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Abstract

Strong variable X-ray emission from the nearby low luminosity Seyfert 1 galaxy NGC 4051 has been discovered during observations with the Imaging Proportional Counter (IPC) of the Einstein Observatory. During one 2304 second observation, the X-ray flux more than doubled in an approximately linear fashion, and a 70% increase for 150 seconds was seen during another 968 second observation. We present evidence that the X-ray spectrum of NGC 4051 is unusually soft compared to Seyfert 1 galaxies or QSOs. The emission mechanism is probably not synchrotron or synchrotron self-Compton, but the emission can be plausibly explained by various black hole accretion models.

I. INTRODUCTION

Variability in the flux from active galaxies has the promise of being a very powerful tool for understanding their emission mechanism(s). Since current models have x-ray emission being generated at the compact central core of the active galaxy, it is plausible that the variability may be most rapid in the X-ray band. General constraints indicate that variability might be seen on time scales of $\sim 5\ L_{42}$ seconds in which L_{42} is the luminosity in units of 10^{42} erg s^{-1} (Fabian and Rees 1979). Variations on this time scale allow us to study structure on smaller scales than can be spatially resolved. Multi-frequency observations can test predictions of various models of the relation between emission at different wavelengths.

Despite the keen observational interest in the short characteristic times predicted, reports of rapid X-ray variability in active galaxies have been rare. Tananbaum et al. (1978) did present evidence for variability on a time scale of 730 seconds from the Seyfert 1 galaxy NGC 4151, but pointed out that each of the three most statistically significant events had less than 3σ confidence. Subsequent experiments with larger area and better signal to noise have not seen such rapid variability from NGC 4151 (cf. Tennant and Mushotzky 1982). Short term ($\sim$ 100s) fluctuations of high statistical significance were seen from the Seyfert 1 galaxy NGC 6814 by Tennant et al. (1981). However, Tennant and Mushotzky (1982) in a survey of 38 active galaxies found no other instances of rapid variability besides that from NGC 6814. Evidence for 200 second variability in the quasar 1525+227 has been recently presented by Matilsky, Shrader, and Tananbaum (1982) who suggest beaming effects may be necessary to explain the rapid changes in X-ray luminosity. Since observations of rapid variability are so rare, it is uncertain whether rapidly variable sources are fundamentally different than other sources.

II. OBSERVATIONS

Table 1 is a log of the six observations of NGC 4051 made using the IPC on the Einstein Observatory (Giacconi et al. 1979) and gives the observed mean counting rate (summing all IPC channels) for each observation. The χ^2 for a constant flux model is also listed. Since the background is about 0.01 s^{-1}, in all cases the background is very small compared to the source counting rate.

III. RESULTS

1. Variability

The observed variability in the counting rate for each of the six observations was compared to that expected for a constant source intensity. The data were binned in 51.2 s intervals for the first five observations; the final observation was binned into 99.8s intervals due to the reduced counting rate. As shown by the χ^2 listed in Table 1, a constant flux model was acceptable for all observations except No. 1 and No. 4.

The strongest evidence for variability is for observation No. 4; light curves of the counting rate and ratio of low energy rate to high energy rate in 99.8s intervals are shown in Figure 1. During this 2304s observation the counting rate increased in an approximately linear fashion from about 1 s^{-1} to about 2.5 s^{-1}. Since the probability of a χ^2 as large as 418.5 for a constant rate is less than 10^{-60}, such a large variation should not have occurred by chance even if we had examined every observation with the Einstein Observatory. We have ascertained that the IPC remained in its nominal mode throughout the observation. The background in the IPC away from the source remained constant during the observation and no variation was seen in other (weaker) sources in the field of view. The source was very near the center of the field of view and so the count rate could not be affected by the struts or edge effects. The detector gain does change, but gradually over several days. In addition the near constancy of the color ratio and of the background during the observation does not indicate any large change in detector response. Therefore we conclude the change in count rate is due to a change in the flux from NGC 4051.

