/$\sigma_{rms}^2$(XM$_3$) $\approx 5.6 \pm 2.7$ (Table 2). When the temporal range 1993(t3) is excluded from the analysis, however, $\sigma_{rms}^2$ is consistent with being independent of energy ($\sigma_{rms}^2$(XM$_1$)/$\sigma_{rms}^2$(XM$_3$) $\approx 1.0 \pm 0.7$. The behavior of the source is therefore consistent with a steepening of the continuum during the ‘outburst’ during 1993(t3). This is discussed further in §5.2.
5.1.2. The 1995 observations

For the parameter-space indicated by the best-fitting model, the ionized absorber only has a significant effect on the XM$_2$ band (the XM$_3$ band is dominated by the transmitted continuum, whilst the XM$_1$ band is dominated by the unattenuated continuum, see Fig. 3d). Only changes in $N_{H,z}^{\text{ion}}$ by an order of magnitude will have a significant effect on the observed X-ray colors. Similarly, the X-ray colors are insensitive to $U_X$ for a constant absorbing column density of $N_{H,z}^{\text{ion}} \sim 3 \times 10^{21}$ cm$^{-2}$. On the other hand, the X-ray colors are very sensitive to the spectral index of the underlying continuum ($\Gamma$) and the fraction of this continuum allowed to escape without attenuation ($D_f$).

In Fig. 3b), curve F shows the locus of variations in $D_f$ (only) from $D_f = 1.0$ (where curve F intersects line A) to $D_f = 0.03$. The region G delineates the area on the color–color diagram covering a factor 0.5–2 from the mean value of $D_f$ and spectral index in the range $1.1 \leq \Gamma \leq 1.7$, with $N_{H,z}^{\text{ion}}$ and $U_X$ fixed at their mean values. The observed colors are in good agreement with this region. Thus we suggest that the major cause of the variations in the XM$_1$/XM$_3$ and XM$_2$/XM$_3$ colors observed during 1995 is, again, variations in the underlying spectral index, possibly accompanied by relatively small variations in $D_f$.

5.2. Spectral Analysis

Given the evidence for variability in the slope of the underlying continuum found from the color–color analysis in §5.1, here we report the results from the spectral analysis of selected temporal ranges. This allows us to test the results from the color–color analysis and investigate a number of implications. The temporal ranges are denoted by 1993(t1)–(t4), 1995(t5)–(t8), and are shown in Fig. 4. As in §4.1, we initially exclude the 5–7 keV band from this analysis to avoid the effects of the Fe K-shell emission.

In Table 4 we list the results assuming our best-fitting generalized model found in §4.1. This model consists of an underlying powerlaw absorbed by two screens of neutral material ($N_{H,z}^{\text{Gal}}$ and $N_{H,z}^{\text{new}}$) and a screen of ionized material ($N_{H,z}^{\text{ion}}$ and $U_X$), with a fraction $D_{f}$ of the continuum escaping within suffering attenuation by $N_{H,z}^{\text{ion}}$. This model provides an acceptable description of all the time-resolved spectral datasets, and extrapolates in an acceptable manner <0.6 keV. The contours of the 90% confidence regions projected onto the $N_{H,z}^{\text{ion}}$–$U_X$ and $N_{H,z}^{\text{ion}}$–$\Gamma$ planes are shown in Fig 6. Despite the large uncertainties arising as a result of the reduced signal–to–noise ratio in the time-resolved spectra, the two epochs are clearly distinct in this three-dimensional model space. From both Table 4 and Fig 6 it can be seen that this separation is primarily the result of an increase in column density of
the absorbing material by approximately an order of magnitude (from \(N_{H,z}^{\text{ion}} \sim 3 \times 10^{21} \text{ cm}^{-2}\) to \(\sim 30 \times 10^{21} \text{ cm}^{-2}\)) between the the 1993 and 1995 observations. From the \(N_{H,z}^{\text{ion}}-U_X\) plane (Fig 3a) it can be seen that the datasets for both epochs are consistent with the values derived from the analysis of their respective time-averaged spectra (filled circles), and all are consistent with an ionization parameter in the range \(0.006 \lesssim U_X \lesssim 0.06\). However, on the projection onto the \(N_{H,z}^{\text{ion}}-\Gamma\) plane (Fig 3b), the 1993(t3) dataset is inconsistent with two of the other datasets obtained during that epoch. During the temporal period 1993(t3) the observed spectral index is steeper \((\Delta \Gamma \sim 0.1-0.2)\) than that derived from the analysis of the time-averaged spectrum during this epoch.

### 5.2.1. The Effects of Excluding the 1993(t3) Data

We have repeated the spectral analysis of the ASCA data obtained during 1993, but excluding the data obtained during the temporal period 1993(t3). We find an acceptable fit \((\chi^2/dof = 999/998)\) with an underlying spectral index \(\Gamma = 1.60^{+0.08}_{-0.05}\), absorption due to neutral material of column density \(N_{H,z}^{\text{neu}} = (1.1^{+0.7}_{-1.1}) \times 10^{21} \text{ cm}^{-2}\), plus absorption by ionized material with parameters \((N_{H,z}^{\text{ion}} = (4.3^{+3.7}_{-0.9}) \times 10^{21} \text{ cm}^{-2}, U_X = 0.05^{+0.06}_{-0.06})\) consistent with those obtained from our analysis of the time-averaged spectrum at this epoch (§ 4.1.1). The constraints on any unattenuated continuum provided by these data is \(D_f \lesssim 30\%\) (at 90% confidence). The location of the best-fitting model on the \(N_{H,z}^{\text{ion}}-U_X\) and \(N_{H,z}^{\text{ion}}-\Gamma\) planes are shown by the open circles in Fig 3. In Fig. 7 we compare the 1993(t3) data to this model. The spectrum obtained during the 1993(t3) brightening is indeed consistent with a steepening in the observed spectral index, pivoting around 10 keV. Returning the 5–7 keV band to the analysis and assuming a diskline profile for the Fe emission (§ 4.2.2), we find an acceptable fit \((\chi^2/dof = 1190/1204)\) when the intensity of the Kα line \(I(K\alpha) = (5.1^{+2.4}_{-1.8}) \times 10^{-5} \text{ photon cm}^{-2} \text{ s}^{-1}\) \((EW(K\alpha) = 170^{+80}_{-60} \text{ eV})\) and \(\beta = 2.0^{+0.5}_{-0.7}\).

The upper limits on the energy and inclination of the putative disk are \(E_z \lesssim 6.59 \text{ keV}\) and \(i \lesssim 45\) degrees (at 90% confidence, respectively). The best-fitting values of the other parameters \((N_{H,z}^{\text{neu}}, N_{H,z}^{\text{ion}}, U_X, D_f)\) were consistent with the values found above.

