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# X-RAY OBSERVATIONS OF A FLARE IN NGC4151 FROM OSO-8

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## ABSTRACT

We have observed the 2-60 keV flux from NGC4151 change by a factor of two on a timescale of 1.5 days. We do not detect any fluctuations in excess of a factor of three on timescales less than four hours. During a total observation of $\sim$ 11 days there was no statistically significant changes in spectral shape. The spectrum can be fit by a power law with photon index $\alpha \sim 1.42 \pm 0.06$ and column density $N_H \sim 7.5 \pm 0.5 \times 10^{22}$ at/cm$^2$. A $2\sigma$ residual to this fit implies fluorescent Fe line emission with E.W. $\sim$ 240 eV. Both synchrotron self-Compton and thermal Compton models are consistent with the X-ray data.

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## I. INTRODUCTION

NGC 4151 has been the most intensively studied Seyfert galaxy in both the X-ray and optical frequency bands. Medium energy, 2 - 15 keV, proportional counter observations (Ives, Sanford and Penston 1976) combined with higher energy, 10 - 200 keV, scintillator results (Baity et al. 1975; Paciesas, Mushotzky and Pelling 1977) have shown that the X-ray spectrum can be best described by a power law with a low energy turnover due to photoelectric absorption. However, there has not been a single observation which covers the 2 - 60 keV band. The combination of 3 Ariel 5 observations (Barr et al. 1977) has indicated that the continuum remained constant in both intensity and spectral index while the column density varied by a factor of 5. Elvis (1976) observed an increase in the 2 - 10 keV flux of $\sim$1.7 over a time scale of $\sim$ 3 days. He interpreted this as due to a variation in the continuum, but the lack of spectral data does not allow the unambiguous determination of its origin in either the continuum or the column density.

We present here the results of an 11 day observation, days 145-156 of 1977, over the 2 - 60 keV band from the Goddard Space Flight Center Cosmic X-ray experiment on OSO-8. This experiment and the methods of analysis have been described by Serlemitsos et al. 1976.

## II. RESULTS

### A. Intensity Variability

The 2 - 60 keV intensity of NGC 4151 (Figure 1) changed in an irregular fashion during our observation with the most obvious feature being a factor of 2 increase from .014 $\pm$ .001 cts/cm$^2$ sec to .027 $\pm$ .001 cts cm$^2$ sec over a rise time of 1.5 days. This rise corresponds to a change in the 2 - 6 keV flux of $4.3 \times 10^{-11}$ ergs/cm$^2$sec to $8.2 \times 10^{-11}$ ergs/cm$^2$sec using our best fit spectral parameters. The flux then decreased to an approximately constant level of .02 cts/cm$^2$sec over the next 2-3 days. We note that these changes are not sharp but are gradual and can be approximated by exponentials with a rise time of $\sim$ 2 days and a decay time of $\sim$ 7 days. These flux levels are similar to the range of 4.8 - $12.7 \times 10^{-11}$ ergs/cm$^2$sec seen by UHURU (Ulmer 1977). Thus the entire range of reported variability can occur on a time scale of less than 1 week. In contrast to the spectral changes accompaning the intensity variability seen by Ariel 5 (Barr et al 1977) there was no change in either spectral index or column density seen during our observation with an upper limit of $\Delta\alpha \sim .15$ and $\Delta N_H \sim 1 \times 10^{22}$. This is quite similar to the intensity changes in Cen-A reported by Mushotzky et al. (1978) which had a time scale of $\sim$3 days and a 50% amplitude.

There has been a report by Tananbaum et al. (1978) of variability on time scales of 10 minutes or less up to a factor of $6^{+2}_{-2.2}$ over the average rate. We have examined our data on time scales from 10 sec to 3 hours and have found no evidence for such variations in the source inconsistent with fluctuations in the background. We can set a $3\sigma$ upper limit of no fluctuation greater than a factor 3 on any time scale in excess of 10 seconds during our 11 days of observation. During our observation the source had the same intensity range as that seen in the period when Tananbaum et al. observed the strong fluctuations. We conclude therefore that these short scale fluctuations, if real, are much less frequent than would be implied by the UHURU data.