The rate of change in the flux was estimated by making a linear fit to the count rate. Although the fit was unacceptable statistically, the slope of 0.76 s^{-1} $(1000s)^{-1}$ is indicative of the trend of the data. This corresponds to a 0.5 - 4.5 keV luminosity change of 2.5×10^{41} erg s^{-1} $(1000s)^{-1}$.

The evidence for variability during the first observation (Fig. 2) is quite strong but not so compelling. The probability of a χ^2 as large as observed for a constant source is 2×10^{-5} (or 4.1 σ confidence) and modelling a simple linear increase does not improve the fit. The poor fit is due to the final three data points; without them χ^2 is 24.3 for 15 degrees of freedom and only 15.1 for a linear fit with a slope of -0.37 s^{-1} $(1000s)^{-1}$. The average flux during the last 154s is 72% higher than during the remainder of the observation, but no significant change is found in the color ratio.

2. Spectrum

Accurate spectral determinations with the IPC are difficult due to the limited bandpass, limited spectral resolution, and uncertainty in the gain (although reprocessing may eventually reduce this uncertainty). Spectral parameters are derived only for the fourth observation (in which the most photons were detected). Since there is only marginal (< 95% confidence) evidence for variability in the color ratio during this observation (Figure 1), a time-averaged spectrum was determined. Following Zamorani et al. (1981) we compute a hardness ratio of 1.2 - 3.0 keV counts to 0.5 - 1.2 keV counts. For the most likely gain parameter of 19, the hardness ratio is 0.63 ± .03; in the unlikely event the gain parameter was as low as 17, the hardness ratio is 0.78 ± .04. Only 2 of the 27 QSOs examined by Zamorani et al. had hardness ratios softer than 0.8. We are not aware of a similar survey of hardness ratios for Seyfert 1 galaxies. If a power law spectrum is assumed and a hydrogen column density of 3×10^{20} cm^{-2} (Tolbert 1971) adopted, the best fit photon spectral index Γ is 2.5 with a flux of 2.7×10^{-11} erg s^{-1} cm^{-2} in the 0.5 to 4.5 keV band or a luminosity of 5.2×10^{41} erg s^{-1} for H_0 of 55 km s^{-1} Mpc^{-1}. A gain parameter of 17 gives a Γ of 2.3. Simultaneous observations with the Monitor Proportional Counter (MPC) detected a weak source with a 2-6 keV flux of 0.94×10^{-11} ergs s^{-1} cm^{-2}. As shown in Figure 3, this flux lies above the extrapolated IPC spectrum unless $\Gamma \gtrsim 2.0$.

Seyfert 1 galaxies typically have spectral indices between 1.3 and 2.0 at energies greater than 2 keV (Mushotzky et al. 1980), and a similar result has been found in the 0.5 to 4.5 keV band (Petre et al. 1982) although exceptions are known (e.g. Pravdo et al. 1981). The observed hardness ratio indicates that NGC 4051's spectrum is also softer than typical for QSOs, which are in many ways similar to high luminosity Seyfert 1 galaxies (e.g. Kriss and Canizares 1982).

IV. DISCUSSION

a) Broad Band Spectrum

NGC 4051 is an optically bright Seyfert 1 whose most remarkable characteristic heretofore is being the nearest Seyfert galaxy (cz of 700 km s^{-1}) listed in the review by Weedman (1977). Its nucleus is one of the weakest known for an active galaxy. In Yee's (1980) survey of the optical continuum and emission line luminosity of active galaxies, only NGC 6814 had a weaker non-thermal continuum luminosity (L_{NT}) among Seyfert 1 galaxies. Yee found a strong correlation in active galaxies and quasars between L_{NT} and H_{β} and [OIII] luminosities, and NGC 4051 had appropriately weak line luminosities for its unusually weak L_{NT}. NGC 4051's 0.5 to 4.5 keV luminosity is also low compared to other Seyfert 1's and NELGs--in the survey of Lawrence and Elvis (1982) only the strongly absorbed NGC 4151, NGC 6814 and NGC 7582 have weaker soft X-ray luminosities.