The detection of a steepening of the spectral index of the underlying continuum in an AGN, on a timescale \(\sim 10^4 \text{ s}\) and a pivot at \(\sim 10 \text{ keV}\), may be highly pertinent to our understanding of the mechanism giving rise to the 'primary' X-ray continuum (§ 6.1). Since such a steepening is inferred from a comparison between the data obtained during 1993(t3) and those obtained during the remaining temporal periods of the 1993 observations, it is important to investigate whether we might be being misled. Given the bandpass of ASCA and the signal-to-noise ratio of the 1993 data, the delusory effect most likely is
Compton Reflection of the primary continuum. As stated above, the lack of effective area $\gtrsim 10$ keV makes the amplitude of such a component difficult to constrain with ASCA with this signal-to-noise ratio. We find that the inclusion of a Compton-reflected continuum (with the inclination of reflector equal to that in the Fe K$\alpha$ emission line) offers no significant improvement to the 'quiescent' spectrum observed during 1993 (i.e. excluding 1993(t3)), with an upper limit of $R \sim 1.6$ (at 90% confidence). Fixing $R = 1$, however, the index of the underlying powerlaw to steepen to $\Gamma \simeq 1.71$ (and the best-fitting value of all other parameters consistent with those found when $R = 0$). A similar spectral index was found from a similar analysis of the time-averaged spectra at both epochs in §4.2. More significantly however, with $R = 1$, the spectral index is consistent with that obtained for the 1993(t3) dataset alone ($\Gamma \simeq 1.73$, Table 4). We conclude that we are unable to make any definitive statements regarding variations in the 'primary' X-ray continuum with these data due to uncertainties in the amplitude of any Compton-reflection.

6. DISCUSSION

The ASCA observations performed in 1993 and 1995 reveal NGC 3227 to have exhibited significant spectral variability both within the 1993 observation and between the two epochs. Detailed analysis of the data obtained during 'quiescent' periods of the 1993 observation show the spectrum can be adequately described by a powerlaw continuum (with $\Gamma \sim 1.6$). Imprinted on this continuum are absorption features due to ionized gas (with an equivalent hydrogen column density $N_{H,z}^{\text{ion}} \simeq 3 \times 10^{21}$ cm$^{-2}$ and X-ray ionization parameter $U_X \simeq 0.01$) and Fe K-shell emission (with $EW(K\alpha) \simeq 170$ eV). The observed continuum steepened (to $\Gamma \simeq 1.7$) during the 'flare' comprising the temporal period 1993(t3). Unfortunately the data do not allow us to determine whether this represents a true steepening of the underlying continuum, or whether the index observed during the quiescent periods is flatter due to the presence of a Compton-reflector. From a joint analysis of the ASCA and ROSAT PSPC data at this epoch we also find evidence for an additional screen of neutral material with $N_{H,z}^{\text{neu}} \simeq 4 \times 10^{20}$ cm$^{-2}$. The spectrum at energies $\gtrsim 3$ keV observed during the 1995 observations is identical to that observed in 1993. The spectrum at lower energies is, however, dramatically different and consistent with $\approx 90$% of the underlying continuum suffering attenuation by material with $N_{H,z}^{\text{ion}} \simeq 3 \times 10^{22}$ cm$^{-2}$ whilst the remaining fraction of the continuum is absorbed by neutral material with $N_{H,z}^{\text{neu}} \lesssim 10^{21}$ cm$^{-2}$.

In this section we review these findings in more detail, compare them to previous results and briefly discuss the prospects in the future.
6.1. The Underlying Continuum

The slope of the observed continuum in NGC 3227 ($\Gamma \sim 1.5–1.7$) is flatter than that seen in the majority of Seyfert galaxies ($\Gamma \sim 1.9$; Nandra & Pounds 1994), consistent with the findings of most previous measurements of this source (Turner & Pounds 1989; Turner et al 1991; Weaver, Arnaud & Mushotzky 1995). Furthermore, during the temporal period 1993(t3) we found clear evidence that the observed continuum steepened (by $\Delta \Gamma \sim 0.1$, on a timescale $\sim$ few $\times 10^{4}$ s) as the source brightened (by $\Delta L_{0.1–10} \sim 40\%$). If this steepening in the observed continuum is in fact due to a steepening in the ‘primary’ X-ray continuum, then it is of relevance to our understanding of the generation of the X-ray continuum. The most popular model for the production of the underlying continuum in the X-ray band in Seyfert galaxies is that it produced by the Compton upscattering of lower energy photons. The electrons (and possibly positrons) responsible for this upscattering could be within either a highly relativistic, nonthermal plasma (e.g. Svensson 1994) or mildly relativistic, thermal plasma (e.g. Sunyaev & Titarchuck 1980; Ghisellini & Haardt 1994). Given CGRO observations of a break in the spectra of some Seyfert galaxies in the $\sim$50–300 keV regime (e.g. Johnson et al 1993), attention has shifted recently back to thermal (or quasi-thermal) models (Svensson 1996 and references therein). Several geometries have been proposed for the UV and Compton scattering regions, with a popular configuration having an accretion disk emit the UV seed photons, and a fraction of these photons are up-scattered into the X-ray band in a (possibly patchy) corona above the disk (e.g. Stern et al 1995; Haardt, Maraschi, Ghisellini 1997). Interestingly, as discussed by Haardt, Maraschi, Ghisellini (1997), a pivoting of the spectrum at $\sim 10$ keV accompanying relatively small changes in the X-ray luminosity (factor $<2$) is predicted by models in which the optical depth to $e^\pm$-pair production is $\lesssim 0.1$ and weakly coupled to the coronal luminosity.

Whilst we find no statistical requirement for a Compton-reflection component in NGC 3227, the possible presence of such a component cannot be excluded, with $R \lesssim 1.2$ at 90% confidence (§4.2). Previous Ginga observations find $R \simeq 1 \pm 0.5$ (Nandra & Pounds 1994), and the strength of the Fe K-shell emission ($EW(K\alpha) \sim$100–250 eV, §4.2) provides circumstantial evidence for $R \gtrsim 0.5$ (e.g. George & Fabian 1991). Preliminary results from a recent RXTE observation suggest a relatively weak Compton-reflection component in NGC 3227 (Ptak et al 1998).

Finally we note that whatever the cause of the spectral variability observed during 1993(t3), when these data are excluded from the analysis the source still exhibits relatively large values of the excess variance $\sigma^2_{rms} \sim 0.03$ over the full 0.5–10 keV SIS band (Table 2). Nandra et al (1997a) have shown $\sigma^2_{rms}$ to be inversely correlated with X-ray luminosity for a sample of Seyfert 1 galaxies (including the 1993 data from NGC 3227). As shown in
Yaqoob et al (1997), the correlation between $\sigma_{r_{rms}}^2$ and X-ray luminosity remains when the lower value of $\sigma_{r_{rms}}^2$ found for the 1995 observation of NGC 3227 is included.

