NASA

Technical Memorandum 83966

The Absence of Rapid X-Ray Variability in Active Galaxies

A. F. Tennant and R. F. Mushotzky

(NASA-TM-83966) THE ABSENCE OF RAPID X-RAY VARIABILITY IN ACTIVE GALAXIES Ph.D. Thesis - Maryland Univ. (NASA) 41 p HC A03/MF A01 N82-30204
CSCL 03B Unclas
G3/90 30366

JUNE 1982

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

THE ABSENCE OF RAPID X-RAY VARIABILITY IN ACTIVE GALAXIES[1]

Allyn F. Tennant[2] and R.F. Mushotzky

Laboratory for High Energy Astrophysics
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

ABSTRACT

We have searched for variations on time scales ranging from minutes to several hours in the X-ray flux from 54 observations of 38 active galaxies. Our sample is composed mostly of Seyfert I galaxies but also includes radio galaxies, NELG's, BL Lacs and 3C 273. Only NGC 6814 varied on time scales as short as 100 sec. No other source was observed to vary with a time scale of less than 12 hours. We conclude that large-amplitude short-term variations are not a characteristic of the X-ray emission from active galaxies. Upper limits on σ_I/I ranged from 2% for Cen A, 5% for NGC 4151, to ~ 20% for sources giving 1 ct/sec in our detector. Three objects NGC 3227, NGC 4151 and MCG 5-23-16 show variability consistent with a time scale of ~ 1 day.

We consider ways to reconcile the rapid variability seen for NGC 6814 (and NGC 4051) with the general stability observed for the other objects. If the lack of variability is due to the growth of a new, constant source of soft photons (such as thermal re-radiation from dust) then the X-ray plasma must be much larger than the size implied by the variations seen in NGC 6814. Other possibilities are that the "originally lumpy" accretion flow stablizes or that NGC 6814 is different from other galaxies.

Subject headings -- Galaxies: nuclei - Galaxies: Seyfert - X-ray: sources

[1] From a dissertation to be submitted to Graduate School, University of Maryland, by Allyn F. Tennant in partial fulfillment of the requirements for the Ph.D. degree in Physics.

[2] Also Dept. Physics & Astronomy, Univ. of Maryland

I. INTRODUCTION

It is currently popular to assume that the X-rays from active galactic nuclei are produced deep in the potential well near a super massive object (see Rees, Begelman and Blandford 1981 for recent discussion). If the X-ray flux from this dense gravitationally confined plasma is observed to vary then the shortest time scale for variability will be on the order of the light travel time across the most stable orbit in a Schwarzschild geometry. This is given by

$$\Delta\tau \sim R/c \sim 10\ GM/c^2 \sim 50\ \mathrm{sec}\ M_6$$

where M_6 is the mass of the central object in units of $10^6\ M_0$. Since M_6 is expected to be in the range of 1 to a 1000 the relevant time scales range from ~ 1 minute to ~ 1/2 day. Lack of variability on these time scales could be an indication that the X-ray emitting plasma is not gravitationally confined.

Recently, Guilbert, Ross and Fabian (1982) have discussed a model which accounts for the simple power law energy spectrum observed from these sources. In their model a region of hot electrons produces X-rays and cools via inverse Comptonization. Since the cooling time is much shorter than the period in which a good spectrum can be obtained the observed spectrum will be a time average. Sources powered with this mechanism should show a low amplitude flicker with a time scale of minutes.

On the observational side, before the launch of the HEAO observatories only two active galaxies, Cen A and NGC 4151, were bright enough to have had their X-ray flux accurately measured in less than 12 hours. Both show variability on time scales less than one day. Winkler and White (1975) saw a factor of 1.6 change during a 6 day observation of Cen A. The angular size implied by such a change is less than 1 marc sec. Delvaille, Eptein and Schnopper (1978) found evidence of a 25% increase in Cen A during a few hours, confirming rapid variability. Lawrence, Pye and Elvis (1977) have shown that Cen A is continuously variable in its X-ray flux over extended periods of time.

The second brightest extragalactic X-ray source NGC 4151 also has a long history of observations of X-ray variability. Mushotzky, Holt and Serlemitsos (1978) reported a flare with a factor of 2 change observed over 1.5 days. Lawrence (1980) using Ariel 5 data extending over several years finds that such flare-like events are rather common. Although the absorption column does vary in NGC 4151 and causes some of the observed flux variations (Barr et al. 1977) there are no indications of changes in the absorption or spectral index during the more rapid changes (Mushotzky, Holt, Serlemitsos 1978; Baity et al. 1982).

Since the two brightest active galaxies are highly variable on time scales as short as one day, it was expected that this should be a property of all active galaxies. In the pre-HEAO days it was difficult to detect rapid variability due to small collecting areas and low on source duty cycles. Ariel 5 results (Pounds 1979; Marshall, Warwick and Pounds 1981) support the possibility that all active galaxies (occasionally at least) show variability on time scales as short as one day. However, it was impossible for Ariel 5 to measure time scales shorter than one day for weak sources.

In this paper we report on the results of a search for rapid variability from active galaxies using the HEAO-1 A2* experiment (Rothschild et al. 1979). Since we are interested in the most rapid time scales we have used the pointed data. In this mode the spacecraft observed the source of interest more or less continuously for a period lasting from 3 to 18 hours. There were 54 pointings which gave data useful for this analysis. The high on source duty cycle combined with the low background, large bandwidth and large collecting area resulted in high sensitivity to variations with time scales ranging from ~ 1 minute up to ~ 3 hours. Longer time scales will be discussed by Mushotzky et al. 1982.

II. METHOD OF ANALYSIS

For this analysis we used data from one Xenon detector, HED 3, which means that we are most sensitive to X-rays from 3 to 15 keV. We selected data with low veto rates (electron quiet) and low McIlwain L values (see below). We also excluded times when the earth or earth's atmosphere was in the field of view. These data selection criteria resulted in ~ 70% of the data being rejected for further analysis. We subtracted a constant background rate and then corrected for effective exposure to the source to obtain the source flux. Errors in the source flux were assumed to be purely statistical with an additional term due to the uncertainty in the absolute level of the background.

It was then possible to compute χ^2 testing the assumption that the source did not vary during a given observation. Since the probability of observing

*The A2 experiment on HEAO-1 is a collaborative effort led by E. Boldt of GSFC and G. Garmire of CIT, with collaborators at GSFC, CIT, JPL and UCB.

any given value of reduced χ^2 (that is χ^2 per degree of freedom denoted by χ^2_N) is a strong function of the number of degrees of freedom N, we computed

$$X = (\chi^2_N - 1)/\sqrt{2/N}. \qquad (1)$$

For large values of N one can convert X into a probability of X being less than or equal to this value by chance, using Table 26.1 of Abramowitz and Stegun (1970). We have found that for N ranging from a few to infinity using X = 1.3 gives a 90% confidence upper limit for detection of variability. The usefulness of X is lost if $\chi^2_N < 1.0$, thus for X values of less than 1.3 we define a 90% confidence upper limit by computing how much the source would have had to vary to generate an X value of 1.3 exactly.

We have separated the variance σ^2_I in the source intensity I from the variance introduced by counting statistics using

$$\beta^2 \equiv \left(\frac{\sigma_I}{I}\right)^2 = ((\chi^2_N - 1)\ N/\sum_j \sigma_j^{-2})/\langle I\rangle^2. \qquad (2)$$

In equation (2) σ_j is the error in I_j for the jth data bin (see Appendix A); where β is a measure of the source variability and is a function of the time scale over which one averages and the "true" timescale for source variability. Since σ_I is normalized by dividing by the source intensity the resulting number is dimensionless and so measures an intrinsic property of the source (independent of distance). We have numerically tested equation (2) by generating "phantom" data with a known amount of "source" variance and adding in the correct amount of counting statistics variance. We have found that for X > 1.3 equation (2) did allow us to separate "source" variance from photon noise.

For a variable source the value of β is a function of the size of the time bins one used to calculate χ^2. For example if the bin size is shorter than all relative time scales β will be at a high and roughly constant value. However, for longer bin sizes one starts to average more than one "event" into a single bin and the value of β will decrease. For a plot of β vs bin size for Cyg X-1 see Doi (1980). An early version of this analysis was done by Boldt et al. (1975).

It will be useful below to consider the value of β for the case where the intensity is uniformly and randomly distributed between a low of I_0 and a high of I_1. When the bin size is smaller than the transition time, we find

$$\beta = \frac{2}{\sqrt{12}} \frac{I_1 - I_0}{I_1 + I_0} = \frac{\Delta I}{\langle I \rangle \sqrt{12}} \tag{3}$$

where $\Delta I = I_1 - I_0$ and $\langle I \rangle$ is the average. For bin sizes equal to or longer than the variation time scale, one starts to average over fluctuations which will cause the observed value of β to be reduced from the value given above. Thus on a β vs. bin size plot, the location at which the curve rolls over is related to the time scale of the dominant source of variance in the data.