The average non-thermal flux in the 3000 A to 9500 A is plotted in Figure 3 along with observations in other wavelengths (discussed below). Since Yee determined L_{NT} by subtracting a large, model-dependent stellar contribution from the observed flux from NGC 4051, no attempt has been made to deduce a spectral shape. Penston et al. (1974) deduced the nuclear component in several broad optical and infrared bands by comparing fluxes using different apertures. Penston et al. suggested that NGC 4051 was variable by about 0.2 magnitudes in the V band by comparing to other published observations. Similar size variations in the U band on a time scale of a day have been reported by Lyutyi (1977). If these variations are real, the variations of the nuclear region may be larger since even with a 10" aperture Yee (1980) found most of the optical flux to be due to stars.

As are most Seyfert 1 galaxies, NGC 4051 is a weak radio source. deBruyn and Wilson's (1976) survey lists the 1415 MHz flux as 0.021 Jy, but this is from an extended source and so is only an upper limit for the nucleus.

NGC 4051 has not been previously reported as an X-ray source. A weak source consistent with being NGC 4051 was detected during the first scan across this region with the HEAO-A2 hard X-ray detectors. Assuming the source to be at the position of NGC 4051, the R15 count rate (defined in Marshall et al. 1979) is 0.88 $s^{-1} \pm 0.41\ s^{-1}$ (90% confidence limits) during days 333 through 337 of 1977. For spectral indices of 1.5 and 2.5, this corresponds to

2 to 6 keV fluxes of 1.1 and 1.7 x 10^{-11} erg s^{-1} cm^{-2} respectively. Six months later the rate was 0.5 ± 0.5 s^{-1} (90% confidence). NGC 4051 is not in the HEAO-A2 Soft X-Ray Catalog (Nugent et al. 1983). A 2σ confidence upper limit is about 2.0 s^{-1} corresponding to a 0.44 to 2.8 keV flux of about 5 x 10^{-11} erg s^{-1} cm^{-2} for Γ of 2.5 (Nousek 1982) which is larger than the flux seen with the IPC.

b) Emission Mechanism

Numerous emission mechanisms, usually involving massive condensed central objects, have been proposed as the power source for Seyfert galaxies. Observations to date have been insufficient in general to select the correct model(s). With the usual assumptions, variability time scales constrain the size of the emitting regions. Since NGC 4051 varies substantially in $\lesssim$ 1000s, we use the ratio of the radius of the emitting region to 1000 light-seconds ($\equiv r_3$) as a parameter in the following.

The soft low energy X-ray spectrum and variability of NGC 4051 are characteristic of at least some BL Lac objects for which there are strong reasons to believe that a synchrotron self-Compton (SSC) model with relativistic beaming is correct (e.g. Urry and Mushotzky 1982; Worrall et al. 1982). The broad-band features of the spectrum of NGC 4051 shown in Figure 3 could be described as a synchrotron spectrum cutoff in radio by self absorption. However simple estimates of the radiative lifetime of the relativistic electrons assuming a uniform sphere and using the 0.5 to 4.5 keV photon density give a Compton lifetime of 7000 $r_3^2\ \gamma^{-1}$ s where γ is the relativistic factor for the electrons. For the electrons to live long enough to fill the emitting volume, γ must be less than about 6 r_3. This produces synchrotron photons of $\lesssim$ .003 $r_3^2\ B_4$ eV where B_4 is the magnetic field in units of 10^4 Gauss. Consequently, the synchrotron emission spectrum will turn over at energies less than the infrared band because the high energy electrons do not survive. Synchrotron self-Compton will not produce the X-rays either since the photon energy is boosted by only about γ^2. This lifetime problem can be avoided by invoking relativistic beaming as was done for BL Lac's. However the normal ratio of permitted line luminosity to L_{NT} found by Yee (1980) for NGC 4051 argues against relativistic beaming. The permitted line luminosity is reprocessed non-thermal continuum so if the continuum is beamed into a small solid angle toward the observer only a small part of the broad line region would be illuminated and the lines would be relatively weak. This is observed for BL Lac's which have at most very weak emission lines. Relativistic blast models (cf. Blanford and McKee 1977) may still be viable models.