6.2. The Neutral-absorber

In all the models presented here we have assumed the observed spectrum is attenuated by screen of neutral material at $z = 0$ (completely covering the cylinder–of–sight) with a column density $N_{gal}^{H,0} = 2.1 \times 10^{20} \text{ cm}^{-2}$. This screen is adopted to model absorption within our galaxy, with $N_{gal}^{H,0}$ fixed at the value derived from 21 cm measurements towards NGC 3227 (Murphy et al. 1996). However the analysis of the joint ASCA/ROSAT datasets from 1993 (§4.1.1) implies an additional screen of neutral material ($N_{neu}^{H,z} \simeq (4 \pm 1) \times 10^{20} \text{ cm}^{-2}$) which we assume is intrinsic to NGC 3227. The 1995 observations are also consistent with the presence of such a screen.

From observations carried out in 1988 using a beam of FWHM $\sim 13$ arcsec (i.e. probing a region $\sim 3 \times 10^3$ light-years across within NGC 3227), Mundell et al (1995a) found evidence for H$\text{I}$ absorption at the systemic redshift of NGC 3227, implying an average column density $N_{HI}^{H,z} \sim 6 \times 10^{20} \text{ cm}^{-2}$ towards the nucleus. More recent observations, taken with an angular resolution a factor $\sim 3$ higher, imply $N_{HI}^{H,z} \simeq (11 \pm 1) \times 10^{20} \text{ cm}^{-2}$ (Mundell, private communication). Interestingly, Meixner et al (1990) detected elongated CO emission straddling the nucleus. As noted by Mundell et al (1995a) this emission may represent the structure that is responsible for collimating the ultraviolet radiation giving rise to the anisotropic [OIII] emission observed by Mundell et al (1995b). Our ASCA observations imply that the column density of neutral material within the narrow cylinder–of–sight to the central X-ray source (with a diameter $\lesssim 10^4$ light-seconds) is a factor $\sim 2$ smaller than the mean value of $N_{HI}^{H,z}$ on scale-sizes a factor $\sim 10^6$ larger.

We postpone the discussion of the large addition column density observed during the 1995 observations (which as noted in §4.1.2 is formally consistent with neutral material) until §6.4.

6.3. The Ionized-absorber

The 1993 data provide evidence for absorption by a screen of ionized material with column density $N_{ion}^{H,z} \simeq 3 \times 10^{21} \text{ cm}^{-2}$ and an X-ray ionization parameter $U_X \sim 0.01$. Absorption by ionized material is believed to be a common feature in the X-ray spectra of Seyfert galaxies (Reynolds 1997; G98) and these values of $N_{ion}^{H,z}$ and $U_X$ are some of the
lowest yet observed. G98 found a range $10^{21} \lesssim N_{\text{ion}}^{\text{H,}\alpha} \lesssim 10^{23}$ cm$^{-2}$ and $0.01 \lesssim U_X \lesssim 0.1$ for ionized absorbers in a sample of Seyfert 1 galaxies. NGC 3227 has a relatively low X-ray luminosity ($\sim 10^{42}$ erg s$^{-1}$ in the 2–10 keV band) compared to other Seyfert 1s in that sample ($\sim 10^{43}–10^{45}$ erg s$^{-1}$), and this may affect conditions in the absorber. Also, as noted in §1, the optical depths of O$^{\text{vii}}$ and O$^{\text{viii}}$ are $\lesssim 0.05$ for $N_{\text{ion}}^{\text{H,}\alpha} \lesssim 10^{21}$ cm$^{-2}$ making it difficult to detect with the signal-to-noise ratio of most ASCA observations.

The column density appeared to increase between 1993 and 1995, consistent with a cloud moving into the cylinder–of–sight. As discussed in §4.1.2, the ASCA data are only able to constrain the ionization parameter to be $U_X \lesssim 0.06$ during this epoch (i.e. consistent with neutral material). However, the 1993 data clearly show evidence that the absorber is ionized and in the context of this model the appearance of such a cloud increased the column of ionized material by an order of magnitude. These results are consistent with the suggestion of Turner & Pounds (1989) that the differential variability between the soft and medium X-ray bands seen in the EXOSAT observations of NGC 3227 is most likely due to variations in the absorbing column. Ginga observations revealed evidence for an Fe K-shell absorption edge, with a depth corresponding to $N_{\text{ion}}^{\text{H,}\alpha} \sim \text{few} \times 10^{22}$ cm$^{-2}$ (Nandra & Pounds 1994). The current ASCA data do not allow any meaningful constraints to be placed on such a feature.

6.3.1. A Dusty warm-absorber?

Dust is clearly present at some locations within the host galaxy, as revealed by the detection of molecular emission and absorption features (see §4) and implied by two thermal components observed in the 10–300$\mu$m band (Rodríguez Espinosa et al 1996). In common with many other Seyfert galaxies, the component dominating the 10–30$\mu$m band (with a temperature $\sim 160$ K) is likely to arise as a result of the heating of dust by radiation sources $\lesssim 10$ kpc from the nucleus (e.g. Rodríguez Espinosa & Pérez García 1997). Both the active nucleus and emission from any starburst activity provide such radiation sources. The question here is whether any dust exists within the immediate circumnuclear regions ($\lesssim 10$ pc) and, if so, whether it is in any way related to the ionized absorber.

As reviewed by K97, there are a number of indicators which can be used to probe the circumnuclear environment of NGC 3227. First, the underlying continuum in the optical and UV bands is unusually red compared to other Seyfert galaxies (Winge et al 1995). Using the ratio of the observed fluxes at 125 nm and 220 nm (rest frame, which are relatively free of line emission) and a standard Galactic composition for the dust, G98 found a column density $\sim 5 \times 10^{21}$ cm$^{-2}$ brought the intrinsic flux ratio into agreement
with that observed in most other unobscured Seyfert galaxies. Making slightly different assumptions K97 obtained a similar result. Second, from the observed ratio of the broad Hα and Hβ lines and assuming a Galactic dust/gas mass ratio, K97 calculate an effective hydrogen column density to the broad emission line region of \( \sim 3 \times 10^{21} \) cm\(^{-2}\). As noted by Netzer (1990) the use of such line ratios in this way is potentially misleading as the intrinsic Balmer decrement is uncertain. Nevertheless, we note that the implied column density is similar to that required to produce the observed reddening of the optical/UV continuum. Thus it seems likely that the same (dusty) material is responsible for these observational characteristics. The material must lie at a radius larger than of the BELR (\( \sim 10–20 \) light-days, Salamanca et al 1994; Winge et al 1995) both in order to give rise to a depressed ratio of the intensity of broad Hα and Hβ lines, and since dust is unable to survive for long in the intense radiation field of the central source at smaller radii (e.g. Laor & Draine 1993). Interestingly the column density implied from such arguments (\( \sim \text{few} \times 10^{21} \) cm\(^{-2}\)) is very similar to that of the ionized absorber implied by the ROSAT observations (K97) and that derived from the ASCA observations in 1993 (above; G98). It seems unlikely that this is purely coincidental. As suggested by K97 and G98, it is more plausible that a substantial fraction of the ionized gas in NGC 3227 contains embedded dust, thus placing the ionized absorber outside the BELR.