III. SOURCES OF ERROR

In any search for variability one expects to find a few events that are statistically quite rare but nonetheless are not "real" events. This can arise from two quite different causes. First, extremely rare non-X-ray related events can occur in the detector giving rise to spurious variability. Secondly, there can be a small amount of residual noise in the detector which gives rise to an excess variance (above Poisson noise). The residual noise can be totally invisible in a single observation but can, in the case of a large number of observations, give rise to more than the expected number of "3σ" detections of excess variance. In this section we consider both types of errors.

A. Non-X-Ray Events

Twice out of a total of 102 observations, once observing NGC 526a and once observing NGC 4593, we observed a short duration "flare". For the case of NGC 4593 the flare increased the "source intensity" by greater than a factor of 5 on a time scale of ~ 500 sec. In both cases the counting rate in the detector not observing the source (see Tennant et al. 1981, Appendix A) also increased. Therefore, in neither case can the variability be considered to be coming from the source. We believe these events occur during times when the particle flux has an unusual energy spectrum and a flux low enough not to trigger any of our flags indicating particle events.

B. Aspect

The standard aspect solution provided by Goddard can be in error by up to $.15^{\circ}$ during pointed observations. We obtained ~ 25 aspect solutions from the A-3 experimenters who generate better solutions. We found that for most cases the Goddard supplied aspect was accurate to better than $.05^{\circ}$. An error in aspect of this magnitude will produce a σ_I/I of less than 2% for our $3^{\circ} \times 3^{\circ}$ field of view. Since we have used the A3 solution for most of the brighter sources and the more variable weaker ones we believe that the residual variations found for some of these sources is not related to aspect uncertainties.

C. McIlwain's L Parameter

The background counting rate in our detector is related to the value of McIlwain's L parameter (McIlwain 1961). Roughly speaking McIlwain L is the distance from the center of the Earth of a trapped particle when it crosses the geomagnetic equator. Observations during points at "blank sky" (that is times when no source of flux > 3 x 10^{-11} ergs/cm^{2}sec was in our field of view) showed that the excess counting rate ΔC, which is correlated with L, fits the model $\Delta C \sim 2(L-1)$ ct/sec for 800 cm^2 of detector. This linear fit is accurate to ~ 20% for L ranging from 1 to 1.5 (units of earth radii). Since HEAO-1 was in low earth orbit, L was generally below 1.2 but occasionally values of 1.5 or more were encountered. We decided to discard all data with L values of 1.2 or greater.

This has become one of the standard data selection criteria which was used to analyze all pointed observations of active galaxies and blank sky. This flag caused ~ 30% of previously good data to be discarded but decreased the excess variance by a factor of greater than 60%. If we assume that the remaining L values are uniformly distributed between 1 and 1.2 we can then apply equation 3 to estimate that the excess variance due to the residual McIlwain L effect is roughly

$$\begin{aligned}\sigma_L &= \Delta C/(\sqrt{12}\ A)\\ &= .20\ \text{ct/cm}^2\text{-ksec}\end{aligned}$$

where we have assumed that the mean area A during pointed observations is close to 600 cm^2. We note that $\Delta C/\sqrt{12}$ = .12 ct/sec is only 0.8% of the total (internal and diffuse X-ray) background counting rate of ~ 14 cts/sec.

D. Background Fluctuations and Source Confusion

The background is uncertain to about 3% at any point on the sky in our 3 x 3^0 beam. This is due to weak unresolved sources below our source confusion threshold. This absolute uncertainty in the background flux introduces two types of errors into our results. First, this "sky confusion" noise, also called fluctuations in the diffuse X-ray background, introduces an irreducible uncertainty in our absolute flux level of ~ 0.5 ct/cm^2-ksec. For this reason we have not considered any sources with fluxes less than 1 ct/cm^2-ksec.

The second way background fluctuations can affect our results has its origin in the fact that HEAO-1 was not always pointed at the source of interest during a given observation but rather drifted over a band that allowed offsets up to 1/2°. Although the counting rate has been corrected for mean exposure, we find that the different sky backgrounds observed by the detector as it looks at slightly different parts of the sky can cause an excess variance to appear in the data. To estimate the amount we first note that if the detector explores the entire area of the sky that it is allowed to, then only 50% of the total solid angle viewed during the observation is in the field of view at all times. We expect the variance for overlapping fields to be less than the ~ 3% observed for independent 3° x 3° fields. To first order, background fluctuations will introduce uncertainties of up to 0.32 ct/cm^2-ksec (1.5% of total detector background). Therefore, including both residual particle events and background fluctuations, the maximum excess variance we expect is ~ 0.4 ct/cm^2-ksec. We note that the observed excess variance can be much smaller than this if the sky background flux is relatively uniform in the observed region or if the detector does not explore the full region of sky available to it or if the value of McIlwain's L parameter was unusually constant for a given observation.

IV. RESULTS

A. Variance

In Table 1 we have summarized the results of our tests for source variability (the list is alphabetic by source name). Columns 7 and 8 give the value of σ_I/I for two different bin sizes. Also included in Table 1 is the day the observation was made where day 1 = Julian day 2441344.5 = Jan 1, 1977,

ORIGINAL PAGE IS
OF POOR QUALITY

and the mean flux <I> for the observation. Here and throughout the paper we report fluxes with units of ct/cm^2-ksec. A flux of 1 ct/cm^2-ksec in the Xenon detector corresponds to 1 x 10^{-11} ergs/cm^2-sec in the 2-10 keV band or 1.8 x 10^{-11} ergs/cm^2-sec in the 2-20 keV band assuming a power law spectrum with energy slope $\alpha = 0.7$. Again we point out that <I> is uncertain by ~ 0.5 ct/cm^2-ksec due to the 3% uncertainty in the sky background.

We have plotted β, obtained using a 328 sec bin size vs. source intensity in Figure 1. Since β is computed using the entire observation, Figure 1 is relevant for time scales ranging from 300 sec to about 3 hours. The solid line in Figure 1 corresponds to a constant standard deviation of 0.4 ct/cm^2-ksec which was estimated in the last section to be the upper limit for systematic errors. Thus any positive detections below this line could be due to residual sky plus detector noise. Only three objects, NGC 6814, NGC 4151 (one time) and Cen A (one time), lie significantly above the curve.

We have examined β down to a bin size of 5.12 sec (a detector readout time). Due to counting statistics our upper limits at 5.12 sec are about two times larger than the corresponding values at 328 sec. Since there are fewer positive detections of variability at 5.12 sec than at 328 sec we conclude that there is not a large source of variance with time scales of less than 328 sec. We conclude that large-amplitude, $\sigma_I/I > 10\%$, short term variations on timescales $5 < \tau < 10^4$ sec are not a characteristic of the X-ray emission from active galaxies.

As one goes to longer bin sizes then most of the residual non-source related noise is averaged into a single bin. Since the spacecraft look position generally samples the entire area available to it during one spacecraft orbit, sky noise is greatly reduced for a 90 min bin size. For a 90 min bin size one also averages over the particle background for one spacecraft orbit. A plot of β vs. source flux for a ~ 90 min bin size is shown in Figure 2.

We have attempted to determine our systematics for the 90 min bin size by performing the equivalent test for variability during observations of "blank sky". Of 49 observations of "blank sky", 17 were not constant at the 90% confidence level. Since for all active galaxies, except Cen A, the background gives more counts than the source, we would expect a similar fraction of the active galaxies to show variability. Thus we expect 18 ± 4 positive detections when in fact the observed value was 21. Thus, to first order, the majority of our positive detections only indicate that there is a small amount of excess variance, beyond counting statistics, not included in our χ^2 test for variability.

If the same excess variance accounts for both the increased number of positive detections for the "blank sky" and the active galaxies then the magnitude of the variance should help us decide if any detected variability is real or not. In Figure 3b we have plotted a histogram of the standard deviation σ_B in the background counting rate B normalized by dividing by B for a ~ 90 min bin size. The white areas represent upper limits and the shaded boxes correspond to observed values. We have computed the excess variance for the entire set of observations by adding together the excess variance from each observation. For the 90 min bin size this gave σ_B/B of 0.7% which is what one would expect if most of the excess noise was due to background fluctuations only. Thus the observed distribution is consistent with the expected excess variance being due to "confusion noise".

For observations of active galaxies we expect a slightly different distribution. First, when the detector is pointed at an active galaxy the counting rate is higher (by definition). This means that our sensitivity to non-source related variance is smaller during observations of active galaxies. This is shown by the fact that the distribution of upper limits has moved to the right (Figure 3a). Since the flux from active galaxies was first area corrected for effective exposure, to convert to σ_I/B we multiplied σ_I/I by S/B where S is the source counting rate (source flux times mean area). This means we have effectively ignored corrections due to changing area as the detector passes over the source.

Based on the results of Figure 3, we divide the sources into 3 groups: 1) Those with $\sigma_I/B > 2\%$, 2) Those with $1.5\% \leq \sigma_I/B < 2\%$ and 3) those with $\sigma_I/B \leq 1.5\%$. Sky fluctuations cannot account for the variability seen for the 3 sources in group 1, whereas any variability seen in group 3 can be totally due to sky noise. Sources in group 2 are suspect and need further checks. In the next section we will consider the sources in groups 1 and 2 in greater detail

B. Light Curves

The most variable source was NGC 6814 (Figure 4). As was discussed before in Tennant et al. (1981) this source is highly variable and shows factor of two changes in flux on all time scales down to a few minutes. Table 1 shows β maintains a value near 43% for all the bin sizes considered up to 90 min. Using the published light curve from the Einstein Observatory Imaging Proportional Counter (IPC) observation of NGC 6814 (Tananbaum 1980) we find that $\beta \sim 21\%$ for a 3 hour bin size. This could indicate that either the dominant source of variance has a time scale of hours or that β decreased perhaps due to a decrease in flux between the HEAO-1 A2 and the IPC observations.

