ASCA OBSERVATIONS OF SEYFERT 1 GALAXIES. I. DATA ANALYSIS, IMAGING, AND TIMING

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ABSTRACT

We present the first in a series of papers describing the X-ray properties of a sample of 18 Seyfert 1 galaxies, using data obtained by ASCA. The imaging data reveal a number of serendipitous hard X-ray sources in some source fields, but none contribute significantly to the hard X-ray flux of the active galactic nuclei. All but one of the Seyferts show evidence for variability on timescales of minutes to hours, with the amplitude anticorrelated with the source luminosity, confirming previous results. In at least eight sources there is evidence that the variability amplitude below 2 keV is greater than that in the hard X-ray band, perhaps indicating variable components other than the power law in the soft band. Ultrarapid variability, implying significant power at frequencies greater than $10^{-3}$ Hz is detected in at least five sources but is difficult to detect in most cases, because of the sampling and signal-to-noise ratio. In Mrk 766 and MCG – 6-30-15 there is also an indication that the high-frequency power spectra are variable in shape and/or intensity. There is similar evidence in NGC 4151 but on longer timescales.

Subject headings: galaxies: active — galaxies: nuclei — galaxies: Seyfert — X-rays: galaxies

1. INTRODUCTION

The Ariel V and HEAO 1 surveys showed that the brightest class of active galactic nuclei (AGNs) in the hard X-ray band are nearby Seyfert 1 galaxies. While it is unclear whether or not such sources are representative of the AGN phenomenon in general, the high signal-to-noise ratio enables them to be studied in most detail in the X-ray band.

Long term (days to years) variability is a property of these sources established early in the history of X-ray astronomy (e.g., Marshall, Warwick, & Pounds 1981), with variations in amplitude of factors up to 1 order of magnitude being common. Only two sources showed evidence for more rapid variability in the HEAO 1 or Einstein data; NGC 4051 (Marshall et al. 1983) and NGC 6814 (Tennant & Mushotzky 1983). In the latter case, the variability is most likely to be due to a nearby cataclysmic variable (Madejski et al. 1993).

Long duration, uninterrupted X-ray observations of AGNs were first afforded by EXOSAT, which showed that the previous lack of detection was caused primarily by low signal-to-noise ratio and observation duration. EXOSAT’s highly elliptical orbit eliminated constraints due to Earth occultation and SAA passage for up to four days. Examination of the light curves from short (~20,000 s) observations showed that rapid variability was common, contrary to the conclusions from low Earth orbit satellites. (e.g., Lawrence et al. 1985; Pounds, Turner, & Warwick 1986). In a study of a sample of 48 Seyfert galaxies, at least 30% showed clear rapid X-ray variability (Turner 1988).

EXOSAT also provided the first evenly sampled light curves of AGNs, and therefore an opportunity to estimate the power-density spectrum (PDS) to reasonable accuracy. The PDS can be used to identify characteristic timescales in the variability, which might be related to physical sizes in the source. However, early efforts showed scale-invariant variability, with a $f^{-2}$ “red-noise” noise spectrum, possibly with $\alpha \sim 1$ (Lawrence et al. 1987; McHardy & Czerny 1987). Improved techniques have revealed further information. Lawrence & Papadakis (1993) reported on a series of EXOSAT “long-look” observations and found that the power-spectrum slopes were consistent with a mean value of $\alpha = 1.55 \pm 0.09$. Using different techniques, Green, McHardy, & Lehto (1993) presented similar results for a larger sample and found $\alpha = 1.7 \pm 0.5$. However, both sets of authors presented evidence that the amplitude of the PDS depends on the source luminosity, confirming a similar result based on the doubling timescale given by Barr & Mushotzky (1986). Green et al. (1993) also reported that the low-energy (LE) power spectra of two sources were steeper than the medium-energy (ME) spectra. It is still unclear whether there are any characteristic timescales in the X-ray variability of AGNs. With the best example of a periodicity, NGC 6814, having evaporated, the strongest evidence is of quasi-periodic oscillations in the EXOSAT power spectra of NGC 5548 and NGC 4051 (Papadakis & Lawrence 1993, 1995). These observations await confirmation with other satellites. Unfortunately, all the data taken since the demise of EXOSAT have been sampled unevenly. When combined with the relatively high Poisson noise level associated with sources of this strength, further progress in our knowledge of the power spectra has been severely hampered.

After introducing our sample in § 2 and our analysis methods in § 3, we discuss the ASCA imaging data in § 4. We demonstrate the hard X-ray emission we describe here is consistent with an origin in a pointlike source centered on the optical galaxy and is therefore associated with the AGNs, rather than some contaminating source. The time dependence of the X-ray emission of our Seyfert 1 galaxies is discussed in § 5. Finally, we discuss our results in § 6.

2. THE SAMPLE

Here we present an analysis of ASCA observations of Seyfert 1 galaxies performed prior to 1994 May 1. All such observations are now available in the public archives. We define Seyfert 1 galaxies as AGNs at redshifts $z < 0.05$, with
TABLE 1