Dusty ionized absorbers have also been suggested in the infrared-bright quasar IRAS 13334+2438 (Brandt, Fabian & Pounds 1996) and the Seyfert MCG–6-30-15 (Reynolds & Fabian 1995; G98). As pointed out in K97, the presence of dust can give rise to different model spectra, primarily as a result of the different depletion of the various elements in the gas-phase. We have not attempted a detailed treatment of such cases here as most of the differences occur at energies below the ASCA bandpass. If the dust is similar to that observed within the interstellar medium of the Galaxy, the composition of the gas-phase will be depleted in C and O by factor of \( \sim 0.4 \) and \( \sim 0.6 \) (respectively) compared to ”cosmic composition”, and N and Ne suffering no significant depletion (e.g. Cowie & Songaila 1986). As can be from Fig. 3 the main features imprinted on the underlying continuum in the ASCA bandpass by the ionized absorber are due to O\( ^{\text{vii}} \) and O\( ^{\text{viii}} \). Thus if there is indeed embedded dust, and thus O is depleted in the gas-phase, one might expect the values of \( N_{H,z}^{\text{ion}} \) derived above to have been underestimted by a factor \( \sim 1.7 \). The differential depletion of the various elements gives rise to a subtle changes in the form of the spectrum across the 0.6–1 keV band. Given the interplay between \( N_{H,z}^{\text{ion}} \) and \( U_X \) during the spectral fitting of ASCA data, the effect of including dust is more likely to increase the best-fitting value of \( U_X \) (by a factor \( \sim 3 \) compared to dust-free models) rather than \( N_{H,z}^{\text{ion}} \). Future observations with the grating-spectrometers onboard AXAF and XMM will allow a direct comparison between the depths of the edges from the highly-ionized, gas-phase
ions and those of the neutral, dust-phase species. Such observations will therefore provide stringent constraints on any dust embedded within the ionized gas.

6.3.2. Constraints for Photoionization Equilibrium

In the absence of other sources of heating and cooling, the gas will be in photoionization equilibrium if the photoionization and recombination timescales of the dominant species (\( t_{\text{ion}} \) and \( t_{\text{rec}} \) respectively) are shorter than the timescale (\( t_{\text{var}} \)) for large-amplitude variations in the intensity of the illuminating continuum. To first order \( t_{\text{ion}} \approx N_{H,z}/U_{X} n_{c} \) s. Thus substituting the mean values derived from the 1993 observations (\( N_{H,z} \approx 3 \times 10^{21} \) cm\(^{-2} \) and \( U_{X} = 0.01 \)), we have \( t_{\text{ion}} \approx 10^{13} n^{-1} \) s. The recombination time of O\( \text{viii} \) is longer than that for O\( \text{vii} \) and given by \( t_{\text{rec}}(\text{O\( \text{viii} \)}) \approx 3 \times 10^{8} T^{0.5} n^{-1} \) s for a gas at an equilibrium temperature \( T \) (e.g. Verner & Ferland 1996). Thus for plausible values of \( T (\sim 10^{5} \) K), \( t_{\text{ion}} \) is more important than \( t_{\text{rec}}(\text{O\( \text{viii} \)}) \) when determining whether or not material illuminated by a variable ionizing continuum will be in equilibrium. Thus the material will be equilibrium (\( t_{\text{var}} > t_{\text{ion}} \)) when \( n \gtrsim 10^{13} t_{\text{var}}^{-1} \) cm\(^{-3} \). Unfortunately the assignment of an appropriate value for \( t_{\text{var}} \) is problematic since little is know about the detailed variability characteristics of NGC 3227 in the X-ray band and, as a class, Seyfert 1 galaxies appear to exhibit a ‘red-noise’ power-density spectrum (e.g. Lawrence & Papadakis 1993; Green, McHardy & Lehto 1993, and references therein). However for illustration, here we assume \( t_{\text{var}} = 2 \times 10^{4} \) s (the approximate timescale in which factor \( \sim 2 \) changes in flux are observed during the temporal period 1993(t3) in Fig. 1), leading to the requirement that \( n \gtrsim 5 \times 10^{8} \) cm\(^{-3} \) for the ionized absorber to be in equilibrium. Such a density is consistent with that assumed in our ION models for the ionized material. From the definition of \( U_{X} \) and assuming \( L_{0.1-10} = 1.6 \times 10^{42} \) erg s\(^{-1} \), such values of \( n \) require \( r \lesssim 10 \) light-days. Thus, if the ionized absorber contains embedded dust (as suggested in §6.3.1) it must be at a larger radius and hence will not be in perfect equilibrium for some time after the temporal period 1993(t3). Unfortunately, however, it is impossible to quantify just how far out of equilibrium the ionized material may have become, or the time taken for equilibrium to be restored, without a detailed knowledge of the ionized material, and a complete knowledge of the variations in the ionizing continuum both before temporal period 1993(t1) and after temporal period 1993(t4).
6.4. The Variable Absorption

In [1] we found the absorbing column density to have increased by a factor $\sim 10$ (from $N_{\text{ion}}^{H,z} \sim 3 \times 10^{21} \text{ cm}^{-2}$ to $\sim 30 \times 10^{21} \text{ cm}^{-2}$) between the 1993 and 1995 observations. As noted in §4.1.2 the ASCA data do not allow us to place stringent constraints on the ionization state of the material during the latter epoch, with value of $U_X = 0$ (neutral material) to $U_X \sim 0.06$ (highly ionized) being consistent with the observations. We suggest that the most likely explanation is that a cloud of material moved into the cylinder–of–sight. The location and kinematics of such a cloud clearly cannot be determined with the current data. However within some radius Keplarian motion (alone) is able to move material completely through the cylinder–of–sight (of diameter equal to the size of the X-ray emitting region) in the 2 years between the observations. The X-ray emitting region in NGC 3227 can be estimated to be $10^4$ light-seconds across from the variability behaviour observed during 1993. From G98, the fiducial radius is $r_{\text{ld}} \lesssim 20(f_{\text{bolX}}/f_{\text{Edd}})L_{X42}$ light-days, where $f_{\text{bolX}}L_{X42} \times 10^{42}$ erg s$^{-1}$ is the bolometric luminosity and $f_{\text{Edd}}$ is the fraction of the Eddington luminosity at which the object is emitting. Thus, for NGC 3227 (with $L_{X42} \sim 1$) and assuming $f_{\text{bolX}}/f_{\text{Edd}} \sim$ few, it is feasible that tranverse motion of a cloud within the inner regions of the AGN responsible for the change in column density. It would be interesting to see whether any of the other reddening indicators in NGC 3227 vary on a timescale of years, especially the reddening towards the BELR.