In Figure 5 we illustrate the difficulties in determining the time scale for a poorly sampled observation. The light curve is for our most variable observation of NGC 4151. In the top panel we fit all 6 points to a straight line and calculate a χ^2 of 11.12 for 4 degrees of freedom (dof) which is an unacceptable fit to the data. (This compares to $\chi^2 = 39.80$ for 5 dof calculated assuming the source was constant). In the second panel we have tried a model of a step function. For this case $\chi^2 = 5.39$ for 4 dof which is acceptable. Although it appears (to the eye at least) that the transition occurred over the 3 bins nearest where we located the step we point out that a small systematic deviation lasting 45 min could easily be introduced by a spacecraft orbital effect. In the 3rd panel we have again fitted a straight line to the data but in this case have thrown out the first point. For the third case $\chi^2 = 4.76$ for 3 dof. If the source continued to brighten at the rate indicated in the 3rd panel then it would double its intensity in 12 hours. Thus statistically we cannot distinguish between a 12% flux increase on a time scale of 15 min or the start of a 12 hour flare. We prefer the latter interpretation since it is consistent with previous observations of variability from NGC 4151 (Mushotzky et al. 1978; Lawrence 1980). This ambiguity as to the correct model is not resolved as one goes to shorter bin sizes, for this case at least, since the smaller bin size generates no new information.

The third most variable source is Cen A (Fig. 4). We note that HEAO-1 scanning data for Cen A show it to be slightly extended, presumably due to weak nearby sources. Marshall and Clark (1981) have reported a nearby source which will appear in our field of view. This source confusion can explain most of the observed variability. Notice that there is no indication of a linear charge over the 12 hour observation.

We now consider the sources with only weak evidence for intrinsic changes. First consider the light curve for H1649-595 in Figure 4 (H1649-595 was tentatively identified with NGC 6221 by Marshall et al. 1979). This light curve clearly shows that most of the excess variance is due to short duration "flares" near the end of the observation. For this source the three high points are due to a bright confusing source. This was clear when we noticed the source "flared" only when the detector was looking at a certain region of the sky. Since all light curves were looked at by eye, we know that no other source showed such flare like events. We have included H1649-595 in our sample as a warning that "statistically real" variability could have many causes.

Both NGC 3227 and MCG 5-23-16 showed evidence for a linear increase in flux. If such a rate increase continued then the source flux would double in 10 hours for NGC 3227 and 28 hours for MCG 5-23-16. Although the "time required to double the source flux" is not a measure of source "size" it is still a very useful time scale. For example, it can be applied to the Fabian and Rees relation (1979).

Finally, we come to the MCG 8-11-11 observation shown in the center panel of Figure 4. In this figure we see small peaks near 2.1, 3.9 and 5.5 hours. Since these points are ~ 1.5 hour apart, i.e. one spacecraft orbit, we suspect that these are not real events. A σ_I/B of ~ 1.6% confirms that the variability seen can be due to confusion noise. If one ignores the short term variability then a weak linear increase is seen which will double the source flux in a few days. We are unable to judge the reality of such a trend.

It is interesting to note that all the variable objects in our sample, NGC 3227, NGC 4151, NGC 6814 and MCG 5-23-16 are low luminosity objects with $L_X < 3 \times 10^{43}$ erg/sec. This agrees with the HEAO-1 longer time scale data (Mushotzky et al. 1982) which show that lower luminosity sources have a greater probability of being variable. In addition, with the exception of NGC 6814, the observed variability is consistant with a time scale of about one day. This result agrees with the Ariel 5 observation (Marshall, Warwick and Pounds 1981) that many sources show a one day time scale.

Variability on longer time scales will be reported by Mushotzky et al. (1982). However, we can compare the count rate for different pointed observations of the same source to obtain some information about longer time scales. We find that Cen A and NGC 4151 show large changes over 6 months. MK 509, observed four times in two weeks, shows a large amplitude charge. This was reported by Dower et al. (1980) using the HEAO-1 A3 data. Our data for days 657 to 666 show that the time required for $\Delta L = \langle L \rangle$ is 22 days. Thus we confirm the general nature of the variability reported by Dower et al. but indicate a slightly longer time scale.

V. DISCUSSION

Our observations lead us to conclude that the active galaxies in our sample do not vary on time scales ranging from minutes up to a few hours (upper limits from Table I) with $\sigma_I/I > .1$. In our sample only NGC 6814 showed evidence of variability on time scales of less than 10^4 sec. NGC 4151, the source with the second largest value of σ_I, had a β of less than one-eighth the value for NGC 6814. To our knowledge the only other active galaxy which clearly varies on a time scale of less than 10^4 sec is NGC 4051 (Marshall et al. 1981). In this section we try to reconcile the rapid variability observed from NGC 6814 and NGC 4051 with the lack of similar variability from other galaxies. Although we will consider ways that NGC 6814 is similar to other objects, we note that it could be quite different.

A. A New Class of Active Galaxies?

In this section we will consider NGC 6814 and NGC 4051 together and search for any characteristic that sets them apart from other active galaxies. Rieke (1978) found both of these objects had low, but not unusually low, IR luminosities. When he compared his measurements with those from Stein and Weedman (1976) the two objects that differed the most were NGC 4051 and NGC 6814, although Rieke points out that Stein and Weedman's value for NGC 6814 was probably in error. The difference may be considered as weak evidence for IR variability. More recently, Glass (1979), reporting on IR observations of active southern galaxies, notes that from an IR point of view NGC 6814 (and NGC 3783?) are only marginally Seyfert like.

Concerning optical correlations Yee (1980) reports on the very strong correlation between the luminosity in $H\beta$ and the "nonthermal" luminosities for quasars and both broad and narrow line active galaxies. NGC 6814, NGC 4051 and NGC 3227 lie near each other on the correlation but are a factor of 50 weaker than the next strongest Seyfert I galaxy in Yee's sample. Lawrence and Elvis (1981) have shown that the X-ray flux correlates with various optical and IR parameters for most objects. However, NGC 6814 and NGC 4051 are under luminous in [OIII], 3.5μ and 10μ flux relative their X-ray luminosities compared to the sample as a whole.

We speculate that these correlations are consistant with the idea that the X-ray emission began only a short time ($\sim$ 100 yrs) ago for these objects. The probability of seeing one object in about 40 in the process of turning on depends greatly on the totally unknown X-ray lifetime of these objects. Consider the following possibility. After the X-ray source turns on, it will take some time $\tau = R/c$ to illuminate the entire broad line region. This will be the turn on time. The clouds quickly heat up and accelerate to $v/c \sim 1/50$ and proceed to escape from the nuclear region. The escape time will be 50τ. After the clouds escape both the X-ray source and the broad lines turn off. Thus one expects to see one object in $\sim$ 50 in the process of turning on, which is consistant with our interpretation. Of course, if this is true then it implies that an active nucleus has gone through many on-off cycles in the history of the galaxy.

If one turns on an X-ray source in an originally "normal" nucleus then one expects first to detect the effects on material closest to the nucleus. Since the broad line region is often less than one pc in size, an external observer would see the entire region illuminated in only a few years. However, the narrow line region which is 100-1000 pcs across will only be partially illuminated for "new" objects. Thermal reradiation from dust exterior to the nucleus should turn on with the narrow line region. In this picture Seyfert II galaxies represent the class which is turning off. Thus a large faction of the observed differences in Seyfert galaxies would represent different snapshots of a single process. However tempting such a model is we note it does have problems. Dust near the nucleus will be at the highest temperature and will be observed to turn on first. This is contrary to observations in that NGC 6814 does have 10μ emission (Rieke 1978) indicating a cool temperature and NGC 1068 (a Seyfert II) has an IR spectra requiring a dust temperature of ~ 1000 K (Jones et al. 1977).

B. Inverse Compton Reflection

In the inverse Compton reflection model, low energy (soft) photons enter a region of energetic electrons. The soft photons inverse Compton scatter from the electrons to emerge from the cloud as X-rays. In this section, we will examine the inverse Compton reflection process (Lightman and Rybicki 1980) and find a constraint on the temperature of the soft photon source. We will make no assumptions about the electron population i.e., the distribution can be either thermal or non-thermal. We will assume that the X-ray emitting plasma is quite small and stable. By stable we mean that any variability seen is due to variations in the soft photon source and not due to changes in the plasma itself. Tennant et al. (1981) using the results of Lightman and Rybicki (1979) pointed out that the lack of spectral change during the intensity variations observed in NGC 6814 is consistent with this interpretation. Thus the lack of rapid variability in most sources could be explained by the growth of another "stronger" but more constant source of soft photons. If the X-ray source is slowly heating up its environment as mentioned in the last section then thermal re-radiation could be the new, constant, strong source of soft photons. This is consistent with the observed deficient IR flux for the rapidly varying galaxies.