Disk models for accretion onto massive black holes (Eardley et al. 1978) appear to be consistent with the observations. First we note that NGC 4051 may well be far from its Eddington limit luminosity L_{Ed}. The fastest time scale for variability is expected to be comparable to the light travel time across the most stable orbit in a Schwarzschild geometry or about 50s M_6 where M_6 is the black hole mass in units of 10^6 solar masses, while L_{Ed} is about 1.3 x 10^{44} erg s^{-1} M_6. Thus the variability time for NGC 4051 would limit its mass to about 20 M_6 r_3 corresponding to a L_{Ed} of 2.6 x 10^{45} r_3 erg s^{-1} or about 5000 r_3 times the observed soft X-ray luminosity. Examination of Figures 2 and 3 of Eardley et al. indicates the standard disk model with M_6 of about 0.01 and L/L_{Ed} of about 0.03 would have Γ of about 2 in the 0.5 keV band. The time scale for variability would not be a problem since a black body of less than 1 light-s radius can radiate 5.2 x 10^{41} erg s^{-1}. This model does not directly connect the soft X-ray flux and optical flux, and predicts a further softening of the X-ray spectrum at higher energies.

A thermal-Compton model, in which the X-rays are produced by Compton scattering soft photons in a hot gas, would be favored if the X-ray spectrum does not soften at higher energies. An attractive feature is that the spectral index is very insensitive to changes in luminosity. Following Tennant and Mushotzky (1982), we can calculate a minimum temperature of the soft photon source by assuming that these photons originate in a sphere of radius r_3 which emits a blackbody spectrum. To produce at least as many photons as observed in the 0.5 to 4.5 keV band, the source temperature must be greater than $6.6 \times 10^3\ ^{o}K\ r_3^{-2/3}$. The flattening of the optical spectrum toward the UV seen by Penston et al. for NGC 4051 suggests a second component, which could be the source of soft photons.

V. CONCLUSIONS

X-ray emission variable on time scales from ~ 150 s to ~ 1000 s has been discovered from the Seyfert 1 galaxy NGC 4051. The observed spectrum appears unusually soft with a photon index greater than 2.0 with no evidence for absorption intrinsic to NGC 4051. Simple synchrotron or synchrotron self-Compton models are not viable, but approximately isotropic relativistic motion (blast wave) may be consistent with the observations. Black hole accretion models can explain the data in a natural way.

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FIGURE CAPTIONS

FIGURE 1 - The IPC counting rate and color ratio for the fourth observation of NGC 4051. The upper panel is the ratio of the counts in channels 1 through 3 (nominally 0.1 to 0.3 keV) to the counts in channels 4 through 13 (nominally 0.3 to 4.2 keV).

FIGURE 2 - Light curve for first observation. The nominal energy bands for the color ratio are now 0.1 to 0.4 keV and 0.4 to 3.6 keV.

FIGURE 3 - The broad band spectrum of the nucleus of NGC 4051. The radio observation (□) is from deBruyn and Wilson (1976), the IR and optical observations from Penston et al. (1974) (.) and Yee (1980 (X), and the X-ray observations (IPC and MPC) from the present work. Two IPC spectra are given, assuming photon spectral indices of 2.0 and 2.5.