| Name       | Alternative Name | R.A. (J2000) | Decl. (J2000) | z             | Class          | $N_H$ (Gal)* |
|------------|------------------|--------------|---------------|----------------|---------------|--------------|
| Mrk 335    | PG               | 00 06 19.4   | 20 12 11      | 0.025          | 1.0 (W92)     | 3.7          |
| Fairall 9  |                  | 01 23 45.7   | -58 48 21     | 0.046          | 1.0 (W92)     | 3.2          |
| 3C 120     | Mrk 1506         | 04 33 11.0   | 05 21 15      | 0.033          | 1.0 (G95)     | 12.3         |
| NGC 3227   |                  | 10 23 30.5   | 19 51 55      | 0.003          | 1.5 (O93)     | 2.1          |
| NGC 3516   |                  | 11 06 47.4   | 72 34 06      | 0.009          | 1.5 (O93)     | 2.9          |
| NGC 3783   |                  | 11 39 01.7   | -37 44 18     | 0.009          | 1.2 (W92)     | 9.6          |
| NGC 4051   |                  | 12 03 09.5   | 44 31 52      | 0.002          | 1.0 (O95)     | 1.3          |
| NGC 4151   |                  | 12 10 32.4   | 39 24 20      | 0.003          | 1.5 (O95)     | 2.2          |
| Mrk 766    | NGC 4253         | 12 18 26.6   | 29 48 46      | 0.012          | 1.5 (W92)     | 1.8          |
| NGC 4593   | Mrk 1330         | 12 39 39.3   | 05 20 39      | 0.009          | 1.0 (W92)     | 2.0          |
| MCG -6-30-15 |                | 13 35 53.3   | -34 17 48     | 0.008          | 1.0 (G95)     | 4.1          |
| IC 4529A   |                  | 13 49 19.2   | -30 18 34     | 0.016          | 1.0 (W92)     | 4.6          |
| NGC 5548   | Mrk 1509         | 14 17 59.5   | 25 08 12      | 0.017          | 1.5 (O95)     | 1.6          |
| Mrk 841    | PG               | 15 04 01.1   | 10 26 16      | 0.006          | 1.0 (O95)     | 2.2          |
| NGC 6814   |                  | 19 42 40.5   | -10 19 24     | 0.006          | 1.2 (W92)     | 9.8          |
| Mrk 509    |                  | 20 44 09.6   | -10 43 23     | 0.035          | 1.2 (W92)     | 4.4          |
| NGC 7469   | Mrk 1514         | 23 03 15.5   | 08 52 26      | 0.017          | 1.0 (O95)     | 4.8          |
| MCG -2-58-22| Mrk 926          | 23 04 43.4   | -08 41 08     | 0.047          | 1.2 (W92)     | 3.5          |

* Galactic H I column density from 21 cm measurements in units of $10^{20}$ cm$^{-2}$.

REFERENCES.—V93: Veron-Cetty & Veron 1993. G95: Giuricin, Mardirossian, & Mezzetti 1995; O93: Osterbrock & Martel 1993; W92: Whittle 1992. $N_H$ values are from Elvis, Lockman, & Wilkes 1989; Stark et al. 1992; Murphy et al. (1996) or Dickey & Lockman (1990).

As our intention is to study the mean properties of the sample we do not include a detailed discussion of individual sources. However, we note that many of these observations have already been published in the literature and direct the reader to the references noted in Table 2 for analyses of the individual objects.

3. DATA SELECTION AND ANALYSIS

Detailed information regarding ASCA and the analysis of data from that satellite can be found in Tanaka, Inoue, & Holt (1994), Day et al. (1995) and references therein. Four co-aligned, grazing-incidence, foil-mirror telescopes (Serlemitsos et al. 1995) are employed to direct X-rays onto four focal-plane instruments simultaneously. There are two CCD detectors, the solid-state imaging spectrometers (SIS; Gendreau 1995) and two gas-scintillation proportional counters, the Gas Imaging Spectrometers (GIS; Ohashi et al. 1996).
Our ASCA SIS data were obtained in one of two data modes (known as FAINT and BRIGHT), one of three clocking modes (1, 2, or 4 CCD modes) depending on the number of CCD chips being read out and one of three telemetry modes (LOW, MEDIUM, and HIGH bit rates). A given observation invariably contains a mixture of these modes. Analysis of FAINT mode data alone allows correction for Dark Frame Error (DFE) and "echo" effects (Otani & Dotani 1994), which permits utilization of the maximum energy resolution of the instruments. However, they cannot then be combined with the BRIGHT mode data. Thus, if signal-to-noise ratio is a more important consideration than spectral resolution, the FAINT data can be converted into a format identical to the BRIGHT mode data and thus the two types of data can be combined. Combining data taken in different clocking modes can cause problems in the analysis, due to different background and CCD zero levels and are generally not combined. In principle telemetry modes can be combined.

The vast majority of the GIS data described here were taken in so-called PH mode, which provides the maximum energy and spatial resolution.

Our data were obtained from the US public archive (located at the HEASARC, NASA/GSFC). Table 2 shows the observation catalog. A total of 30 observations were made of our sources, where we define an "observation" as a distinct dataset within the archive. The starting point for our analysis were the "raw" event files from the database. These were created from the original telemetry file and have been corrected to produce linearized detector coordinates, gain corrected pulse-height values and sky coordinates determined from the spacecraft attitude. Furthermore, the SIS FAINT data have been converted to both BRIGHT mode format and an alternative form corrected for DFE and echo effects and compressed in PHA space, so-called BRIGHT2 data. In cases where the majority of the data were taken in FAINT mode, we adopted the BRIGHT2 data. Otherwise we combined the FAINT mode data with the BRIGHT mode, to maximize the signal-to-noise ratio. The data modes we used are listed in the fourth column of Table 2. In the case of mixed clocking modes, we chose only the mode with the highest exposure time. This is tabulated in brackets after the data mode.