We will now find the minimum temperature that a thermal source can have and still provide enough photons (for Comptonization) to generate the observed spectrum. If the soft photons are at a temperature of kT then the observed power law will extend from ~ 3 kT out to energies determined by the temperature of the scattering cloud. For the case of NGC 6814 the total number of photons radiated in the Comptonized spectrum is given by

$$N_c = 4.7 \times 10^{-3}\, 4\pi\, d^2 \int_{3\,\mathrm{kT}}^{10\,\mathrm{keV}} E^{-1.7}\, dE \qquad (4)$$

which corresponds to $1.2 \times 10^{52} \frac{\mathrm{ph}}{\mathrm{sec}} \left(\frac{\mathrm{kT}}{\mathrm{IeV}}\right)^{-0.7}$ at a distance d of 16 Mpc. The number of black body photons impinging onto the X-ray region is given by

$$N_{BB} < 4.5 \times 10^{49}\, r_{100}^2 \frac{\mathrm{ph}}{\mathrm{sec}} \left(\frac{\mathrm{kT}}{\mathrm{TeV}}\right)^3 \qquad (5)$$

where r_{100} is the radius of the X-ray emitting region in units of 100 lt sec. N_{BB} is maximum when the dilution factor is equal to unity. Since for Compton scattering photon number is conserved, we set $N_C = N_{BB}$ and find that

$$kT \geq 4.5\ r_{100}^{-1/2}\ \mathrm{eV}.$$

If $r_{100} < 1$ then we find the thermal source must have $kT > 4.5$ eV (52,000 K). Dust grains at this temperature would quickly vaporize. This leads us to conclude that thermal radiation from dust cannot provide enough photons to generate the observed spectrum for a small X-ray source. This problem is serious for NGC 6814 where the "hot spots" which provide the soft photons must be small and few in number in order to account for the rapid, large amplitude variability seen. If these spots reside outside the X-ray region then the dilution factor must be very small and hence $kT \gg 4.5$ eV.

C. Source Size

To summarize, if the source of soft photons is thermal in nature and if some of the optical and/or IR emission comes from the X-ray plasma directly, then the X-ray cloud must have $r_{100} \gg 1$. Since there appears to be some correlation between 3.5μ IR emission and X-ray flux for most active galaxies (Lawrence and Elvis 1981) and since a large source size is consistent with the absence of rapid X-ray variability reported here, we will consider the possibility of large X-ray regions. In order for 1000K blackbody photons to be the soft photon source we find that $r_{100} > 2700$ (= 3 lt days). This size is consistent with previous observations of variability (Marshall, Warwick and Pounds 1981). An X-ray plasma this large could be generated in one of two ways in the black hole accretion picture. Either the central object is large, hence very massive, or else the X-rays come from a large region not directly related to the central object.

If the X-rays come from a region only ~ 10 gravitational radii from the central object and if the general lack of variability on time scales of less than one day tells us anything about the size of the region then the central object must have a mass of 10^9 M_0's or greater. Pounds (1979) speculated that all active galaxies contained a 10^9 M_0 central object. The Eddington limit for such an object is 10^{47} erg/sec which is much greater than the luminosity of any object in our sample. Of course, if most active galaxies contain a 10^9 M_0 object then one is forced to explain why NGC 6814 is so small. It is possible that most active galaxies contain dead quasars (Lynden-Bell 1969) whereas objects like NGC 6814 might never have gone through a "quasar like" phase.

If the X-ray plasma is not confined to the central object then it could fill a large volume of space. In this picture electrons are heated via some unknown mechanism, perhaps in a small volume and then proceed to fill a volume of space about one light day across. This may occur in a two temperature disk model (Shapiro, Lightman and Eardley 1976). Since the virial temperature of the protons is much higher than the corresponding electron temperature an accretion disk can have two temperatures. If the electrons are not effectively cooled then interactions with protons can heat them to temperatures greatly exceeding their virial temperatures. Lightman (1982), considering the possibility of relativistic electron plasmas, listed several non-gravitational ways to confine the electrons. Since it is notoriously difficult to confine plasmas via electromagnetic forces, it is entirely possible that the central object is boiling off some matter. Thus the X-ray emission can come from two components, the region near the black hole and the extended volume.

To further consider a two component model for the X-ray source let us assume that the total power produced by a galactic nucleus comes out in two forms, first the immediate production of X-rays L_i, and some initially unobserved power P. The latter could be in the form of relativistic electrons as mentioned above or in γ rays as in the Penrose photoproduction model (Leiter 1980). P will slowly fill a reservoir with energetic electrons. When steady state is reached, the luminosity of the reservoir will be $\langle P \rangle$. Therefore, the total X-ray luminosity L_X will be

$$L_X = L_i + \alpha \langle P \rangle = L_i + r \langle L_i \rangle$$

where α is the fraction of the reservoir's luminosity which comes out as X-rays and r is $\alpha \langle P \rangle / \langle L_i \rangle$. Below we will assume r is constant and that $\alpha \sim 1$.

Since only L_i will show rapid variability let us consider what happens to β when one adds a variable source to a source of constant intensity I_0. If we assume that the intensities of the variable component are uniformly distributed between 0 and ΔI then β for the sum is given by

$$\beta \equiv \sigma_I / I = \Delta I / (\sqrt{3}\ (2\ I_0 + \Delta I)). \qquad (6)$$

We will now assume that the reservoir does not vary on the time scales we have sampled and also that the X-rays produced near the central object are highly variable. If we set $I_0 = r \langle L_i \rangle$ (the luminosity of the reservoir) and $\Delta I = 2 \langle L_i \rangle$ (the range of luminosities for immediate X-ray production) then

$$\beta = \frac{1}{\sqrt{3}\ (1+r)}. \qquad (7)$$

We define F to be the fraction of the total X-ray flux coming from the compact-variable region which is given by $1/(1+r) = \sqrt{3}\quad F$.

We can check the consistency of this model by assuming that $F = 75\%$ and that the average flux is 4 for NGC 6814. Thus, if the assumption of a uniform distribution of intensities is correct, we would expect to see the source vary from ~ 1 to ~ 7. The NGC 6814 flux shown in Figure 4 varies from ~ 2 to ~ 7 cts/cm^2-k sec which is in rough agreement with our model.

Since our upper limits typically lie in the range of 10% we find that F is typically less than 17%. For NGC 4151 which has a $\beta \lesssim 6\%$ we find that $F \lesssim 10\%$. Thus the constant component would have to grow by a factor of 10 (relative to the variable component) in order for β to decline from the NGC 6814 value to the level observed for NGC 4151. One possibility is that NGC 6814 has not filled its reservoir and thus has not come to steady state. This is unlikely since it implies that when steady state is reached the luminosity will be 10 times what it is now. As shown in Tennant et al. (1981) such a high total luminosity, if it were variable, would clearly violate the Fabian and Rees relation (1979). However it is unclear as to whether the Fabian and Rees relation applies in this case since we are talking about a steady state condition. If the X-rays from the variable component pass through the reservoir, electron scattering could reduce the amplitude of variability. If the electrons have the correct power law distribution, scattering will not greatly alter the spectrum. One could also argue that NGC 6814 does not have a reservoir for some unknown reason or that the X-ray production efficiency α for the reservoir is low.

D. Shot Noise

In the Guilbert, Ross and Fabian (1982) model a cloud is heated via some unknown mechanism and then allowed to cool via inverse Comptonization. Since the cooling times are very short the observed X-ray spectrum is a time average. Their calculated "averaged" spectrum is in good agreement with observations of the X-ray spectra of active galaxies. However, if the X-ray source is powered by discrete events, these events should give rise to low amplitude variability. To illustrate we apply the shot noise model. In this model λ events per time interval each rise to amplitude h and then exponentially decay away with time scale τ. Thus using $I = \lambda h \tau$ and $\sigma_I^2 = \lambda h^2 \tau/2$ we construct

$$\beta = (2/\lambda\tau)^{1/2}.$$

We set $N = \lambda\tau$ which represents the number of "simultaneous" events taking place. If we assume that τ is longer than the smallest bin size we used (see Sutherland, Weisskopf, and Kahn 1978 Appendix A, to see how σ_I^2 is a function of bin size) and that λ is greater than one shot per day, then we can use β from Table 1. For NGC 6814 N ~ 10 which says that at any one time on the average 10 clouds dominate most of the X-ray flux. A more typical value of β near 10% implies that N ~ 200, and for Cen A, N is greater than 1000. Since Cen A, NGC 4151 and NGC 6814 all have roughly the same luminosity, accounting for the lack of rapid variability in Cen A and NGC 4151 by increasing the number of shots only works if the shots become <u>much</u> more numerous and as a result each event much less luminous.

One way to reconcile the Guilbert, Ross and Fabian model with the lack of variability is to assume that the heating and cooling are taking place in a continuous manner. This argues for a <u>stable</u> accretion flow.

E. Stabilized Accretion Flow

Here we point out that a lack of variability can be due to dynamic stability. It is clear from our observations of Cen A that there are periods when this highly variable source is quite stable. For example, if the source was in the process of doubling its flux in N days, we can apply equation 3 and find, in a 12 hour observation, that $\beta = 1/(2N\sqrt{12})$. If the observed value of β near 2% was mainly due to a linear trend then the doubling time must be 7 days (or longer). Thus periods of stability are observed in addition to the variability previously reported in the literature.