6.5. The Unattenuated Component

During the 1995 observations we found spectroscopic evidence for $\sim 13\%$ of the observed continuum to be unattenuated by the absorber with $N_{\text{ion}}^{H,z} \approx 30 \times 10^{21} \text{ cm}^{-2}$. Such a model is consistent with both the case where only a fraction of the cylinder–of–sight to NGC 3227 is covered by the absorbing material (say in the form of clouds), and to the case where the whole cylinder–of–sight is covered by the material but in which a fraction of the continuum escapes by another light-path. We consider both explanations equally plausible. The latter, however, raises the question as to the location and conditions within the material responsible for scattering the unattenuated component back into our cylinder–of–sight. Since we find no evidence for any strong emission or absorption features in the spectrum at energies $\lesssim 1 \text{ keV}$, the material must be highly ionized. In particular we see no evidence for any emission lines due to the H-like and He-like species of the abundant elements which are commonly seen in the scattered X-ray spectra of Seyfert 2 galaxies (e.g. Turner et al 1997), with upper limits $\sim 30 \text{ eV}$ at 90% confidence. Unfortunately any variations in the XM$_1$ and XM$_3$ bands during the 1995 observations (which are dominated by the scattered and
'transmitted' components respectively under this hypothesis) are of insufficient amplitude to offer any insight into the location of the material responsible for scattering.

Finally, we note that the X-ray spectrum of NGC 3227 during this epoch is rather similar to that of NGC 4151 (Weaver et al 1994a,b; G98), although the latter source has $D_I \sim 5\%$ and a somewhat larger value of $N_{H,z}^{\text{ion}}$ at most epochs.

6.6. The Fe Regime

Our data confirm the presence of Fe K-shell emission within NGC 3227, with an equivalent width $\sim 100$–300 eV. We find evidence that the emission line is broad, most likely with an asymmetric profile. Thus our findings confirm the suggestion from the earlier Ginga observations (e.g. George, Nandra & Fabian 1990), and show that the Fe K-shell emission within NGC 3227 is fairly typical of other Seyfert 1 galaxies (e.g. Nandra et al 1997b, and references within) and some Seyfert 2 galaxies (Turner et al 1998). We find no compelling evidence that the Fe emission varied in either shape or equivalent width either within the individual observations or between the 1993 and 1995 epochs. Thus we find no evidence for significant changes in the distribution of Fe emissivity.

7. CONCLUSIONS

ASCA observations of NGC 3227 performed during 1993 and 1995 show evidence for marked spectral variability both within and between the observations. The source shows evidence for a column $N_{H,z}^{\text{ion}} \simeq 3 \times 10^{21}$ cm$^{-2}$ of ionized material with an X-ray ionization parameter $U_X \simeq 0.01$ during 1993, increasing by an order of magnitude by the 1995 epoch. The slope of the continuum steepened by $\Delta \Gamma \simeq 0.1$ during a flare within the 1993 observation. However, the data do not allow us to distinguish between a steepening of the 'primary' continuum, or a change in the relative strengths of the power-law and a putative Compton-reflection component.

We thank Lorella Angelini (NASA/GSFC) for useful discussions, and Carole Mundell (Univ. Maryland) for communication of her results prior to publication. We acknowledge the financial support of the Universities Space Research Association (IMG, TJT, TY), NASA (AP), the National Research Council (KN), and a special grant from the Israel Science Foundation & by the Jack Adler Chair of Extragalactic Astronomy (NH). This research has made use of the Simbad database, operated at CDS, Strasbourg, France; and
of data obtained through the HEASARC on-line service, provided by NASA/GSFC.
REFERENCES