### Table 2: ASCA Observation Log

| Name           | ASCA Sequence | Date               | CCD Mode (SIS) | $t_{exp}$ (SIS0) (ks) | Count Rate (SIS0) | Reference |
|----------------|---------------|--------------------|----------------|-----------------------|--------------------|-----------|
| Mrk 335        | 71010000      | 1993 Dec 09        | FAINT (2)      | 19.3                  | 0.584 ± 0.006      | P94       |
| Fairall 95     | 71027000      | 1993 Nov 21        | BRIGHT (1)     | 22.0                  | 1.003 ± 0.007      |           |
| 3C 120W        | 71014000      | 1994 Feb 17        | FAINT (1)      | 47.4                  | 1.871 ± 0.006      |           |
| NGC 3227       | 70013000      | 1993 May 08        | BRIGHT (4)     | 33.4                  | 0.665 ± 0.005      |           |
| NGC 3516       | 71007000      | 1994 Apr 02        | FAINT (1)      | 33.7                  | 2.500 ± 0.010      |           |
| NGC 3783       | 71041000      | 1993 Dec 19        | BRIGHT (1)     | 17.5                  | 1.067 ± 0.008      | G95       |
| NGC 4051       | 71040100      | 1993 Br. 23        | BRIGHT (2)     | 14.9                  | 1.324 ± 0.010      | G95       |
| NGC 4051       | 70010000      | 1993 Apr 25        | BRIGHT (4)     | 27.6                  | 1.063 ± 0.006      | M94       |
| NGC 4151 (1)   | 70000000      | 1993 May 24        | BRIGHT (4)     | ...                   | ...                |           |
| NGC 4151 (2)   | 70000100      | 1993 Nov 05        | FAINT (1)      | 13.4                  | 2.149 ± 0.013      | W94       |
| NGC 4151 (3)   | 70019030      | 1993 Dec 04        | BRIGHT (2)     | ...                   | ...                | Y95       |
| NGC 4151 (4)   | 71019020      | 1993 Dec 05        | FAINT (2)      | 10.8                  | 2.190 ± 0.015      | Y95       |
| NGC 4151 (5)   | 70019010      | 1993 Dec 07        | BRIGHT (2)     | 11.7                  | 2.479 ± 0.015      | Y95       |
| NGC 4151 (6)   | 71019000      | 1993 Dec 09        | FAINT (2)      | ...                   | ...                | Y95       |
| Mrk 766        | 70014000      | 1993 Dec 18        | FAINT (1)      | 33.7                  | 0.903 ± 0.006      |           |
| NGC 4593       | 71024000      | 1994 Jan 09        | FAINT (1)      | 23.1                  | 1.567 ± 0.009      |           |
| MCG – 6-30-15 (1) | 70016000     | 1993 Jul 09        | BRIGHT (2)     | 29.8                  | 1.961 ± 0.009      | F94       |
| MCG – 6-30-15 (2) | 70016010     | 1993 Jul 31        | FAINT (1)      | 31.4                  | 1.290 ± 0.007      | F94       |
| IC 4329A        | 70005000      | 1993 Aug 15        | BRIGHT (4)     | 20.4                  | 1.933 ± 0.010      | M95       |
| NGC 5548       | 70018000      | 1993 Jul 27        | BRIGHT (4)     | 30.5                  | 0.477 ± 0.004      | G96       |
| Mrk 844 (1)    | 70090900      | 1993 Aug 22        | BRIGHT (2)     | 20.9                  | 0.355 ± 0.004      | G96       |
| Mrk 841 (2)    | 71040000      | 1994 Feb 21        | BRIGHT (2)     | 40.3                  | 0.029 ± 0.001      |           |
| NGC 6814 (1)   | 70012000      | 1993 May 04        | BRIGHT (4)     | 40.3                  | 0.029 ± 0.001      |           |
| NGC 6814 (2)   | 70012010      | 1993 Oct 21        | BRIGHT (4)     | ...                   | ...                |           |
| NGC 6814 (3)   | 70012020      | 1993 Nov 01        | BRIGHT (4)     | ...                   | ...                |           |
| Mrk 509        | 71013000      | 1994 Apr 29        | FAINT (1)      | 40.1                  | 2.120 ± 0.008      | G94       |
| NGC 7469 (1)   | 71028030      | 1993 Nov 24        | FAINT (2)      | ...                   | ...                | G94       |
| NGC 7469 (2)   | 71028010      | 1993 Dec 02        | FAINT (2)      | 14.5                  | 1.175 ± 0.009      | G94       |
| NGC 7469 (3)   | 70004000      | 1993 May 25        | FAINT (2)      | 13.3                  | 0.444 ± 0.006      | W94       |

* ELV > 5.
  * Some data excluded due to saturation.
  * BR_EARTH > 25 (SISO).
  * Observation rejected due to bad attitude.
  * Observation rejected due to low exposure.
  * Affected by GIS3 BITFIX problem.
  * ANG3_DIST < 0.02.

References—F94: Fabian et al. 1994; G94: Guainazzi et al. 1994; G95: George, Turner, & Netzer 1995; M94: Mihara et al. 1994; M95: Mushotzky et al. 1995; P94: Ptak et al. 1994; W94: Weaver et al. 1994; W95: Weaver et al. 1995; Y95: Yaqoob et al. 1995.
LOW bit rate and such data were generally avoided, although in one case saturation occurred in 1 CCD mode and another in MEDIUM bit-rate. Otherwise, we combined the LOW, MEDIUM, and HIGH bit-rate data.

We applied data selection and cleaning algorithms using the ASCASCREEN script supplied with the FTOOLS/XSELECT package version 3.4. Table 3 shows the selection criteria which were applied to the data sets, unless otherwise noted in Table 2. Flexible criteria (such as BR_EARTH, ELV, and ANG_DIST) were determined from an examination of the housekeeping data. For the SIS, the constraints on BR_EARTH and ELV were determined from an inspection of the SIS event rates (for the on-source chip: SIS0 chip 1 or SIS1 chip 3) as a function of these parameters. A marked increase in the event rate is observed below the angle where significant contamination occurs. In cases where the attitude (ANG_DIST) varied wildly (by \( \geq 1' \)) during the majority of the observation, that observation was rejected. In two observations, the attitude was relatively stable, but the angle between the source and pointing position often exceeded the default criterion of ANG_DIST \(< 0.01 \) used by ASCASCREEN resulting in unacceptable data loss. In these cases we allowed ANG_DIST \(< 0.02 \). Finally, we applied the standard algorithm to remove "hot" and "flickering" pixels from the SIS data.

The exposure times for the screened events files are listed in the fifth column of Table 2. We have excluded observations where the exposure in either SIS was less than 10 ks to ensure a similar baseline for timing analysis and sufficient signal-to-noise ratio for spectral analysis. Details of the the spectral analysis are presented in Nandra et al. (1996a) and George et al. (1996, hereafter Paper III). This left 23 observations suitable for further analysis.

4. SPATIAL ANALYSIS

After extracting the event files we accumulated and examined the images for each instrument. The source centroids were generally within \(~1'\) of the optical position of the Galaxy (Fig. 2), which is consistent with the positional uncertainty due to attitude reconstruction errors (Gotthelf & Ishibashi 1996). Mrk 335 and NGC 4051 have larger offsets \((\sim 1.5')\). Nonetheless, in both cases we are confident that the AGNs are the sources of the X-rays observed by ASCA, as the ROSAT PSPC positions, which are more accurate than those derived from the SIS, are consistent with the optical nuclei and show no other bright sources within the SIS point-spread function (PSF).