B. Spectra

At all times during our observation the spectrum (Figure 2) can be adequately fit by a power law with photon index $\alpha = 1.42 \pm .06$ and with absorption due to cold material in the line of sight with cosmic abundance (Brown and Gould 1970; Fireman 1974) of $N_H = (7.5 \pm 0.5) \times 10^{22}$ $cm^2$ with a $\chi^2$ per degree of freedom $\leq$ 1.35 (Fig. 2a). A thermal fit is not well determined but we require kT $\geq$ 70 keV, corresponding to a temperature at which the knee is higher than our highest observing energy. The observation of the source at this time out to 200 keV (Beall et al. 1978) requires kT $\geq$ 150 keV.

There is an indication of a 6.4 keV Fe fluorescent line at the 2.5 level. The best fit model has an equivalent width of $240^{+270}_{-170}$ eV ($1\sigma$ error). If real, this indicates (as does the Ariel 5 edge data, Barr et al) a Fe overabundance of $\sim 2$ relative to a solar abundance of $4 \times 10^{-5}$. The OSO-8 edge data are also consistent with this. Because of the extreme weakness of this feature we cannot comment on any variability.

## III. DISCUSSION

Our results appear to confirm the original somewhat weaker result of Elvis that NGC 4151 varies on time scales less than a week. The time-scales seen by us and by Elvis are similar and perhaps indicate the scale size of the source of a few light days. Our absorption column density differs from any of those reported by Barr et al. from Ariel 5 and therefore confirms that the absorption in NGC 4151 varies on a timescale of months. However all spectral data are consistent with a constant spectral index.

We shall try to construct a self consistent model of the nuclear region of NGC 4151 which can, in a qualitative way, explain the X-ray absorption variations, the X-ray continuum and the optical and IR spectra of the source.

1) Low energy absorption, optical reddening and IR spectrum.

In principle the X-ray column density should be linearly related to the optical reddening (Gorenstein 1975). However in NGC 4151 the relation found by Gorenstein to apply to material in our galaxy seems not to apply. The lowest X-ray column density seen, $3 \times 10^{22}$ at/cm$^2$, would imply a reddening $A_V \gtrsim 19$ mag. However the limit on the optical reddening is $A_V \lesssim .2$ mag (Wu and Weedman 1978). We can interpret this as caused by a low dust to gas ratio since the reddening is due to dust while the X-ray column is due to gas. The required dust to gas ratio is $\sim 1.6 \times 10^{-5}$ by mass or about 1/200$^{th}$ that of "normal". However, this is quite similar to that seen in galactic HII regions (Gillett et al. 1975).

It has been shown for several galaxies (M82, NGC253) that the bulk of the IR flux is due to cold dust. Given the above constraints on dust surrounding the nucleus of NGC 4151 it is of interest to see if the 10$\mu$ IR nuclear component could be due to dust associated with the X-ray absorbing material. Using $N_H \gtrsim 7 \times 10^{22}$ and a gas to dust ratio of $6 \times 10^4$ implies a dust column density of $2 \times 10^{-6}$ gm/cm$^2$. If the dust is optically thin and is silicate material we can calculate the required amount of dust to account for the observed 10$\mu$ flux (Beall et al. 1978). If we assume a dust temperature $T \gtrsim 200^\circ$K which is similar to that of HII regions in our galaxy we require a mass of dust $M_\odot \gtrsim 36\ M_\odot$ in a spherical cloud 30 pc (or .3" at 20 Mpc) in size. This physically oversimplified model would account for the 10$\mu$ flux but could not account for the 3.4$\mu$

flux because of its low temperature. Since the 3.4 flux is variable on a timescale of less than a year (Penston et al. 1974) it must be due to another component. If it is thermal it must be hotter and therefore smaller.

Another possible model to explain the high $N_H$ but low $A_V$ in NGC 4151 would require most of the optical emission to originate in a region outside of the place where the X-ray absorption occurs. This would explain why the optical light is not strongly reddened by the large amount of dust implied by the X-ray column density if normal dust to gas ratios are assumed. In this case one would not expect $N_H$ and $A_V$ to be related.