It is possible that flares could be created whenever a cloud is fed into the central engine. If NGC 6814 is young then there may be many clouds close to the central engine. As the environment heats up the clouds would disperse and the accretion flow becomes a uniform stream of gas. Cowie, Ostriker and Stark (1978) showed that objects radiating with $L \gtrsim 1\%$ of the Eddington luminosity will be highly variable and that less luminous objects will be more stable. However, their model fails to generate the rapid time scale observed for NGC 6814. They assumed that the central object was in a homogenous gas and the shortest time scale they obtained was related to the sound travel time across the sonic radius. Faster time scales may require the accretion of clouds. Although the idea of lumpy vs smooth flow is interesting, an honest treatment of the problem requires detailed work beyond the scope of this paper.

VI. CONCLUSIONS

HEAO-1 observations of 38 active galactic nuclei have shown that rapid X-ray variability is a rare occurrence. Of the objects in our sample only NGC 6814 showed significant variability on time scales less than 10^4 seconds. Three other objects, all low luminosity Seyfert galaxies: NGC 4151, NGC 3227 and MCG 5-23-16, showed variations consistent with doubling times of ~ 1 day. Our upper limits on variability correspond to roughly $\sigma_I/I < 10\%$ on time scales from 300 to 10^4 sec and $\sigma_I/I < 20\%$ on timescales from 5 to 300 sec. For the brightest objects in our sample $\sigma_I/I < 5\%$ and for the weakest $\sigma_I/I < 20\%$.

We discuss the constraints these observations place on scenarios of X-ray production in active galactic nuclei. If these sources consist of two components, one highly variable and one quiescent then the ratio of the quiescent to variable flux is typically greater than 10. If the X-ray emission is due to inverse-Compton scattering of a thermal ($\sim$ 1000K) source of soft photons we find that the typical X-ray emitting region must be larger than 3 light days.

The general lack of variability on short time scales indicates that 1) the X-ray region is typically a light day or more across <u>or</u> 2) the process producing X-ray radiation is extremely stable. If the X-ray region is large then we can infer that either the central object has a mass of $\gtrsim 10^9 M_0$ (implying that the luminosity is typically $< 10^{-3}$ of the Eddington limit) or the X-ray emitting plasma is not gravitationally confined to a few Schwarzschild radii. Our present data do not allow us to discriminate among these possibilities. We also speculate that the difference between the average object and the two objects that show rapid variability, NGC 6814 (Tennant et al. 1981) and NGC 4051 (Marshall et al. 1981) (but see Matilsky, Shrader and Tananbaum 1982) is because these two are in a sense, "newer" objects than the typical Seyfert. That is, many of their properties can be explained if their X-ray emission began recently (t < 100 years).

ACKNOWLEDGMENTS

We thank the HEAO-1 scanning modulation collimator experiment and data reduction and analysis team at CFA and MIT for providing the A3 aspect information. In particular we thank M. Conroy and D. Lengyel-Frey. We also thank E. Boldt, J. Swank and R. Shafer for interesting discussions.

Appendix A

An Expression for σ_I

The value of χ^2 that one calculates is related not only to intrinsic source variability (real or upper limits) but also to many experimental parameters such as the number of photons collected and the amount of background. therefore, we have developed a simple expression which will relate the observed value of χ^2 to a measure of the "true" source variability.

For most of the sources we observed the background contributed more counts than the source. This means that for the smallest bin size of 5.12 sec we had more than 50 total counts (source and background) per bin. This large rate implies that the statistical errors are likely to be Gaussian and thus we can estimate the total variance with

$$\sigma^2 = \frac{\sum_j W_j \, (x_j - \langle x \rangle)^2}{\sum_j W_j} = \frac{\chi^2}{\sum_j W_j} \tag{A1}$$

where $W_j = 1/\sigma_j^2$ and we have used the definition of χ^2. Since our background rate is extremely stable we will assume the total variance has two components, one due to photon noise σ_ρ^2 and another due to source variability σ_I^2. Substituting into equation A1 and solving for σ_I^2

$$\sigma_I^2 = \sigma_\rho^2 \left(\frac{\chi^2}{\sigma_\rho^2 \sum_j W_j} - 1 \right) \tag{A2}$$

The statistical errors are based on the total number of counts seen in that data bin, thus we estimate

$$\sigma_\rho^{-2} = \frac{1}{N} \sum_j W_j \tag{A3}$$

which when substituted into Equation A2 gives

$$\sigma_I^{\ 2} = \left(\frac{N}{\sum_j W_j}\right) (\chi_N^2 - 1). \qquad \text{(A4)}$$

For the case of no background and no data gaps one can set $\sigma_\rho^{\ 2}$ equal to the mean source count rate and then equation A2 reduces to the expression used by Forman, Jones and Tananbaum (1976). For observations with a large background one sets $\sigma_\rho^{\ 2}$ equal to the total (source plus background) count rate. The resulting equation was used by Parsignault and Grindley (1978).

ORIGINAL PAGE IS OF POOR QUALITY

TABLE 1

(1) OBJECT	(2) RA-DEC	(3) DATE	(4) LENGTH	(5) FLUX	(6) L	(7) σ/I	(8) σ/I	(9) σ/B
CEN A	1322-428	384.5	4	49.5	0.57	1.4	<0.7	<1.6
CEN A	1322-428	567.7	11	36.6	0.43	2.8	1.8	3.0
CYG A	1957+406	488.0	6	8.5	95	5.6	<3.3	<0.8
ESO 141-G55	1917-588	466.4	9	3.4	16	<8.1	<5.7	<0.8
H 1649-595	1648-591	629.7	9	4.2	0.28	11.3	10.0	1.9
IC 4329A	1346-301	573.8	6	5.1	4.1	9.7	4.6	1.1
MCG 2-58-22	2302-090	523.2	6	4.3	34	<6.0	<4.0	<0.6
MCG 5-23-16	0945-307	497.7	6	8.1	1.9	7.0	5.7	2.0
MCG 8-11-11	0551+464	643.7	9	3.5	5.1	9.1	9.8	1.6
MK 142	1022+519	699.4	6	1.6	11	<21.7	<13.6	<0.7
MK 279	1352+696	679.4	13	1.2	3.9	36.5	15.7	0.9
MK 279	1352+696	697.4	7	1.2	3.9	<18.4	<11.2	<0.7
MK 335	0003+199	553.8	13	1.1	2.4	31.2	18.3	0.6
MK 421	1057+385	513.1	9	1.8	6.0	26.9	11.6	0.8
MK 421	1057+385	704.4	7	1.2	4.0	<27.6	<17.4	<0.6
MK 464	1353+388	555.8	10	1.4	13	<14.4	<8.9	<0.6
MK 501	1652+398	616.8	6	2.7	10	<10.4	<6.6	<0.7
MK 509	2041-109	493.7	6	4.6	20	5.4	3.7	0.8
MK 509	2041-109	653.5	4	5.3	23	<6.8	<5.3	<1.3
MK 509	2041-109	657.4	18	5.4	24	<4.3	5.3	1.3
MK 509	2041-109	662.3	19	4.6	20	7.3	6.4	1.4
MK 509	2041-109	666.4	12	3.6	16	7.0	6.0	1.0
MK 590	0212-010	564.7	6	1.1	2.8	<19.8	<11.5	<0.6
M 82	0951+699	474.1	5	2.5	0.007	<7.4	<3.9	<0.5
NGC 526A	0121-353	526.8	6	2.1	2.4	17.3	<6.2	<0.9
NGC 931	0225+311	585.0	6	1.5	1.4	<18.7	<12.9	<0.7
NGC 2110	0549-075	647.6	5	5.0	0.87	<5.3	<3.3	<0.8
NGC 2992	0943-141	509.4	3	7.8	1.4	7.4	<2.5	<0.9
NGC 3227	1020+201	692.9	6	1.7	0.064	25.5	20.3	1.6
NGC 3783	1136-375	370.6	3	3.5	1.0	<8.4	<5.5	<0.9
NGC 3783	1136-375	554.8	13	3.1	0.89	14.7	8.7	1.2
NGC 4151	1208+397	340.5	3	10.1	0.38	4.7	3.4	1.5
NGC 4151	1208+397	524.1	3	19.3	0.73	5.8	6.5	5.7
NGC 4151	1208+397	532.1	4	22.8	0.86	<4.6	<4.2	<2.3
NGC 4151	1208+397	533.0	3	18.8	0.71	<2.8	<2.1	<1.8
NGC 5506	1410-030	574.0	6	5.0	0.64	6.0	6.1	1.5
NGC 5548	1415+254	566.9	6	5.7	5.4	<4.9	<3.1	<0.8
NGC 5548	1415+254	736.9	9	4.3	4.1	<5.4	<3.8	<0.8
NGC 6814	1940-104	483.0	7	4.1	0.40	43.6	43.3	8.4
NGC 7213	2206-474	511.4	6	4.2	0.49	<8.4	<5.8	<0.8
NGC 7469	2300+086	547.9	12	1.8	1.7	19.4	16.9	1.3
NGC 7582	2315-426	518.3	6	3.1	0.26	9.2	9.9	1.5
PKS 0548-322	0549-323	638.9	8	2.6	43	<10.1	<6.5	0.7
PKS 2151-304	2151-306	677.7	5	8.1	810	<5.2	5.1	1.6
2A 1219+305	1219+305	516.2	6	3.0	180	<8.5	<5.4	<0.8
3C 111	0415+379	611.2	9	3.9	29	<8.3	<6.4	<1.2
3C 120	0430+052	615.6	9	3.1	12	<7.2	<4.7	<0.7
3C 273	1226+023	533.9	6	9.4	800	4.8	3.3	1.5
3C 273	1226+023	546.4	6	8.5	720	<3.3	<2.3	<0.9
3C 273	1226+023	549.3	8	9.0	760	<3.4	<2.4	<1.0
3C 273	1226+023	551.2	10	8.7	740	<3.3	<2.4	<1.0
3C 382	1833+327	661.5	9	3.2	38	12.2	<6.1	<0.9
3C 390.3	1845+797	723.2	10	2.2	25	<14.1	<9.4	<0.8