We did not find any evidence for extended emission, although this is not surprising considering the width of the PSF. Even at the distance of the closest galaxy, the half-power diameter (HPD) corresponds to a distance of \(~5\) kpc, much larger than the expected size of the nuclear X-ray source. Visual inspection of the SIS and GIS images revealed six fields with evidence for sources other than the target. These are listed in Table 4. In all cases these were much weaker than the Seyfert and did not cause any serious problems in analysis. Other, even weaker sources may be present in the images, but the presence of the central target, which is in general very bright, makes the application of point-source searching algorithms difficult. We have not therefore attempted any more sophisticated spatial analysis, but naturally we avoided the visible contaminating sources when choosing source and background regions.

### Table 3

| Criterion | Description |
|-----------|-------------|
| All instruments: | Satellite outside South Atlantic Anomaly |
| SAA = 0 | Angular offset from nominal pointing position (') |
| ANG_DIST \(< 0.01 \) | Radiation Belt Monitor |
| RBM_CONT \(< 300 \) | Cut-off rigidity (GeV/c) |
| COR \(> 6 \) | Angle from Earth's limb (') |
| SIS only: | Angle from bright Earth (') |
| ELV \(> 10 \) | Time after day/night terminator (s) |
| T_DY_NT \(> 50 \) | SIS pixel threshold |
| Sx_PIXLyb \(< 100 \) | Angle from Earth's limb (') |

\( ^a \) For 1, 2, and 4 CCD modes, respectively.  
\( ^b \) x = SIS number; y = chip number.
Because of small calibration differences between the SIS chips, we restricted our analysis to the primary on-source chip for each SIS (SIS0 chip 1 and SIS1 chip 3). In most cases we used a circular extraction cell for the source region, typically 3’–4’ in radius. However, in cases where the source centroid was close to the gap between SIS chips, a circular extraction cell resulted in an unacceptable loss of counts. In these cases we employed rectangular extraction cells of a similar area. Background counts were taken from source-free regions. For the GIS, the analysis was generally simpler and in all cases we adopted a circular source region centered on the AGNs. Background counts were taken from source-free regions.

5. Timing Analysis

Initially, light curves of the source region were constructed for each observation using the XRONOS package. To increase the signal-to-noise ratio, we combined the SIS0 and SIS1 detectors when analyzing the SIS data; we also combined GIS2 with GIS3. In order to maximize the light curve data thus obtained, we initially accumulated a light curve in 128 s bins, requiring all such bins to be fully exposed in both instruments (SIS0/SIS1 or GIS2/GIS3). This ensured that sufficient counts were obtained in each 128 s integration for Gaussian statistics to be appropriate, even when the light curves were split into different energy ranges (see below). We were then able to test for variability by means of a $\chi^2$ test against the hypothesis that the flux was constant. The reduced-$\chi^2$ values, $\chi^2$, are quoted in Table 5 for four light curves: SIS0 + SIS1 full band (0.5–10 keV; col. [2]), GIS2 + GIS3 hard band (2–10 keV; col. [3]), SIS0 + SIS1 hard band (2–10 keV; col. [4]), and SIS0 + SIS1 soft band (0.5–2 keV; col. [5]). We excluded NGC 6814 from this analysis, which was too weak to search for variations on these short timescales. For the remaining sources, variations in the background have a negligible effect on our analysis. We estimate that variability of the SIS background would contribute less than $10^{-4}$ to the $\sigma_{\text{rms}}$ values quoted in Table 6 and hence a negligible effect on the $\chi^2$ values quoted in Table 5.

For the SIS full-band light curve (col. [2]), 15 of the 17 objects tested showed short-timescale variability at greater than 99% confidence. The exceptions to this are Fairall-9, which showed variability at greater than 95% confidence.

### Table 4

Source Indicated by Photometry

| Field       | R.A.   | Decl.  | Count Rate | Identification | Class | Detectors |
|-------------|--------|--------|------------|----------------|-------|-----------|
| NGC 3516    | 11 02 31 | 72 46 37 | 0.021 ± 0.000 | MS 10590 + 7302 | QSO   | GIS       |
| NGC 4151    | 12 10 25 | 39 29 24 | 0.237 ± 0.005 | 1207 + 39 W4     | BL Lac | SIS       |
| Mrk 766     | 12 18 54 | 29 57 57 | 0.008 ± 0.001 | ...            | ...   | ...       |
| NGC 4593    | 12 40 27 | 05 13 59 | 0.010 ± 0.001 | 1 WGA J1240.4 – 0514 | ...   | GIS       |
| NGC 5548    | 14 18 30 | 25 10 38 | 0.076 ± 0.003 | 1 E1416.2 + 2525 | Cluster | SIS       |
| Mrk 841     | 15 03 40 | 10 16 49 | 0.015 ± 0.001 | ...            | ...   | GIS*      |
| Mrk 841     | 15 04 24 | 10 29 36 | 0.000 ± 0.001 | PKS 1502 + 106  | HPQ   | GIS       |

* Variable source.