2) Implications of X-ray Absorption on Optical Observations

In this section we show how the variability in X-ray absorption determined from Ariel 5 and OSO-8 is consistent with optical observations.

Models accounting for the optical emission line spectrum in NGC 4151 require at least two regions, a broad line region (BLR) producing the broad Balmer lines and a narrow line region (NLR) producing the narrow core of the Balmer lines and the forbidden lines. Since the X-ray emission presumably shines through both of these regions their properties should be reflected in the X-ray absorption and variations therein.

The NLR is characterized by a size of $\sim$50 pc (Ulrich 1973) and a density $n_e \sim 2 \times 10^4$ cm$^{-3}$ (Boksenberg et al. 1975) and a filling factor (the volumne of space taken up by gas) $\epsilon \sim 10^{-3} - 10^{-2}$. This would give X-ray column densities in the range $3 \times 10^{21} - 3 \times 10^{22}$. Thus it seems probable that NGC 4151 would always show X-ray absorption corresponding to the material in the NLR. However there is not enough material in the NLR to account for the total X-ray absorption and, since the lines in the NLR are constant, it is difficult to see how this region could account for variation in the X-ray abscrption. We shall, therefore, assume (Sargent 1973, Barr et al. 1978) that most of the X-ray absorption is due to material in the BLR.

Typical models of the BLR have densities, $n_e \gtrsim 10^9$ cm$^{-3}$, sizes $1 \times 10^{17}$ cm (Anderson 1973) and filling factors of $10^{-3}$ - $10^{-5}$. Thus one expects X-ray column densities in the $10^{21}$ - $10^{24}$ at cm$^{-2}$ range. The fact that the X-ray absorption varies on timescales of years or less implies that we see only a few clouds in the line of sight at any one time and that each cloud has $N_H \sim 5 \times 10^{22}$. We can set limits on the ratio of filament size, r, to tranverse velocity, $V_T$, of these filaments such that $r/V_T < 1 \times 10^7$ sec, the variability time scale seen by Ariel 5. We know that these filaments must cover the X-ray source and thus must have a size $r < 3$ light days ($2.5 \times 10^{15}$ cm). Thus $V_T \geq 2.5 \times 10^8$ cm/sec ($\sim$.01c) which is on the order of the Doppler width of the broad lines, a similar such model was suggested by Ives et al. 1976.

If we assume (Osterbrock 1978) that such velocities are circular the mass of material inward of 2 light weeks ($4 \times 10^{16}$ cm) necessary is $M_c = r\, V_T^2/G \approx 2 \times 10^7\, M_\odot$. This is indirect evidence for large mass concentrations in the core of Seyfert galaxies. If the BLR is larger the mass is larger by $r^3$.

3) The Mechanism of X-Ray Emission

We shall assume for this discussion that the X-ray emission is due to a non-thermal process which is related, in some fashion, to the non-thermal optical and UV emission. We shall discuss the synchrotron self-Compton (SSC) mechanism (Jones, O'Dell and Stein 1974) and a Comptonized accretion disk model due to Katz (1976).

a) In a SSC model we shall attribute the observed rise time of the X-ray flux to the filling of the emission region by an injection of relativistic particles. We shall attribute the decline of the X-ray emission to a combination of synchrotron losses, Compton losses and adiabatic expansion.

In a SSC model the X-ray emission is due to the Compton scattering of the photons produced by synchrotron emission off the same electrons that produced them. In this model the observables necessary to define a physical model are the ratio of Compton to synchrotron flux $E_\nu^{sc}$, the slope of the synchrotron component $\alpha$, and 2 parameters of the synchrotron emission alone, the turnover frequency due to synchrotron self absorption $\nu_n$) and the flux at this turnover $F_{\nu_n}$. Given these observables we are then able, using a series of relations developed by Jones, O'Dell and Stein (1974) to derive physical parameters such as the size, $\theta_s$, the magnetic field B and the loss times $t_s$ due to synchrotron losses and $t_c$ to Compton losses.