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TABLE 1

LOG OF OBSERVATIONS

Observation No.	Start Time (Day of 1979)	Duration (seconds)	Average Rate (counts s^{-1})	No. of Time Bins	χ^2
1	346.242	968	0.74	19	54.0
2	346.289	1772	0.91	34	37.0
3	348.585	1647	0.64	33	37.5
4	350.489	2304	1.57	45	418.5
5	352.199	1691	1.17	32	40
6	735.041	1414	0.13	15	14

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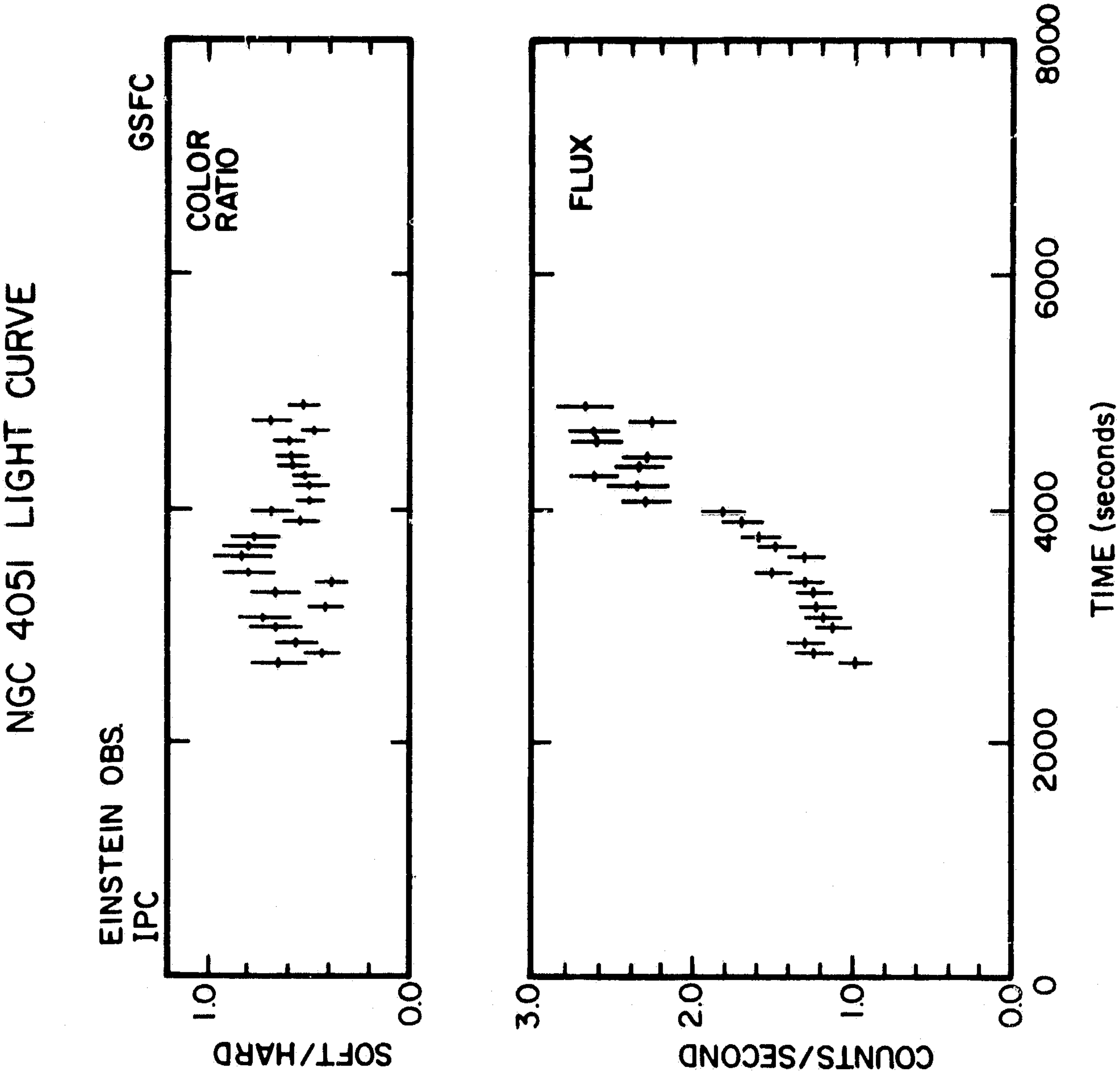