NOTES:

(1) Alphabetic by source name

(2) RA(hours and mins) Dec(degrees and tenths)

(3) Beginning of observation, day of year 1977

(4) Length of observation in hours

(5) Cts/cm^2-ksec

(6) 2-20 Kev luminosity (H=75 km/sec/Mpc) assuming no absorption, units=10^{43} ergs/sec

(7) 328s bin size

(8) 86m bin size

(9) 86m bin size

REFERENCES

Abramowitz, M. and Stegun, I.A. 1970, Handbook of Mathematical Functions with Formulas, Graphs and Mathematical Tables (Washington: U.S. Government Printing Office), p. 966.

Baity et al., in preparation, 1982.

Barr et al. 1980, MNRAS 193, 549, 1977.

Boldt, E.A., Holt, S.S., Rothschild, R., and Serlemitsos, P. 1975, Proceedings of the Intl. Conf. on X-rays in Space 1, 69 (U. of Calgary, Calgary).

Cowie, L.L., Ostriker, J.P. and Stark, A.A. 1978, Ap. J. 226, 1041.

Delvaille, J.P., Epstein, A., Schnopper, H.W. 1978, Ap. J. (Letters) 219, L81.

Doi, K. 1980, Nature 287, 210.

Dower, R.G., Griffiths, R.E., Bradt, H.V., Doxsey, R.E. and Johnston, M.D. 1980, Ap. J. 235, 355.

Fabian, A.C. and Rees, M.J. 1979, in Proc. IAC/COSPAR Symposium on X-ray Astronomy, ed. W.A. Baity and L.E. Peterson (London: Pergamon Press), p. 381.

Forman, W., Jones, C., and Tananbaum, H. 1976, Ap. J. 208, 849.

Glass, I.S. 1979, MNRAS 186, 29p.

Guilbert, Ross and Fabian 1982, M.N.R.A.S. 199, 763.

Jones, T.W., Leung, C.M., Gould, R.J., and Stein, W.A. 1977, Ap. J. 212, 52.

Lawrence, A. 1980, MNRAS 192, 83.

Lawrence, A. and Elvis, M.S. 1982, in press.

Lawrence, A., Pye, P.J. and Elvis, M. 1977, MNRAS 181, 93p.

Leiter, D. 1980, Astr. Ap. 89, 370.

Lightman, A.P. and Rybicki, G.B. 1979, Ap. J. 232, 882.

Lightman, A.P. and Rybicki, G.B. 1980, Ap. J. 236, 928.

Lightman, A.P. 1982, Ap. J. 253, 842.

Lynden-Bell, D. 1969, Nature 223, 690.

Marshall, F.E., Becker, R.H., Holt, S.S. and Mushotzky, R.F. 1981, Bull. AAS 12, 796.

Marshall, F.E., Boldt, E.A., Holt, S.S., Mushotzky, R.F., Pravdo, S.H., Rothschild, R.E. and Serlemitsos, P.J. 1979, Ap. J. (Suppl) 40, 657.

Marshall, F.J. and Clark, G.W. 1981, Ap. J. 245, 840.

Marshall, N, Warwick, R.S. and Pounds, K.A. 1981, MNRAS 194, 987.

Matilsky, T., Schrader, C. and Tananbaum, H., preprint, 1981.

McIlwain, C.E. 1961, JGR 66, 3681.

Mushotzky, R.F., Holt, S.S., and Serlemitsos, P.J. 1978, Ap. J. (Letters) 225, L115.

Mushotzky et al. 1982, in preparation.

Parsignault, D.R. and Grindlay, J.E., 1978, Ap. J. 226, 486.

Pounds, K.A. 1979, Proc. R. Soc. Lond. A. 366, 375.

Rees, M.I., Begelman, M.C. and Blandford, R.D. 1981, 10th Texas Symposium on Relativistic Astrophysics, ed. R. Ramaty and F.E. Jones (New York: New York Academy of Sciences) p. 254.

Rieke, G.H. 1978, Ap. J. 226, 550.

Rothschild, R., Boldt, E., Holt, S., Serlemitsos, P., Garmire, G., Agrawal, P., Riegler, G., Bowyer, S., and Lampton, J. 1979, Space Science Instrumentation 4, 265.

Shapiro, S.L., Lightman, A.P. and Eardly, D.M. 1976, Ap. J. 204, 187.

Stein, W.A. and Weedman, D.W. 1976, Ap. J. 205, 44.

Sutherland, P.G., Weisskopf, M.C. and Kahn, S.M. 1978, Ap. J. 219, 1029.

Tennant, A.F., Mushotzky, R.F., Boldt, E.A. and Swank, J.H. 1981, Ap. J. 251, 15.

Winkler, P.E. and White, A.E. 1975, Ap. J. (Letters) 199, L139.

Yee, H.K.C. 1980, Ap. J. 241, 894.

FIGURE CAPTIONS

Figure 1 - Shows β, a measure of intrinsic source variability (eq. 2), vs source flux. The data was collected into ~ 5 min bins in order to construct this figure. The line is an estimate of the error introduced by source confusion (see text). The solid dots are positive detections of source variance while the bars are upper limits (see Table 1).

Figure 2 - Same as Figure 1 except now the bins are about one spacecraft orbit long.

Figure 3 top - A histogram of σ_I divided by the background counting rate for our observations of active galaxies. The hatched regions represent positive detections of variability whereas the white area above the hatched region represent the 90% confidence upper limit for the non-variable objects.

bottom - Same as top panel except in this case no HEAO-1 sources were in the field of view.

Figure 4 - A sample of 9 of our X-ray light curves. The top 6 panels represent the more variable objects in our sample whereas the bottom 3 represent typical light curves. In all cases a 20 min bin size was used to construct the light curves. The first number is σ_I/I and the number in parentheses is σ_I/B. Both σ_I/I and σ_I/B are constructed for the bin size given in the plot. The best fitting linear trend is indicated by a solid line for MCG 5-23-16 and NGC 3227.

Figure 5 - The most variable observation of NGC 4151 has been fitted to three models: (top) a straight line through all the points, (middle) a step function, and (bottom) a straight line through the last 5 points.