Because in NGC 4151 we have no direct evidence of a compact high frequency component the problem is not well determined. It is however of interest to see if a model which is consistent with the IR data and the microwave upper limits can be constructed. For this self consistent model we have $B \approx 1.5$ gauss, $\nu_n \approx 1.5 \times 10^{11}$ Hz, $F_{\nu_n} \sim 4$ Jy, $\theta_s = 1.1 \times 10^{-10}$ rads ($\sim$ 2 light days), $E_\nu^{sc} \approx 2 \times 10^{-4}$ a synchrotron lifetime $t_s \approx 30$ days and a Compton lifetime $t_c \sim 1$ day. Such a model has a break in the synchrotron spectrum due to energy losses at $\nu_B \sim 8 \times 10^{12}$ Hz ($\sim 40\mu$) and would thus have a steeper slope in the IR than in the millimeter. The X-ray spectrum should deviate from a power law at $\nu_{max} \sim \gamma n^2 \nu_B^2/\nu_n$, where $\gamma_n$ is the relativistic factor of the electrons emitting at $\nu_n$ (Burbidge, Jones and O'Dell 1974), in this model $\nu_{max} \gtrsim 200$ keV. The first order Compton scattered flux would be the dominant continuum flux at $E \gtrsim 200$ eV. The contribution of this component to the near IR, optical and UV flux is difficult to calculate because the short lifetimes of the electrons indicate that repeated injection or reacceleration is important. However in the high frequency limit the slope of the power law should approach $\alpha' \sim 4/3\,\alpha_x + 1$. This slope of $\sim 1.45$ seems to be near the range of values $\alpha' \sim 1.1 - 1.6$ seen by Puschell and Stein (1978). We feel that the UV data of Wu and Weedman (1978) is consistent with a slope $\alpha' \sim 1.4$ as are the U,B,V data of Beall et al (1978).

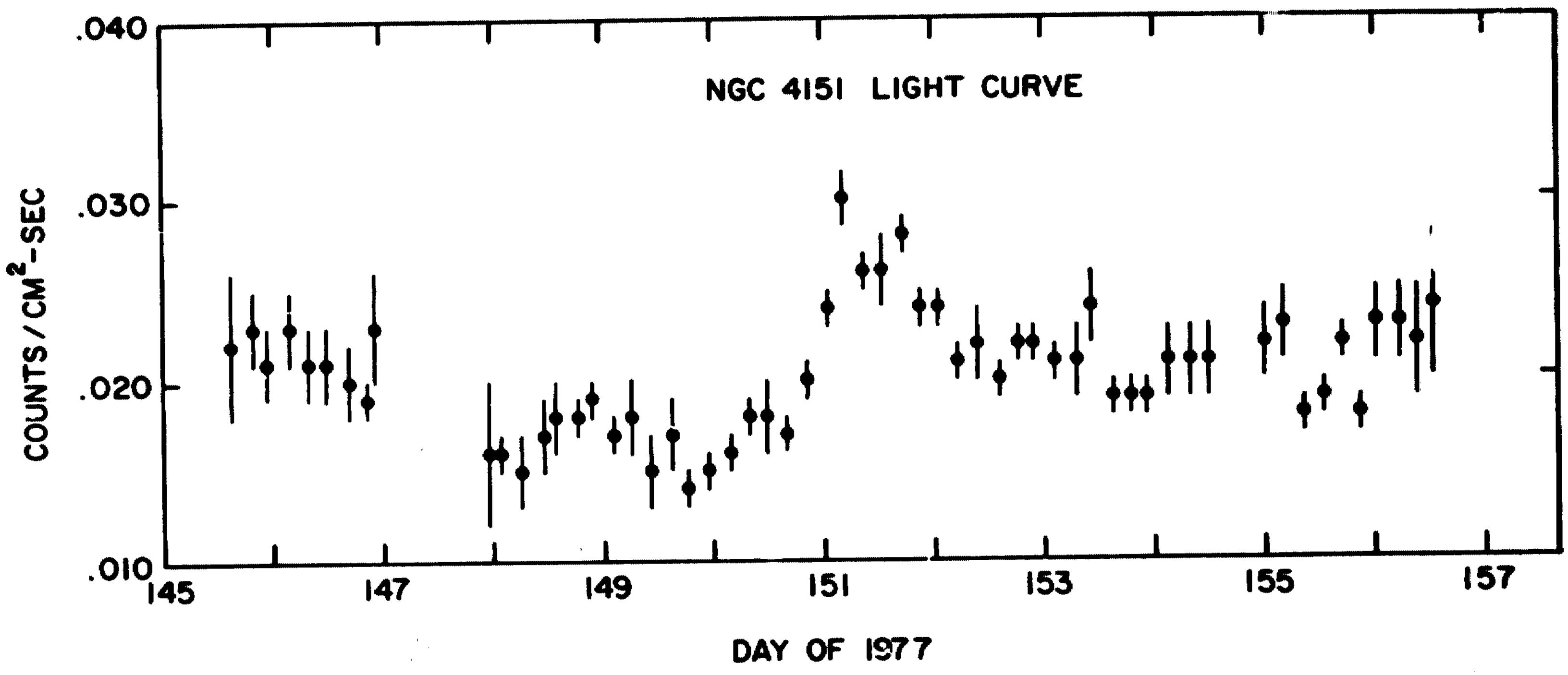
We can crudely estimate the optical variability in this model by assuming that the changes in flux are due only to changes in the number of relativistic particles. In this case the optical flux would vary by $\sim 1.17$ for a factor 2 change in X-ray flux. Thus on a short timescale a factor 2 change in X-ray flux would be accompanied by $\Delta m_v \sim .15$. We also note that the Compton UV component adds an additional source of ionization and heating which should be included in models of the BLR (Mac Alpine 1974).