Arp, H., 1966, *Atlas of Peculiar Galaxies*, (CalTech: Pasadena), plate 94
Arribas, S., Mediavilla, E., 1994, *apj*, 437, 149
Baan, W.A., Haschick, A.D., Uglesich, R., 1993, *ApJ*, 415, 140
Brandt, W.N., Fabian, A.C., Pounds, K.A., 1996, *MNRAS*, 278, 326
Briel, U., et al 1994, *The ROSAT User’s Handbook*
Cowie, L.L., Songaila, A., 1986, *ARAA*, 24, 499
Crenshaw, D.M., 1997, In *Emission Lines in Active Galaxies: New Methods and Techniques*, eds. Peterson, B.M, Cheng, F.-Z., Wilson, A.S. (ASP, San Francisco), p.240
Crenshaw, D.M., Maran, S.P., Mushotzky, R.F., 1998, *ApJ*, 496, 797
Fabian, A.C., Rees, M.J., Stella, L., White, N.E., 1989, *MNRAS*, 238, 729
Fabian, A.C., et al, 1994, *PASJ*, 46, L59
George, I.M., Fabian, A.C., 1991, *MNRAS*, 249, 352
George, I.M., Nandra, K., Fabian, A.C., 1990, *MNRAS*, 242, 28P
George, I.M., Netzer, H., Turner, T.J., Nandra, K., Mushotzky, R.F., Yaqoob, T., 1998a, *ApJS*, 114, 73 (G98)
George, I.M., Turner, T.J., Mushotzky, R.F., Nandra, K., Netzer, H., 1998b, *ApJ*, in press
Ghisellini, G., Haardt, F., 1994, *ApJ*, 429, L53
González Delgado, R.M., Pérez, E., 1997, *MNRAS*, 284, 931
Green, A.R., McHardy, I.M., Lehto, H.J., 1993, *MNRAS*, 265, 664
Guainazzi, M., Mihara, T., Otani, C., Matsuoka, M., 1996, *PASJ*, 48, 781
Haardt, F., Maraschi, L., Ghisellini, G., 1997, *ApJ*, 476, 620
Halpern, J.P., 1984, *ApJ*, 281, 90
Huchra, J.P., Burg, R., 1992, *ApJ*, 393, 90
Johnson, W.N., et al., 1993, *A&AS*, 97, 21
Kikoin, I.K., (ed) 1976, *Tables of Physical Quantities*, Atomizdat, Moscow.
Komossa, S., Fink, H., 1997, *A&A*, 327, 483 (K97)
Kriss, G.A., et al., 1996, *ApJ*, 467, 629
Laor, Ari, Draine, B.T., 1993, *ApJ*, 402, 441
Lawrence, A., Papadakis, I., 1993, ApJ, 414, L85
Makishima, et al 1996, PASJ, 48, 171
Malizia, A., Bassani, L., Stephen, J.B., Malaguti, G., Palumbo, G.G.C., 1997, ApJS, 113, 311
Mathur, S., 1994, ApJ, 431, L75
Mediavilla, E., Arribas, S., 1993, Nature, 365, 420
Meixner, M., Puchalsky, R., Blitz, L., Wright, M., Heckman, T., 1990, ApJ, 354, 158
Mundell, C.G., Pedlar, A., Axon, D.J., Meaburn, J., Unger, S.W., 1995a, MNRAS, 277, 641
Mundell, C.G., Holloway, A.J., Pedlar, A., Meaburn, J., Kukula, M.J., Axon, D.J., 1995b, MNRAS, 275, 67
Murphy, E.M., Lockman, F.J., Laor, A., Elvis, M., 1996, ApJS, 105, 369
Nandra, K., Pounds, K.A., 1994, MNRAS, 268, 405
Nandra, K., George, I.M., Mushotzky, R.F., Turner, T.J., Yaqoob, T., 1997a, ApJ, 476, 70
Nandra, K., George, I.M., Mushotzky, R.F., Turner, T.J., Yaqoob, T., 1997b, ApJ, 477, 602
Netzer, H., 1990, in Active Galactic Nuclei, ed. R.D. Blandford, H.Netzer, L.Woltjer (Berlin: Springer), p107
Netzer, H., 1993, ApJ, 411, 594
Netzer, H., 1996, ApJ, 473, 781
Netzer, H., Turner, T.J., George, I.M., 1994, ApJ, 435, 106
Orr, A., Yaqoob, T., Parmar, A.N., Piro, L., White, N.E., Grandi, P., 1998, A&A, submitted
Osterbrock, D.E., Martel, A., 1993, ApJ, 414, 552
Otani, C., et al., 1996, PASJ, 48, 211
Pounds, K.A., Nandra, K., Stewart, G.C, Leighly, K., 1989, MNRAS, 240, 769
Ptak, A., Yaqoob, T., Serlemsitsos, P.J., Mushotzky, R.F., Otani, C., 1994, ApJ, 436, L31
Ptak, A., et al., 1998, in preparation
Radecke, H.-D., 1997, A&A, 319, 18
Reynolds, C.S., 1997, MNRAS, 286, 513
Reynolds, C.S., Fabian, A.C., 1995, MNRAS, 273, 1167
Reynolds, C.S., Fabian, A.C., Nandra, K., Inoue, H., Kunieda, H., Iwasawa, K., 1995, MNRAS, 277, 901
Rickard, L.J., Bania, T.M., Turner, B.E., 1992, ApJ, 252, 147
Rigopoulou, D., Papadakis, I., Lawrence, A., Ward, M., 1997, A&A, 327, 493
Rodríguez Espinosa, J.M., Pérez García, A.M., Lemke, D., Meisenheimer, K., 1996, A&A, 315, L129.
Rodríguez Espinosa, J.M., Pérez García, A.M., 1997, ApJ, 487, L33.
Salamanca, I., et al, 1994, A&A, 282, 742
Shields, J.C., Hamann, F., 1997, ApJ, 481, 752
Snowden, S.L, Turner, T.J., George, I.M, Yusaf, R., Predehl, P., Prieto, A., 1995, OGIP Calibration Memo CAL/ROS/95-003
Stern, B., Poutanen, J., Svensson, R., Sikora, M., Begelman, M.C., 1995, ApJ, 449, 13
Sunyaev, R.A., Titarchunk, L.G., 1980, A&A, 86, 121
Svensson, R., 1994, ApJS, 92, 585
Svensson, R., 1996, ApJS, 120, 475
Turner, T.J., Pounds, K.A., 1989, MNRAS, 240, 833
Turner, T.J., Weaver, K.A., Mushotzky, R.F., Holt, S.S., Madejski, G.M., 1991, ApJ, 381, 85
Turner, T.J., George, I.M., Nandra, K., Mushotzky, R.F., 1997, ApJS, 113, 23
Turner, T.J., George, I.M., Nandra, K., Mushotzky, R.F., 1998, ApJ, 493, 91
Verner, D.A., Ferland, G.J., 1996, ApJS, 103, 467
Weaver, K.A., Arnaud, K.A., Mushotzky, R.F., 1995, ApJ, 447, 121
Weaver, K.A., et al., 1994a, ApJ, 423, 621
Weaver, K.A., Yaqoob, T., Holt, S.S., Mushotzky, R.F., Matsuoka, M., Yamauchi, M., 1994b, ApJ, 436, L27
Winge, C., Peterson, B.M., Horne, K., Pogge, R.W. Pastoriza, M.G., Storchi-Bergmann, T., 1995, ApJ, 445, 680
Yaqoob, T., Nandra, K., George, I.M., Turner, T.J., 1997, in All-sky X-ray Observations in the Next Decade, ed. M.Matsuoka, N.Kawai (Wako, Japan: RIKEN), 219
Fig. 1.— Light curves for the observations of NGC 3227 reported here, employing a bin size of 128 s. The upper two panels show the summed light curves obtained for ASCA SIS and GIS detectors, whilst the lower panel shows the portion of the ROSAT PSPC light curve obtained during the 1993 ASCA observations (there were no ROSAT observations contemporaneous with the 1995 ASCA observations). The SIS count rate obtained during 1993 has been rescaled in order to compensate for the smaller extraction cell used and hence to be directly comparable to the 1995 data. The UTC times corresponding to the first SIS data point at each epoch are 1993 May 08 03:46 and 1995 May 15 01:49. In all cases, the y-axis is scaled to cover a factor of 0.1 to 2.5 of the mean of the 1993 light curve. Significant variability is clearly apparent in the observed count rates both within the individual observations, and between the 1993 and 1995 epochs. The dotted box in the lower panel shows the total dynamic range observed in the PSPC count rate over the period May 08–19.
Fig. 2.— Light curves for NGC 3227 in 0.5–1.2 keV (XM\(_1\)), 1.5–3.5 keV (XM\(_2\)), and 4.0–10.0 keV (XM\(_3\)) energy bands of the SIS employing a bin size of 512 s. In all cases the y-axis is logarithmic, and is scaled to cover a factor of 0.2 to 7.0 of the mean. Significant variability is apparent both within the individual observations, and (especially at lower energies) between the 1993 and 1995 epochs.
Caption for Fig. 3.
The results from the analysis of the time-averaged spectra of the 1993 (plots a,b & c) and 1995 (plots d & e) ASCA observations of NGC 3227, excluding the Fe K-shell band (see §4.1). In each case the upper panel shows (in bold) the best-fitting model, the model after correcting for all neutral absorption ($N_{HI}^{Gal}$ and $N_{HI,z}^{neu}$), and (dashed) the implied underlying continuum. The lower panel shows the mean data/model ratios. The filled triangles show the (error-weighted) means of the ratios from the individual ASCA detectors for the energy-bands used in the spectral analysis, rebinned in energy-space for clarity. (Note the different y-axis scale in plot a.) The dotted errorbars show the corresponding rebinned, mean ratios when the best-fitting model is extrapolated < 0.6 keV and into the 5–7 keV band. The stars show data/model ratios of the 1993 ROSAT PSPC data, again rebinned in energy-space for clarity. The details of the individual panels are described in §4.1.
Fig. 3.— (caption on previous page)
Fig. 4.— The Upper shows the total SIS count rate as a function of time using 128 s bins (from Fig. [4]). The lower two panels shows the XM$_1$/XM$_3$ and XM$_2$/XM$_3$ X-ray colors (see §3.3) as a function of time using 5760 s bins. In all cases the y-axis is logarithmic. Significant variability is evident in the XM$_1$/XM$_3$ and XM$_2$/XM$_3$ colors during both epochs. During the 1993 observations it is clear that the spectrum becomes softer as the source brightens during temporal period 1993(t3)
The XM$_1$/XM$_3$ – XM$_2$/XM$_3$ color-color diagram for the epochs of the NGC 3227 observations. Also shown are the predictions from various theoretical spectra after being folded through the spectral response of the XRT/SIS instrument (described in §5.1). The filled circle indicates the location of the best-fitting model for the time-averaged spectrum described in §4. During the 1993 observations (left panel), the points with the highest values of both XM$_1$/XM$_3$ and XM$_2$/XM$_3$ occur during the temporal period 1993(t3) defined in Fig. 4.
Fig. 6.— Contours showing the 90% confidence regions in the $N_{H,z} - U_X$ and $N_{H,z} - \Gamma$ planes from the time-resolved spectral analysis of NGC 3227 described in §5.2. The filled circles indicate the best-fitting values from the analysis of the time-average spectra described in §4.1. During the temporal period 1993(t3) there underlying powerlaw appears to be steeper (by $\Delta \Gamma \sim 0.1$) than during the remainder of the observations at that epoch. The open circles indicate the best-fitting values when the 1993(t3) data is excluded from the analysis (see §5.2).
Fig. 7.— The mean ratio of the 1993(t3) data to the best-fitting model to the combined 1993(t1,t2,t4) datasets ($N_{\text{neu}}^{\text{H,z}} = 1.1 \times 10^{21} \text{ cm}^{-2}$, $\Gamma = 1.60$, $N_{\text{ion}}^{\text{H,z}} = 4.3 \times 10^{21} \text{ cm}^{-2}$, $U_X = 0.058$, and $D_f = 0$). The solid curve shows the theoretical ratio assuming a steepening of the underlying continuum by $\Delta \Gamma = 0.13$ pivoting at 10 keV, plus that due to the best-fitting diskline profile ($E_z = 6.43 \text{ keV}$, $\beta = 1.98$, $i = 0$, and equivalent width 170 eV). It can be seen that the the 1993(t3) data are consistent with such an hypothesis. However as discussed in §5.2.1, this steepening may also be the result of a lack of response in a Compton-reflector during the 1993(t3) ‘flare’
| Dates        | Satellite | Seq. No. | $t_{\text{exp}}$ (10^3 s) | Count Rates | $N_{\text{pts}}$ (excl 5–7 keV) | $F_{0.5-2}$ (10^{-11} erg cm^{-2} s^{-1}) | $F_{2-10}$ (10^{-11} erg cm^{-2} s^{-1}) |
|--------------|-----------|----------|---------------------------|-------------|---------------------------------|----------------------------------------|-----------------------------------------|
| 1993 May 08 – 19 | ROSAT     | 700996   | 19.5                      | 0.458 ± 0.005 | 0.020 ± 0.001                   | 187                                    | 0.52 ± 0.03                             | ...                                    |
| 1993 May 08 – 09  | ASCA      | 70013000 | 30.7                      | 0.879 ± 0.004 | 0.018 ± 0.001                   | 1132                                   | 0.70 ± 0.04                             | 2.42 ± 0.12                             |
| 1995 May 15 – 16  | ASCA      | 73068000 | 34.3                      | 0.512 ± 0.003 | 0.036 ± 0.001                   | 1109                                   | 0.23 ± 0.01                             | 2.64 ± 0.13                             |