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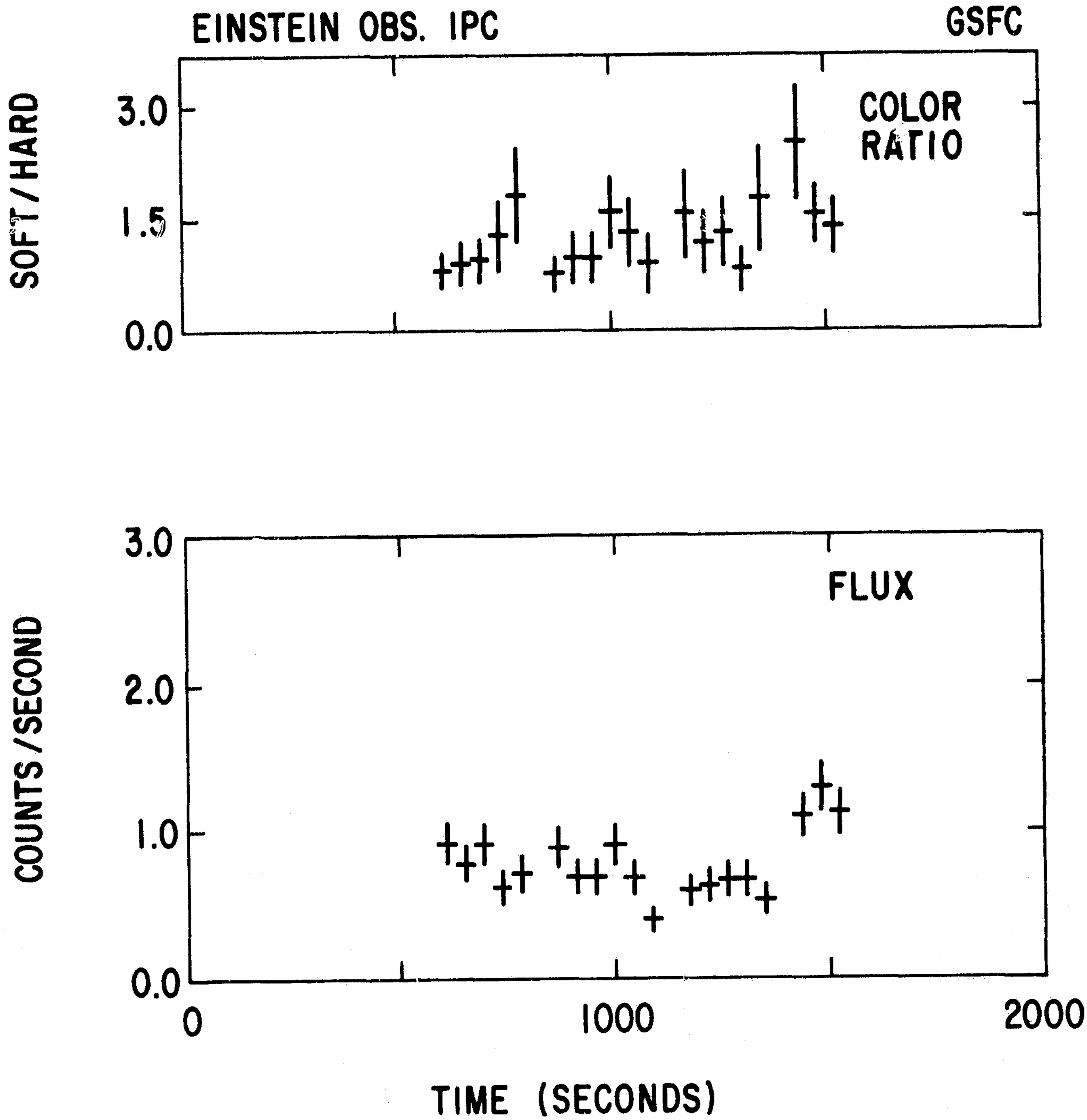
NGC 4051 LIGHT CURVE