b) It has been suggested (Katz 1976; Schnopper et al. 1977) that a model in which an unexplained source of soft photons is Compton scattered by collisions with electrons in a hot cloud may explain the non-thermal emission from QSO's and Seyferts. A similar model has been advanced to explain X-ray emission from Cyg X-1 (Shapiro, Lightman and Eardly 1976).

Fitting the observed timescale of variability and spectral index to Katz's model we would derive a cloud size $R \sim 2 \times 10^{15}$ cm (.77 ℓ.d.) an electron density $n_e \sim 2 \times 10^9$ $cm^{-3}$ and a mass necessary to constrain the cloud of $M \sim 1 \times 10^6$ $M_\odot$. This model gives the proper X-ray luminosity and agrees with the fact that intensity variations are not accompanied by spectral variations. In this model the optical variability should be similar to the X-ray variability and thus factor 2 changes in X-ray flux should be $\Delta m_V \sim .3$ mag.

## IV. CONCLUSIONS

The observational data show that NGC 4151 continuum varies by at least a factor 2 on timescales less than 2 days with no change in spectral properties during this variation. The absorption variation indicated from a combination of Ariel 5 and OSO-8 data is consistent with the variable X-ray absorption due to moving clouds in the broad line emission region. The X-ray emission is consistent with both the synchrotron self Compton mechanism and thermal Compton models. Our data imply that the X-ray emission from NGC 4151 comes from a physical region of the same order as the non-thermal compact cores of radio galaxies (e.g. CenA).