### Table 5

| Name          | SIS Full (0.5–10 keV) | GIS Hard (2–10 keV) | SIS Soft (0.5–2 keV) | SIS Hard (2–10 keV) |
|---------------|-----------------------|----------------------|-----------------------|----------------------|
| Mrk 335       | 1.67/106              | 1.25/134             | 1.45/106              | 1.21/106             |
| Fairall 9     | 1.23/140              | 1.07/245             | 1.12/140              | 1.08/140             |
| 3C 120        | 2.52/259              | 1.25/280             | 2.14/259              | 1.42/259             |
| NGC 3227      | 9.14/93               | 4.06/272             | 7.71/93               | 2.94/93              |
| NGC 3516      | 5.20/183              | 2.85/267             | 4.28/183              | 1.90/183             |
| NGC 3783(1)   | 3.50/89               | 2.02/155             | 2.16/89               | 2.36/89              |
| NGC 3783(2)   | 2.71/83               | 1.97/121             | 1.87/83               | 1.85/83              |
| NGC 4051      | 20.7/83               | 7.07/184             | 17.5/83               | 4.50/83              |
| NGC 4151(2)   | 10.7/62               | ...                  | 3.64/62               | 8.26/62              |
| NGC 4151(4)   | 2.81/52               | 3.00/75              | 1.49/52               | 2.45/52              |
| NGC 4151(9)   | 4.69/64               | 4.65/92              | 1.52/64               | 13.84/64             |
| Mrk 766       | 19.6/195              | 4.37/226             | 17.2/195              | 4.31/195             |
| NGC 4593      | 8.01/136              | 2.76/239             | 6.74/136              | 2.47/136             |
| MCG – 6–30–15(1) | 22.4/163            | 13.4/218             | 16.9/162              | 6.30/162             |
| MCG – 6–30–15(2) | 16.4/176            | 5.37/215             | 12.3/176              | 5.40/176             |
| IC 4329A      | 2.23/52               | 1.36/238             | 1.60/52               | 1.74/52              |
| NGC 5548      | 3.40/19               | 1.47/208             | 3.17/19               | 2.22/19              |
| Mrk 841(1)    | 1.67/184              | 1.20/235             | 1.48/184             | 1.14/184             |
| Mrk 841(2)    | 1.40/95               | 1.05/123             | 1.34/95               | 1.18/95              |
| NGC 6814(1)*  | ...                   | ...                  | ...                   | ...                  |
| Mrk 509       | 1.40/243              | 0.98/121             | 1.34/243             | 1.17/243             |
| NGC 7469(2)   | 2.38/86               | 1.30/136             | 1.95/86               | 1.42/86              |
| MCG – 2–58–22 | 1.19/56               | 1.05/221             | 1.25/56               | 0.90/56              |

* GIS exposure too low for meaningful analysis.

b Source too weak for analysis on this timescale.
and MCG -2-58-22, which showed no significant changes. In most all cases this variability is confirmed in the GIS and in the hard and soft bands of the SIS. We conclude that short-timescale variability is extremely common in Seyfert 1 galaxies, albeit at low amplitude in some cases.

The full-band SIS light curves are shown in Figure 3, and demonstrate a rich diversity of variability characteristics. For example, the individual sources exhibit different amplitudes of variability. To quantify this further, we have calculated the normalized “excess variance,” $\sigma_{\text{rms}}^2$ of each light curve. We designate the count rates for the light curve as with errors $\sigma_i$. We further define $\mu$ as the unweighted, arithmetic mean of the $X_i$. Then,

$$\sigma_{\text{rms}}^2 = \frac{1}{N\mu^2} \sum_{i=1}^{N} [(X_i - \mu)^2 - \sigma_i^2].$$

The error on $\sigma_{\text{rms}}^2$, asymptotically for large $N$, is given by $s_D/[(\mu^2)(N)^{1/2}]$ (M. G. Akritas 1996, private communication) where

$$s_D = \frac{1}{N-1} \sum_{i=1}^{N} [(X_i - \mu)^2 - \sigma_i^2] - \sigma_{\text{rms}}^2 \mu^2,$$

i.e., the variance of the quantity $(X_i - \mu)^2 - \sigma_i^2$. These values are given in Table 6. As noted by Lawrence & Papadakis (1993) $\sigma_{\text{rms}}^2$ depends on the observation length. A more rigorous approach would be to define the amplitude and slope of the PDS. Unfortunately, however, such an analysis is extremely difficult with unevenly sampled data, as afforded by low-Earth satellites such as ASCA. We justify our use of $\sigma_{\text{rms}}$ as a measure of the variability power by noting that the $\sigma_{\text{rms}}$ is correlated with the power-spectrum normalization in the EXOSAT data (Lawrence & Papadakis 1993) and that our observations are not radically different in duration (Table 6). There are clear differences between the sources. Furthermore, as shown in Figure 4, $\sigma_{\text{rms}}^2$ shows a strong anticorrelation with X-ray luminosity, confirming the previous results (see § 6). Note that the duration of variability, $t_D$, is not correlated with luminosity. We find $\sigma_{\text{rms}}^2 \propto L_X^{-0.71 \pm 0.03}$, but with a substantial scatter, particularly for the objects around $10^{43}$ erg s$^{-1}$. We note with interest, and discuss later, the fact that NGC 4151 shows evidence for changes in $\sigma_{\text{rms}}^2$ at different epochs.

We have also employed the energy resolution of the SIS detectors to compare $\sigma_{\text{rms}}$ for two separate energy bands. We compare the hard band (2–10 keV) and soft band (0.5–2.0 keV) variability in Figure 5. There is clearly a strong correlation. However, we find that the amplitude of variability in the soft band is often greater than in the hard band. This implies spectral variability for these sources.

In Table 7 we show tests against the constant hypothesis for light curves in 5760 s bins ($\sim 1$ orbit) for all our observations. The sources show even stronger evidence for variability on these ~ hr timescales, in all instruments and energy ranges. We were also able to test for variability in NGC 6814 on this timescale, but no evidence for significant flux changes was found. The $\sigma_{\text{rms}}$ values are not quoted for these light curves as there are generally insufficient points to make the error bars meaningful.

### 5.1. High-Frequency Variability

The high signal-to-noise ratio of our ASCA data allows us, in principle, to explore the PDS in a regime not accessible to EXOSAT. Above a frequency of $\sim 10^{-3}$ Hz, the latter data were dominated by Poisson noise. The low background rate of the ASCA detectors should allow us to go beyond this point into the regime where we might expect