**Note.** — Cols.(1–3): Observation period, satellite and sequence number. Col.(4): Total exposure time of selected data (SIS0 in the case of the ASCA data). Col.(5): Mean background-subtracted count rate in the 0.2–2.0 keV (PSPC) or 0.6–10.0 keV band (ASCA SIS0, corrected for the counts falling outside the extraction cell - see §3.2). Col.(6): Estimated background count rate rescaled to be directly comparable to source count rate in col.(5). Col.(7): Number of spectral data points used in the spectral analysis presented in §4 (summed over all four instruments in the 0.6–5.0, 7.0–10.0 keV band in the case of the ASCA data). Cols.(8–9): Observed flux in the specified energy bands; quoted errors are statistical or 5%, whichever the larger.
### Table 2

**Variability Amplitude (10^{-2} \sigma_{rms}^2) from the ASCA Observations of NGC 3227**

| Epoch   | SIS (0.5–10 keV) | GIS (2–10 keV) | SIS XM1 (0.5–1.2 keV) | SIS XM2 (1.5–3.5 keV) | SIS XM3 (4–10 keV) |
|---------|------------------|----------------|-----------------------|----------------------|--------------------|
| (1) 1993 | 6.36 ± 0.69      | 3.99 ± 0.41    | 9.90 ± 2.21           | 5.55 ± 1.12          | 1.76 ± 0.75        |
| 1995    | 1.82 ± 0.28      | 2.08 ± 0.29    | 0.91 ± 1.06           | 2.89 ± 0.65          | 0.91 ± 0.54        |

*Excluding the outburst observed during period t3 (see §5 and Fig. 4)*

1993 (exc t3) | 2.83 ± 0.43 | 1.42 ± 0.22 | 2.29 ± 1.19 | 2.38 ± 0.63 | 2.24 ± 0.94 |

**Note:** Col.(1): Epoch of the observation. Cols.(2–6): Normalized excess variance, \( \sigma_{rms}^2 \), and associated error calculated using the prescription of Nandra et al. (1997a), from the light curves with a binsize of 128 s (Cols.(2–3)) and 512 s (Cols.(4–6)).
### Table 3
Results from the Analysis of the Mean Spectra (see §4)

| Fit | Epoch | Instrument(s) | \(N_{H,0}^{\text{den}}\) \((10^{21} \text{ cm}^{-2})\) | \(N_{H,0}^{\text{ion}}\) \((10^{21} \text{ cm}^{-2})\) | \(\Gamma\) | \(U_X\) | \(D_f\) | \(\chi^2\) | \(P\) | \(\frac{\Delta\chi^2}{\Delta N_{H,0}}\) | \(R_{\alpha,6}\) | Figure |
|-----|-------|---------------|---------------------------------|-------------------------------|-------|------|------|------|-----|-----------------|--------|--------|
| (1) | (2)   | (3)           | (4)                            | (5)                          | (6)   | (7)  | (8)  | (9)  | (10)| (11)           | (12)   | (13)   |