ORIGINAL PAGE IS
OF POOR QUALITY

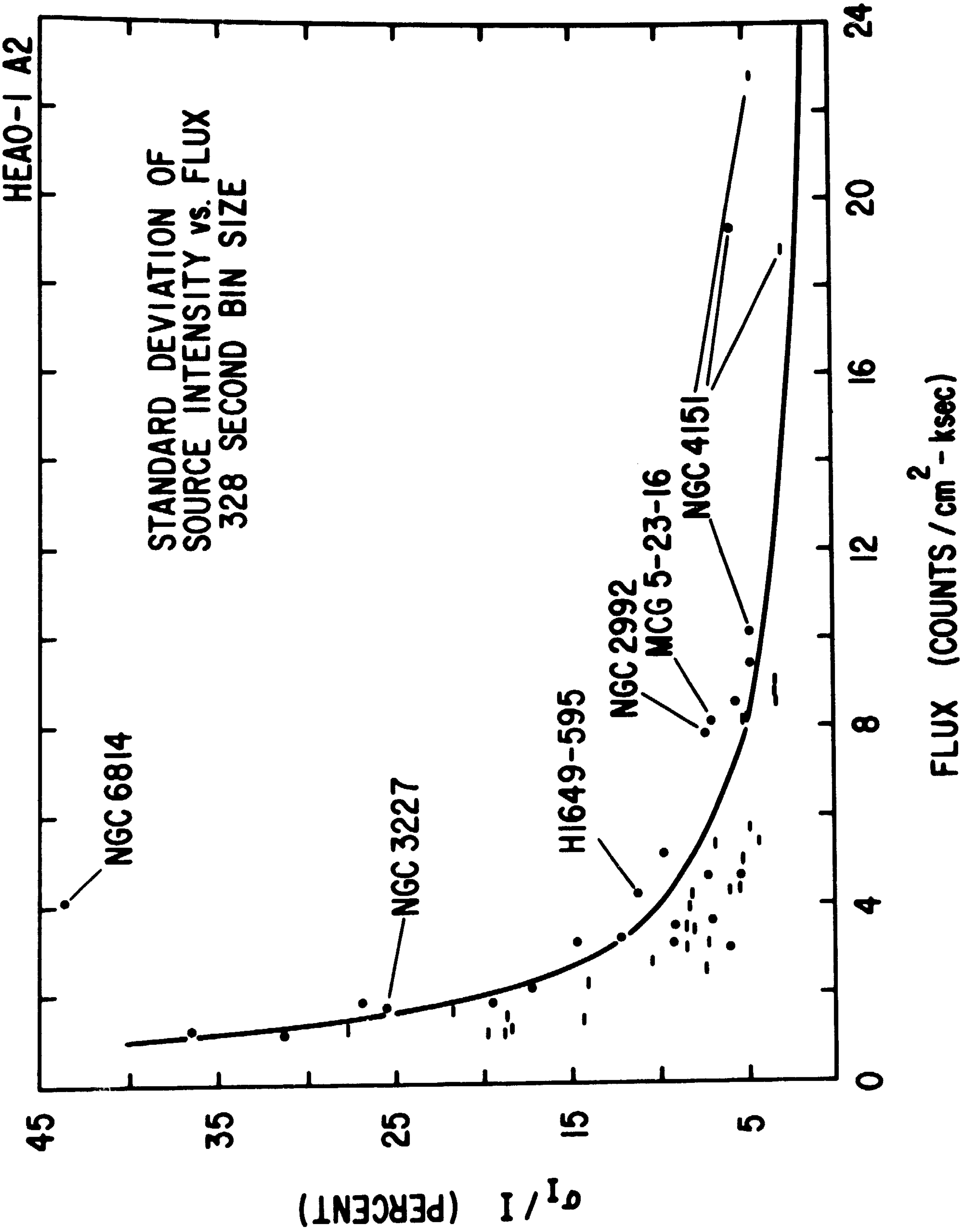

Figure 1

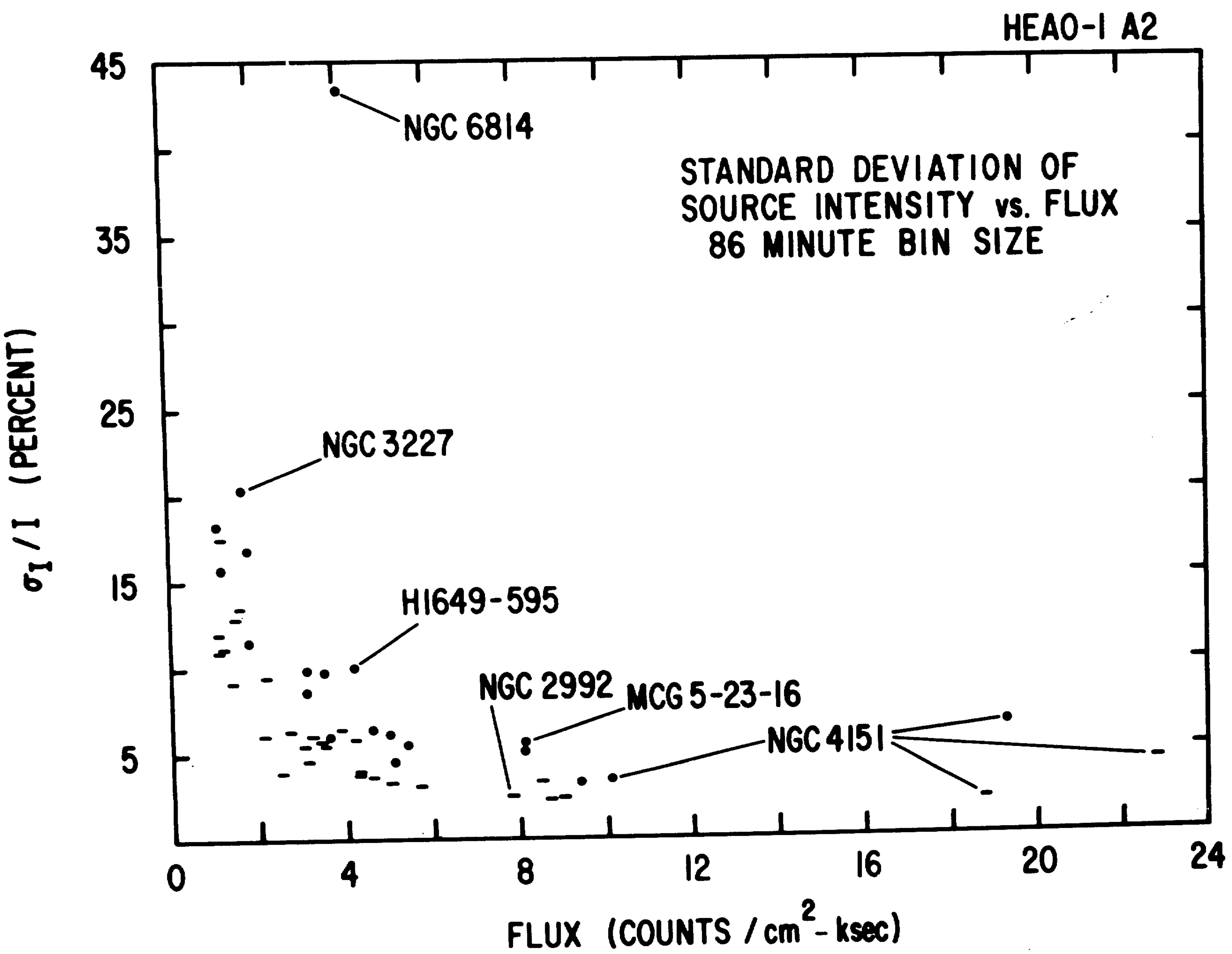
HEAO-I A2
STANDARD DEVIATION OF
SOURCE INTENSITY vs. FLUX
86 MINUTE BIN SIZE
NGC 6814
NGC 3227
H1649-595
NGC 2992
MCG 5-23-16
NGC 4151
45
35
25
15
5
0
4
8
12
16
20
24
σ_I / I (PERCENT)
FLUX (COUNTS / cm^2 - ksec)

Figure 2

HISTOGRAMS OF VARIABILITY

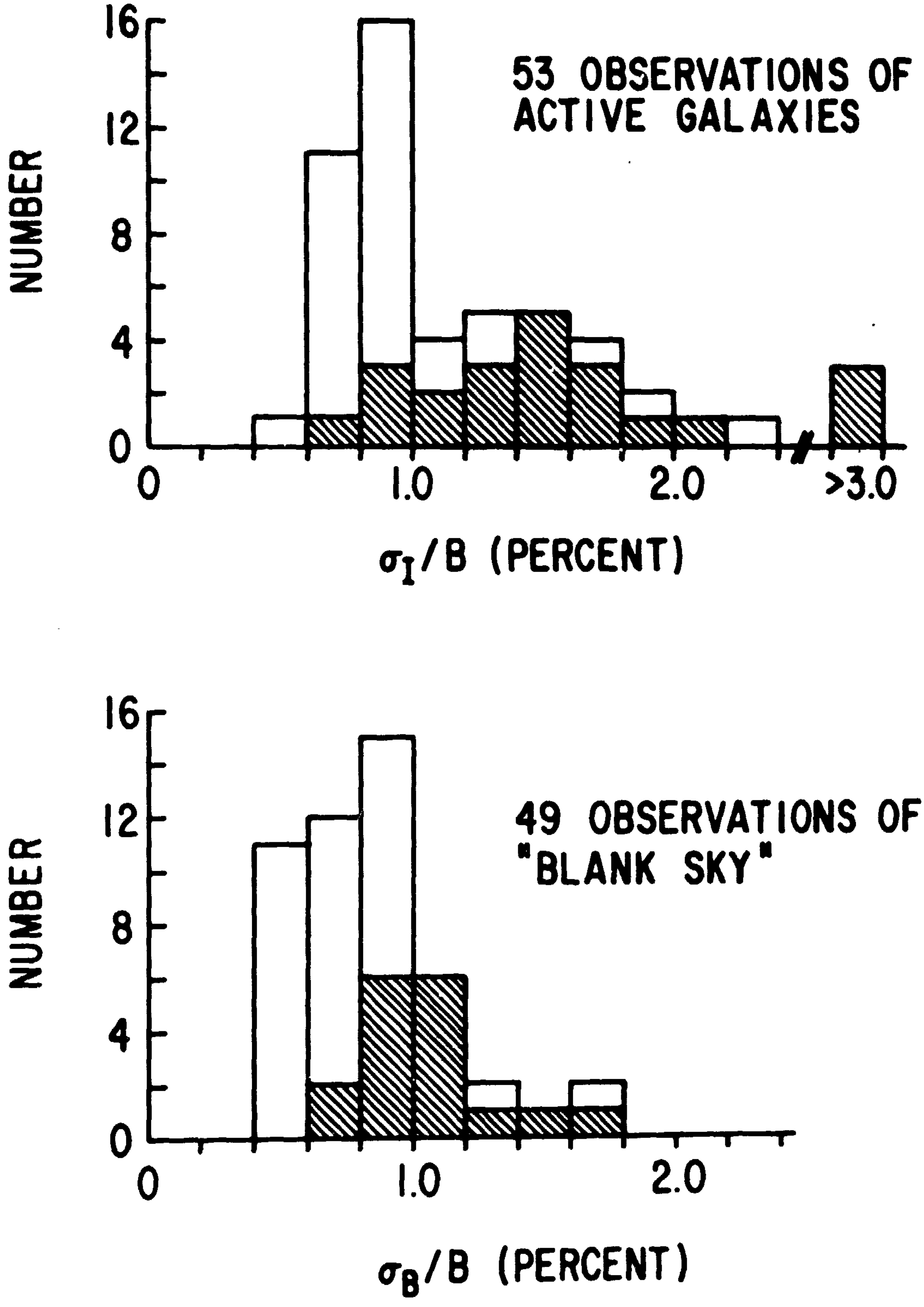

Figure 3

LIGHT CURVES FOR ACTIVE GALACTIC NUCLEI (HEAO-I A2)