| Name            | SIS Full (0.5–10 keV) | GIS Hard (2–10 keV) | SIS Soft (0.5–2 keV) | SIS Hard (2–10 keV) | $t_D$ (ks) |
|-----------------|-----------------------|---------------------|----------------------|---------------------|------------|
| Mrk 335         | 0.47 ± 0.15           | 0.50 ± 0.31         | 0.42 ± 0.16          | 0.74 ± 0.46         | 50.7       |
| Fairall 9       | 0.09 ± 0.06           | 0.11 ± 0.09         | 0.06 ± 0.07          | 0.07 ± 0.20         | 56.7       |
| 3C 120          | 0.38 ± 0.06           | 0.17 ± 0.08         | 0.40 ± 0.07          | 0.35 ± 0.10         | 131.0      |
| NGC 3227        | 0.58 ± 0.90           | 2.80 ± 0.30         | 8.40 ± 1.40          | 3.00 ± 0.60         | 85.8       |
| NGC 3516        | 0.71 ± 0.09           | 0.76 ± 0.08         | 0.86 ± 0.12          | 0.44 ± 0.09         | 79.5       |
| NGC 3783(1)     | 0.93 ± 0.19           | 0.73 ± 0.16         | 0.91 ± 0.24          | 0.92 ± 0.23         | 38.3       |
| NGC 3782(2)     | 0.53 ± 0.11           | 0.64 ± 0.17         | 0.55 ± 0.18          | 0.48 ± 0.16         | 37.5       |
| NGC 4051        | 12.0 ± 1.70           | 5.80 ± 0.74         | 13.1 ± 2.00          | 9.00 ± 1.50         | 54.2       |
| NGC 4151(2)     | 2.60 ± 0.80           | 3.00 ± 1.00         | 2.50 ± 0.80          | 50.9               |
| NGC 4151(4)     | 0.32 ± 0.10           | 0.41 ± 0.08         | 0.55 ± 0.31          | 0.30 ± 0.11         | 29.1       |
| NGC 4151(5)     | 0.62 ± 0.10           | 0.67 ± 0.09         | 0.37 ± 0.24          | 0.58 ± 0.09         | 25.9       |
| Mrk 766         | 7.90 ± 0.60           | 5.20 ± 0.60         | 9.50 ± 0.70          | 5.00 ± 0.50         | 77.8       |
| NGC 4593        | 2.10 ± 0.20           | 2.20 ± 0.30         | 2.40 ± 0.30          | 1.40 ± 0.20         | 96.5       |
| MCG -6-30-15(1) | 4.10 ± 0.40           | 4.40 ± 0.30         | 4.60 ± 0.40          | 3.50 ± 0.40         | 87.9       |
| IC 4329A        | 0.24 ± 0.08           | 0.10 ± 0.03         | 0.20 ± 0.13          | 0.35 ± 0.17         | 85.2       |
| NGC 5548        | 0.47 ± 0.23           | 0.23 ± 0.07         | 0.65 ± 0.28          | 0.08 ± 0.29         | 83.3       |
| Mrk 841(1)      | 0.59 ± 0.14           | 0.58 ± 0.14         | 0.58 ± 0.20          | 0.38 ± 0.36         | 79.5       |
| Mrk 841(2)      | 0.33 ± 0.22           | -0.11 ± 0.34        | 0.58 ± 0.37          | 0.55 ± 0.52         | 60.9       |
| NGC 6814(1)     | 0.08 ± 0.02           | 0.02 ± 0.07         | 0.09 ± 0.03          | 0.11 ± 0.08         | 108.0      |
| NGC 7469(2)     | 0.50 ± 0.14           | 0.35 ± 0.19         | 0.50 ± 0.15          | 0.53 ± 0.32         | 37.4       |
| MCG -2-58-22    | 0.14 ± 0.20           | 0.10 ± 0.22         | 0.40 ± 0.29          | -0.24 ± 0.29        | 83.3       |

a Duration of the observation.

b GIS exposure too low for meaningful analysis.

c Source too weak for analysis on this timescale.
Fig. 3.—Light curves for the sources in our sample, in 128 s bins, for the combined SIS data in the 0.4–10 keV range. The time axis is in modified julian date, mJD-40000. NGC 6814 has been excluded due to its low count rate. The y-axis is scaled to the mean value, to allow comparison of the variability amplitudes, with ymax = 2 mean and ymin = mean/4, except for NGC 4051 where the amplitude of variability is so large that we have had to increase these limits by 50%. Most objects show variability on this timescale and also on longer (∼hr) timescales (see Tables 5 and 7).
Fig. 3—Continued
FIG. 3.—Continued
cutoffs due to the fundamental size scale of the X-ray source. However, the uneven sampling prevents construction of a reliable periodogram from our data. Indeed, as noted before, even the $\sigma_{\text{rms}}^2$ values quoted above are susceptible to scatter because of the sampling patterns. We have tested for the presence of very rapid variability using light curves of the source accumulated in 32 s bins, in the SIS full band. Even for the weakest sources each bin contains ~20 counts, allowing Gaussian statistics to be applied (although once again, we excluded NGC 6814 from the analysis). We searched for contiguous segments with five or more bins in each 32 s light curve and performed a $\chi^2$ test against a constant hypothesis for each segment, flagging each time the probability of obtaining that $\chi^2$ by chance was less than 1%. The results are shown in Table 8. We find at least one “variable” segment (at greater 99% confidence) in 10/23 observations and 9/17 of the sources. However, given that there are typically several tens of segments tested for each observation, the chance of spurious detections is fairly high. We consider there to be firm evidence for ultrarapid variability if two or more segments show an unacceptable $\chi^2$, which is true in 5/17 sources. Unsurprisingly, these tend to be the sources with the largest overall variability amplitudes.

For those sources with significant variability on these short timescales, we also tested the hypothesis that the high-frequency PDS was constant in shape and intensity. We achieved this by calculating the excess variance for contiguous segments constructed to have the same duration. If the process producing the variability were statistically stationary, we would then expect these $\sigma_{\text{rms}}^2$ values to be constant. Given that our prescription for the error bars on the excess variance is only valid in the limit of large $N$, we used only segments with greater than 30 points. This requirement meant that we could not test the constancy hypothesis in NGC 4051 and NGC 3227 since there were no such segments in the SIS light curve. The $\chi^2$ values and the probabilities of obtaining them are given in columns (5) and (6) of Table 8. In two cases, Mrk 766 and MCG −6-30-15(2), we find an unacceptable $\chi^2$ value, indicating that the high frequency PDS in these sources is variable. Although intriguing, we consider this result to be somewhat tentative, particularly in the case of Mrk 766; some of the excess $\chi^2$ in that source comes from $\sigma_{\text{rms}}^2$ values which are less than zero.
While these are expected by chance, they may be exaggerating the significance in this case.

6. DISCUSSION

We have presented *ASCA* imaging and timing data for a sample of Seyfert 1 galaxies, most of which were originally detected by large-beam X-ray instrumentation. The *ASCA* images demonstrate that, aside from the now infamous case of NGC 6814, and despite the lack of spatial resolution of these previous instruments, the Seyfert galaxies identified in the *Ariel V* and *HEAO 1* surveys are indeed the sources of hard X-ray emission. There are weak contaminating sources in some cases, but none which have a measurable impact on our current analysis or seem likely to have contaminated previous observations significantly.