NGC 4151 LIGHT CURVE
COUNTS / CM$^2$-SEC
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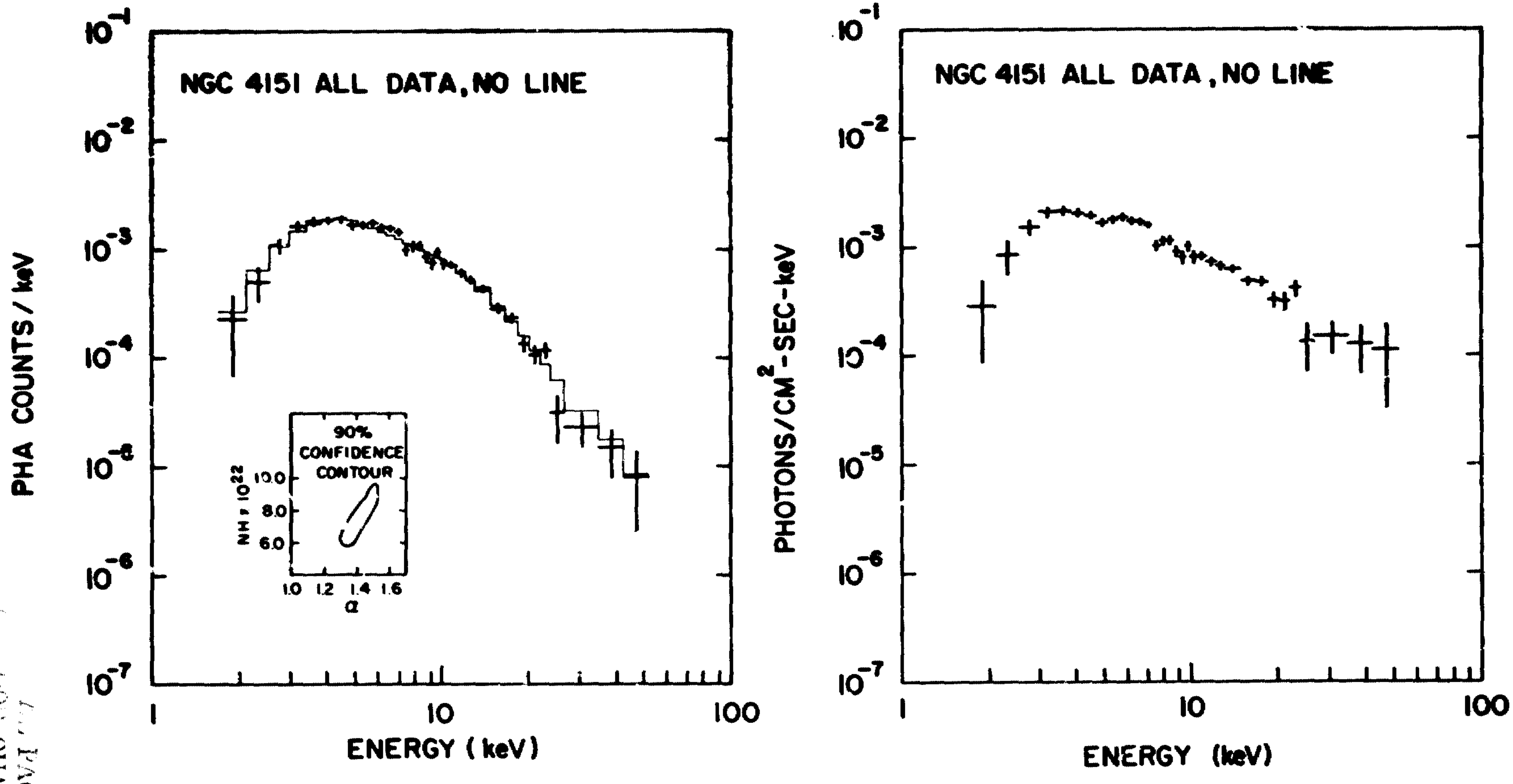
.030
.020
.010
145
147
149
151
153
155
157
DAY OF 1977


NGC 4151 ALL DATA, NO LINE
PHA COUNTS / keV
ENERGY ( keV)
90% CONFIDENCE CONTOUR
NH x 10^22
α
NGC 4151 ALL DATA, NO LINE
PHOTONS/CM^2-SEC-keV
ENERGY (keV)

## FIGURE CAPTIONS

Figure 1 - Light curve of NGC4151 in May-June 1977. The data are binned in 4 hour intervals.

Figure 2a - The pulse height spectrum of NGC4151. The solid line is the best fitting power law with absorption convolved through the detector response. Note the excess flux over the model in the channels near 6.4 keV. The insert shows the 90% confidence contour for this fit.

Figure 2b - The best fitting photon spectrum for a fit without an Fe line. This differs from 2a in that a model is necessary to invert the PHA spectrum.

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