**Model A: all the underlying continuum passes through a screen of neutral material**

1. 1993 ASCA 1.76±0.14 1.53±0.02 0.0 (f) 0.0 (f) 0.0 (f) 1200 0.93 3.6 2.30 ...
2. 1993 ASCA+ROSAT 1.16±0.14 1.46±0.02 0.0 (f) 0.0 (f) 0.0 (f) 1708 1.00 11.6 1.71 3a
3. 1995 ASCA 6.71±0.40 1.04±0.03 0.0 (f) 0.0 (f) 0.0 (f) 1520 1.00 13.2 7.1 ...

**Model B: all the underlying continuum passes through a screen of ionized material**

4. 1993 ASCA 0.0 (f) 1.60±0.03 4.07±0.21 0.010±0.006 0.0 (f) 1122 0.48 1.7 0.90 ...
5. 1993 ASCA+ROSAT 0.0 (f) 1.53±0.02 2.69±0.20 0.001±0.001 (p) 0.0 (f) 1374 0.89 2.7 1.19 3b
6. 1995 ASCA 0.0 (f) 1.19±0.03 16.60±1.11 0.053±0.005 0.0 (f) 1231 1.00 10.1 0.57 ...

**Model C: all the underlying continuum passes through a screen of ionized material & a screen of neutral material**

7. 1993 ASCA 0.61±0.00 0.61±0.00 1.60±0.03 3.98±0.37 0.013±0.005 0.0 (f) 1122 0.49 1.3 0.93 ...
8. 1993 ASCA+ROSAT 0.30±0.05 1.58±0.02 3.24±0.43 0.012±0.005 0.0 (f) 1322 0.60 1.5 1.10 3c
9. 1995 ASCA 3.20±0.36 1.49±0.07 47.86±5.83 0.195±0.013 0.0 (f) 1064 0.92 2.1 1.37 3d

**Model D: a fraction \(D_f\) of the underlying continuum is not attenuated by the ionized material**

10. 1993 ASCA 0.09±0.01 0.02 (p) 1.61±0.04 5.01±3.92 0.019±0.048 0.13±0.27 (p) 1121 0.49 1.6 0.91 ...
11. 1993 ASCA+ROSAT 0.35±0.07 0.09 1.60±0.04 4.90±5.04 0.011±0.007 0.24±0.23 1321 0.60 1.5 1.10 ...
12. 1995 ASCA 0.67±0.67 (p) 1.53±0.09 32.36±3.30 0.016±0.015 (p) 13±0.02 983 0.36 0.8 1.04 3e

**Note.** All models include an additional screen of neutral material at \(z = 0\) with a column density \(N_{H,0}^{\text{den}} = 2.1 \times 10^{20} \text{ cm}^{-2}\). In the case of the ASCA data, the fits were undertaken in the 0.6-10.0 keV band excluding the 5.0-7.0 keV band. The errors on the fit parameters are 68 per cent confidence limits, (f) indicates the parameter was unable to vary during the analysis, and (p) indicates the parameter 'pegged' at the specified limit. Col. (1): Number used to refer to the fit in the text. Col.(2-3): Epoch of the observation, and datasets included in the spectral analysis. Col.(4): Column density of any additional neutral material. Col.(5): Photon index of the underlying continuum. Col.(6-7): Column density (\(N_{H,0}\)) and ionization parameter (\(U_X\)) of the ionized absorber. Col.(8): Fraction of the underlying continuum unattenuated by the ionized absorber. Col.(9): \(\chi^2\)-statistic for the fit for the \(N_{pt}\) data points given in Table 1. Col.(10): Probability that the \(\chi^2\)-statistic should be less than the observed value for the number of degrees of freedom, \(dof\), given by \(N_{pt} - 7\). Col.(11): Ratio of the increase in the \(\chi^2\)-statistic to the number of addition data points when the best-fitting model is extrapolated to the ASCA data below 0.6 keV. Col.(12): Mean data/model ratio for data points below 0.6 keV. Col.(13): Figure in which the spectral model and data/models are plotted.
| Epoch | $N_{H_2}^{new}$ (10$^{21}$ cm$^{-2}$) | $N_{H_2}^{ion}$ (10$^{21}$ cm$^{-2}$) | $U_X$  | $D_f$  | $\chi^2$ | $P$  | $\Delta \chi^2$ | $R_{0.6}$ | $L_{0.1-30}$ | $L_{0.5-2}$ |
|-------|-------------------------------------|-------------------------------------|--------|--------|----------|------|----------------|----------|----------------|----------|
| t1    | $0.06_{-0.08}^{+1.71}$              | $1.48_{-0.08}^{+8.08}$              | $3.47_{-1.96}^{+4.38}$ | $0.016_{-0.008}^{+0.118}$ | $0.00_{-0.00}^{+0.50}$ | 502  | 0.06           | 1.0      | $1.63 \pm 0.08$ | $0.40 \pm 0.02$ |
| t2    | $1.02_{-0.13}^{+0.98}$              | $1.57_{-0.12}^{+3.33}$              | $5.70_{-3.23}^{+6.64}$ | $0.070_{-0.069}^{+0.103}$ | $0.02_{-0.00}^{+0.40}$ | 385  | 0.00           | 1.3      | $1.44 \pm 0.08$ | $0.38 \pm 0.02$ |
| t3    | $0.00_{-0.06}^{+1.14}$              | $1.74_{-0.06}^{+0.07}$              | $4.27_{-1.53}^{+0.52}$ | $0.014_{-0.010}^{+0.050}$ | $0.01_{-0.01}^{+0.41}$ | 735  | 0.72           | 1.4      | $2.13 \pm 0.11$ | $0.60 \pm 0.03$ |
| t4    | $0.05_{-0.10}^{+7.05}$              | $1.60_{-0.12}^{+0.05}$              | $6.17_{-5.85}^{+5.00}$ | $0.006_{-0.005}^{+11.214 (p)}$ | $0.22_{-0.22}^{+0.20 (p)}$ | 563  | 0.16           | 0.9      | $1.48 \pm 0.07$ | $0.39 \pm 0.02$ |

The 1993 Observations

The 1995 Observations

Note. — Columns and symbols as for Table 3

**TABLE 4**

Results from the Analysis of the Time-resolved ASCA Spectra (see §5.2)