Our sources show variability to be very common, albeit at very low amplitudes for some objects. This emphasizes the need for high signal-to-noise ratio observations; this low-level variability was missed with most previous instrumentation. The rms variability amplitude is strongly anti-correlated with the X-ray luminosity of the source, but there

![Figure 4](image1.png)

**Fig. 4.** Normalized, excess variance ($\sigma_{\text{rms}}^2$) versus luminosity. Where there are multiple observations of a source, they have been plotted separately. A highly significant trend of decreasing amplitude is observed with luminosity. Spearman rank and Pearson linear correlations give significances of greater than 99.9% confidence.

![Figure 5](image2.png)

**Fig. 5.** $\sigma_{\text{rms}}^2$ variability amplitude in the soft band (0.5–2 keV) versus that in the hard band (2–10 keV) of the SIS. The dashed line shows a 1:1 relationship. In a number of cases, the amplitude of variability in the soft X-ray band appears to be greater than in the hard X-rays. This implies some spectral variability.

| Table 7 | FOR 5760 S LIGHT CURVES |
|----------------|--------------------------|
| Name          | SIS Full (0.5–10 keV)    | GIS Hard (2–10 keV) | SIS Soft (0.5–2 keV) | SIS Hard (2–10 keV) |
|----------------|--------------------------|
| Mrk 335        | 8.39/7                   | 3.69/7               | 6.16/7               | 2.81/7               |
| Fairall 9      | 2.11/9                   | 0.93/8               | 1.84/9               | 1.25/9               |
| 3C 120         | 16.0/22                  | 4.17/22              | 11.8/22              | 5.36/22              |
| NGC 3227       | 42.8/14                  | 53.1/14              | 37.0/14              | 10.2/14              |
| NGC 3516       | 63.1/12                  | 38.6/12              | 50.9/12              | 15.5/12              |
| NGC 3783(1)    | 32.3/6                   | 28.5/6               | 17.0/6               | 16.3/6               |
| NGC 3783(2)    | 30.8/5                   | 22.1/5               | 16.2/5               | 14.9/5               |
| NGC 4051       | 119.6/12                 | 54.8/12              | 97.7/12              | 23.8/12              |
| NGC 4151(2)    | 101.0/6                  | ...                  | 27.1/6               | 74.4/6               |
| NGC 4151(4)    | 23.1/4                   | 39.0/4               | 6.06/4               | 18.9/4               |
| NGC 4151(5)    | 57.8/4                   | 83.9/4               | 11.0/4               | 46.9/4               |
| Mrk 766        | 233.7/13                 | 40.3/13              | 212.3/13             | 37.1/13              |
| NGC 4593       | 79.8/11                  | 30.5/14              | 65.9/11              | 16.0/11              |
| MCG –6-30-15(1)| 188.7/13                 | 139.8/14             | 143.2/13             | 47.6/13              |
| MCG –6-30-15(2)| 146.8/15                 | 39.2/17              | 105.3/15             | 44.5/15              |
| IC 4329A       | 6.29/12                  | 6.30/14              | 3.59/12              | 4.22/12              |
| NGC 5548       | 4.39/11                  | 5.46/13              | 4.27/11              | 1.25/11              |
| Mrk 841(1)     | 11.8/13                  | 4.16/13              | 9.55/13              | 2.99/13              |
| Mrk 841(2)     | 5.04/10                  | 1.51/10              | 4.78/10              | 1.59/10              |
| NGC 6814(1)    | 0.97/20                  | 0.92/23              | 1.39/20              | 0.63/20              |
| Mrk 509        | 7.45/18                  | 1.92/6               | 5.38/18              | 3.43/18              |
| NGC 7469(2)    | 16.8/6                   | 11.2/6               | 11.8/6               | 6.05/6               |
| MCG –2-58-22   | 1.55/10                  | 1.57/14              | 1.38/10              | 1.95/10              |

* GIS exposure too low for meaningful analysis.
is a substantial scatter. Some of this could be due to the fact that the observation durations differ, although we note that the EXOSAT data also showed a significant spread of power-spectrum normalizations about the correlation. If the sampling and power spectra are identical for all sources, then $\sigma_{\text{rms}}^2$ should be proportional to the amplitude of the PDS at a given frequency. Therefore, we compare our correlation index of 0.71 with that given by Green et al. (1993) of 0.68 and Lawrence & Papadakis (1993) of 0.55. The fact that these agree well, despite the expected deviations due to the sampling patterns, supports the result that the shapes of the power spectra are at least very similar from source to source and that the effects of the observation duration are not severe.

It is currently unclear whether the X-ray source in Seyfert galaxies consists of a single, coherent region or of multiple "hot spots" (Abramowicz et al. 1991; Wiita et al. 1991), although the lack of any obvious characteristic timescale would tend to favor the latter (e.g., McHardy & Czerny 1987). In such a scenario, one could explain an anti-correlation of $\sigma_{\text{rms}}^2$ with $L_X$ by hypothesizing that the higher luminosity sources simply contained more hot spots, such that the large amplitude variability was "washed out." We would then expect $\sigma_{\text{rms}}^2 \propto L_X^{-1}$, which is somewhat steeper than the observed correlation, although we note that the scatter evident in Figure 4 makes precise determination of the relation difficult. Nonetheless, our results, and those derived from the EXOSAT data, would tend to argue that the individual shots carried more power in the higher luminosity sources, rather than simply being more numerous. Alternatively, with a single X-ray–producing region, one might hypothesize that the luminosity is related to the size of that region. For example, if the source size is a fixed number of gravitational radii, we expect it to be proportional to the mass of the black hole. With a fixed accretion rate (with respect to the Eddington limit), $\dot{M}$, we would once again expect $\sigma_{\text{rms}}^2 \propto L_X^{-1}$. Our observed correlation would suggest that $\dot{M}$ increases with $L$, a view supported by some recent ROSAT and ASCA spectral data for quasars (Stewart et al. 1995; Nandra et al. 1996b).