NGC 4051 SPECTRUM

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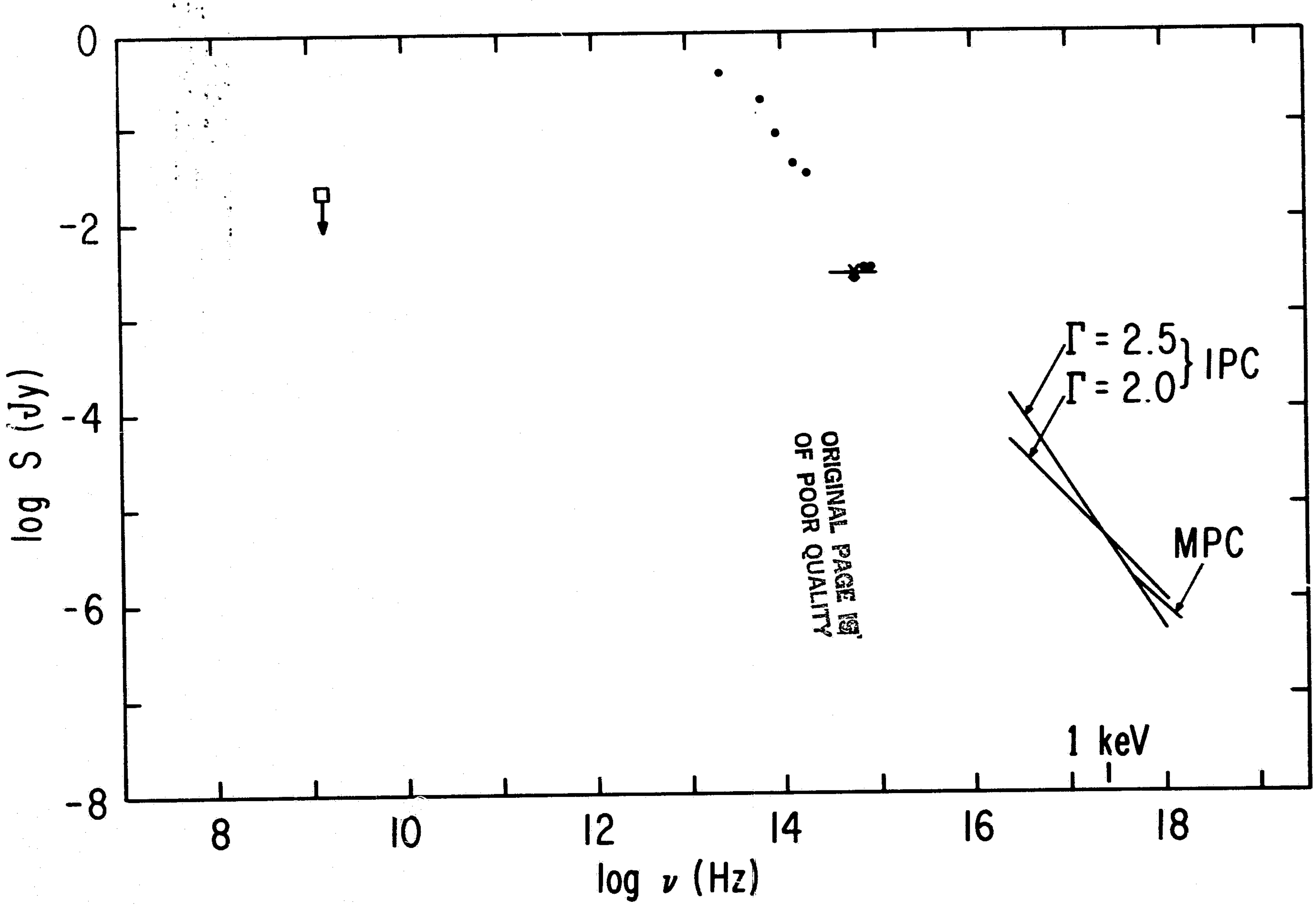

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