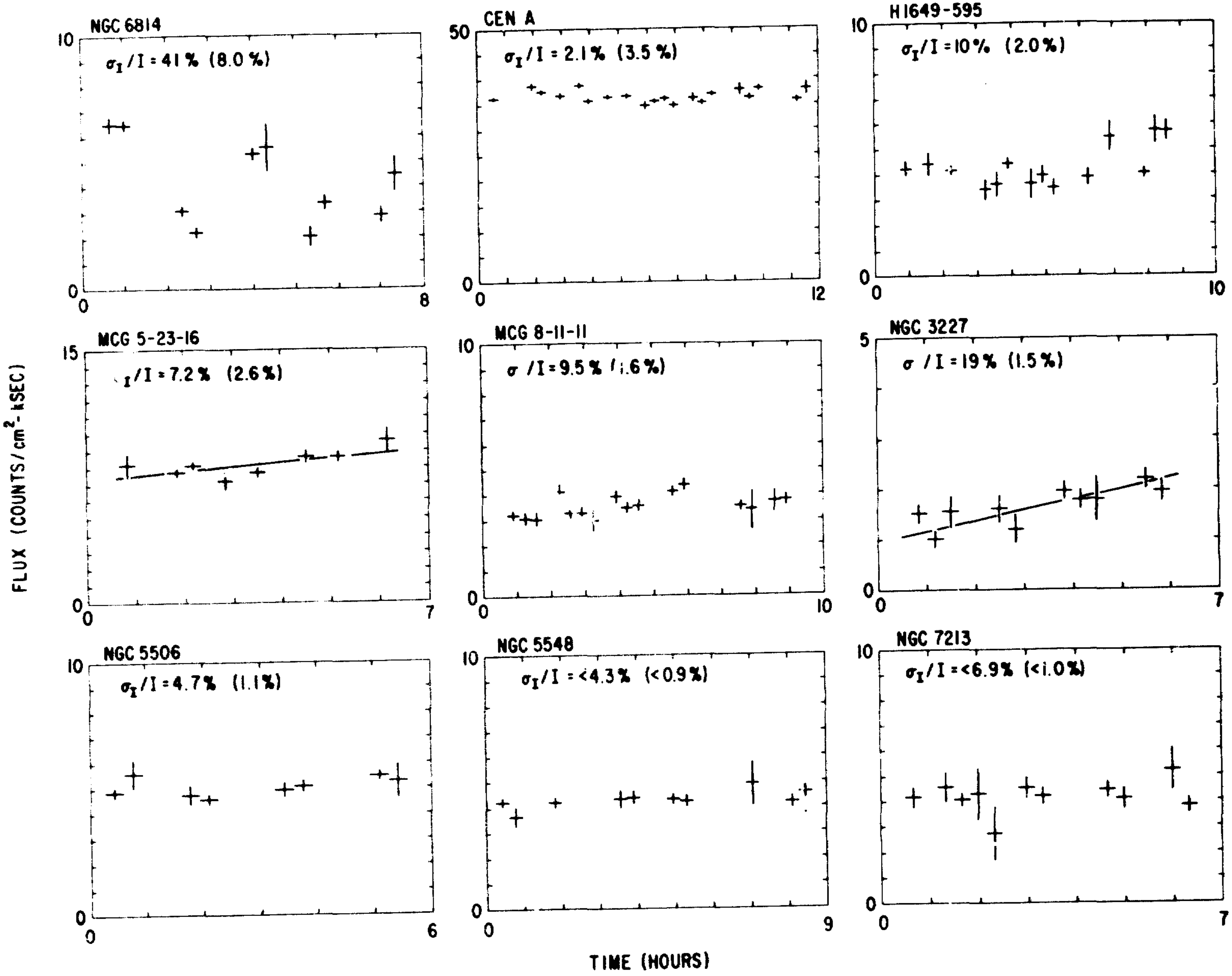

Figure 4

ORIGINAL PAGE IS
OF POOR QUALITY

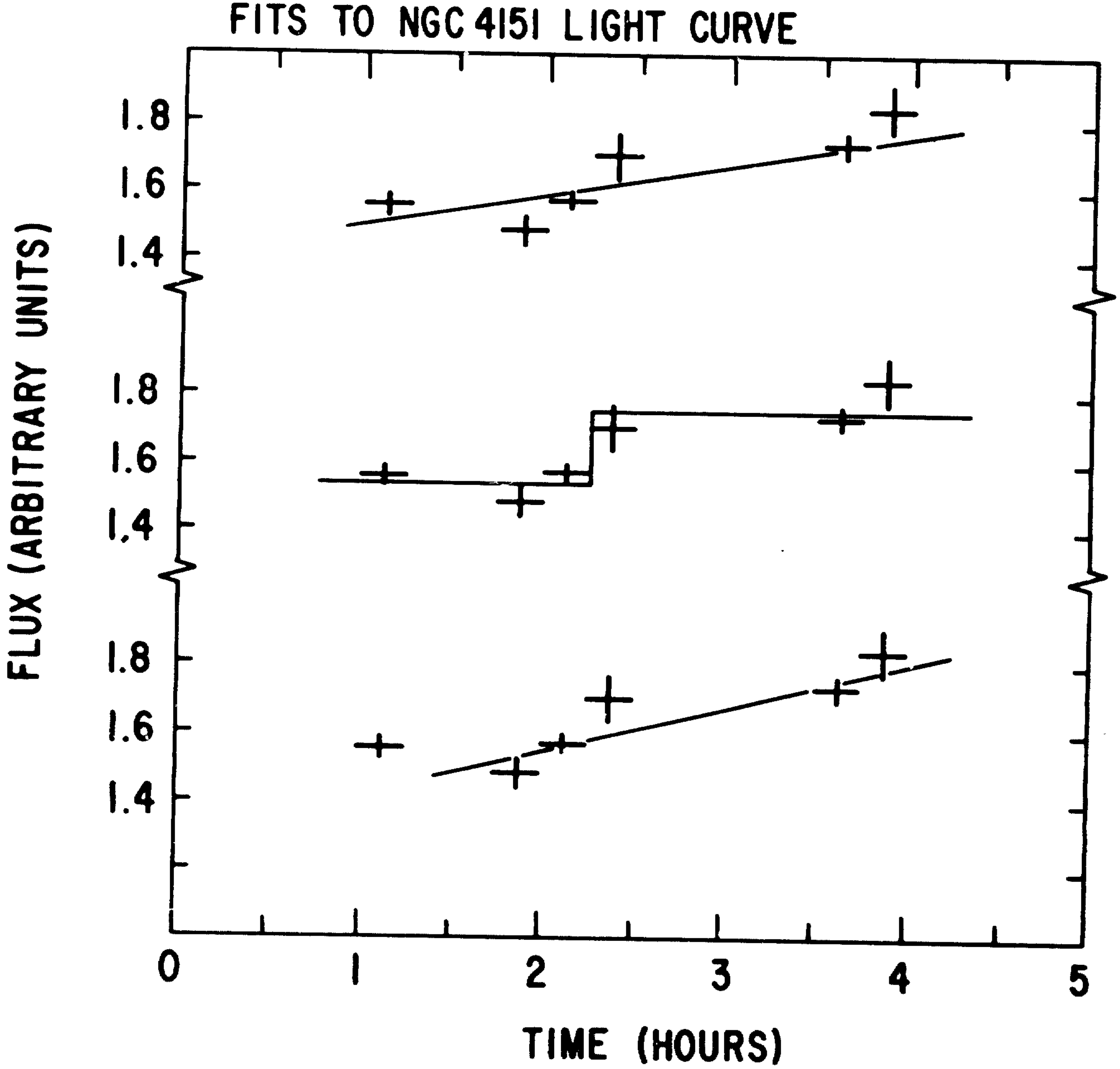
FITS TO NGC 4151 LIGHT CURVE
FLUX (ARBITRARY UNITS)
1.8
1.6
1.4
1.8
1.6
1.4
1.8
1.6
1.4
0
1
2
3
4
5
TIME (HOURS)

Figure 5

ADDRESS OF AUTHORS

RICHARD F. MUSHOTZKY and ALLYN F. TENNANT, Code 661, Laboratory for High Energy Astrophysics, NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771