The soft X-ray emission in our sources generally shows a larger amplitude of variability than the hard X-rays on the timescales considered. In this case the sampling is identical for the hard and soft X-ray light curves, so that if the power spectra were identical in the two bands, we would not expect significant differences in $\sigma_{\text{rms}}^2$. To date, the power spectra in the soft X-ray band (e.g., the EXOSAT LE) are not well known. For two sources with well-defined LE power spectra, NGC 4051 and MCG – 6-30-15 (which are also in our sample), it appears that the power spectra are different in the soft and hard X-ray bands (Green et al. 1993; Papadakis & Lawrence 1995). For those sources the power spectra appear to be steeper in the soft X-ray band, although we note that in both cases there have been claims of quasi-periodic oscillations in the power spectra (Papadakis & Lawrence 1993, 1995), making the spectral slope of the PDS much more difficult to define. It is difficult to compare our result with theirs, as our $\sigma_{\text{rms}}^2$ represents an integration of the power spectrum over some frequency range and cannot be easily equated to the slope. We note, however, that, even in the soft X-ray band, the energy spectrum is probably dominated by the power-law component (see Paper III). Therefore, we would anticipate the variability characteristics in the two bands to be similar. However, additional spectral complexity, and spectral variability, in the soft X-ray band could lead to additional variance. For example, changes in the ionization parameter or column density of a warm absorber (e.g., Halpern 1984; Pan, Stewart, & Pounds 1990) would have most effect in the soft X-ray band, as would any independently variable soft

### Table 8

**RAPID VARIABILITY; 32 s BINS**

| Name             | Number of Segments | Longest (s) | Variable Segments | $\chi^2$/dof ($\sigma_{\text{rms}}^2$) | $\text{Prob}_{\text{rms}}$ ($\sigma_{\text{rms}}^2$) |
|------------------|--------------------|-------------|-------------------|-------------------------------------|-------------------------------------|
| Mrk 335          | 25                 | 2112        | 0                 | ...                                 | ...                                 |
| Fairall 9        | 30                 | 1984        | 0                 | 0.42/4                              | 0.79                                |
| 3C 120           | 69                 | 1632        | 0                 | 1.25/15                             | 0.22                                |
| NGC 3227         | 55                 | 864         | 2                 | ...                                 | ...                                 |
| NGC 3516         | 37                 | 1824        | 2                 | 1.06/12                             | 0.39                                |
| NGC 3783(1)      | 26                 | 1248        | 1                 | ...                                 | ...                                 |
| NGC 3783(2)      | 18                 | 1312        | 0                 | ...                                 | ...                                 |
| NGC 4051         | 46                 | 864         | 2                 | ...                                 | ...                                 |
| NGC 4151(2)      | 22                 | 1152        | 0                 | ...                                 | ...                                 |
| NGC 4151(4)      | 16                 | 1600        | 0                 | ...                                 | ...                                 |
| NGC 4151(5)      | 19                 | 1312        | 0                 | ...                                 | ...                                 |
| Mrk 766          | 37                 | 1760        | 3                 | 2.99/13                             | <10^{-3}                            |
| NGC 4393         | 24                 | 1632        | 0                 | 0.88/9                              | 0.54                                |
| MCG – 6-30-15(1) | 45                 | 1248        | 5                 | 5.95/5                              | <10^{-4}                            |
| IC 4329A         | 31                 | 928         | 0                 | ...                                 | ...                                 |
| NGC 5548         | 19                 | 352         | 0                 | ...                                 | ...                                 |
| Mrk 841(1)       | 39                 | 2112        | 1                 | ...                                 | ...                                 |
| Mrk 841(2)       | 33                 | 1120        | 0                 | ...                                 | ...                                 |
| NGC 6814(1)      | ...                | ...         | ...               | ...                                 | ...                                 |
| Mrk 509          | 62                 | 1632        | 1                 | 1.05/13                             | 0.40                                |
| NGC 7469(2)      | 19                 | 1536        | 0                 | 0.70/4                              | 0.59                                |
| MCG – 2-58-22    | 25                 | 1280        | 1                 | ...                                 | ...                                 |

* For a test of the hypothesis that $\sigma_{\text{rms}}^2$ was constant. We quote values only for those observations with greater than four segments with greater than 30 points and used identical sampling for each segment (see text).

* Probability of obtaining this $\chi^2$ by chance.
excess (e.g., Turner & Pounds 1988; such excesses are also clearly evident in a number of these spectra; see Paper III).

We find evidence that NGC 4151 shows changes in \( \sigma_{rms} \) in apparent contradiction to the suggestion that the process producing the variability is statistically stationary (Green et al. 1993; Papadakis & Lawrence 1995). Lawrence & Papadakis (1993) also found changes in \( \sigma_{rms} \) between observations of NGC 4151, but as they showed, the power spectra for those observations are consistent. Indeed, we find here that the longest observation of NGC 4151(2) has the highest variance, which we expect as we are sampling the longer timescales. Interestingly, however, a comparison of observations 4 and 5 show the latter to have a higher variance, despite a shorter duration. This suggests that the shape and/or normalization of the power spectrum changes at different epochs. The other sources with multiple observations do not show clear evidence for variations in \( \sigma_{rms} \) when the observation durations are taken into account.

We found evidence for variability power on frequencies higher than \( \sim 10^{-3} \) Hz for five sources. In two cases there is also a suggestion that the variability amplitude changes during the observation. This indicates that the high-frequency PDS in these sources is not constant. A variable PDS might imply changes in fundamental timescales in the source. At the high frequency end, this might be related to the size scale of the X-ray producing region(s). Our observations suggest that it might be fruitful to pursue the study of the PDS in the \( 10^{-3} \sim 10^{-2} \) Hz range with future instrumentation.

Note added in manuscript.—Following the acceptance of this paper, we became aware of the work of Bao & Abramowicz (1996) who explain the anticorrelation of variability amplitude with X-ray luminosity in terms of inclination effects in the “bright-spot” model of Abramowicz et al. (1991). Their hypothesis is that, for highly inclined accretion disks, the X-ray luminosity is smaller and the Doppler factors higher, resulting in the observed correlation. Their model provides an explanation for both the anticorrelation and the form of the power spectra and presents an interesting alternative to the models discussed above.

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