X-RAY STUDIES OF QUASARS AND ACTIVE GALAXIES WITH THE EINSTEIN OBSERVATORY

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1. INTRODUCTION

The launch of the Einstein Observatory has added a new and exciting dimension to the study of active galaxies. Not only have a large number of optical and radio active galaxies been detected, but many new examples of high energy activity have been found. The ease with which a large number of quasars may now be studied in the X-ray regime out to a redshift of at least four promises to improve our understanding of the nature of these tremendous powerhouses and the evolution of the universe.

The Columbia Astrophysics Laboratory (CAL) is carrying out an extensive program to study active galaxies with the imaging proportional counter (IPC) on board the Einstein Observatory (Giacconi et al. 1979). These observations have already yielded a large number of positive detections including four Seyferts, five N galaxies, seven BL Lacs, and 17 quasars. Upper limits were obtained for eight additional quasars. Six new Seyfert I and/or quasars have been identified from X-ray observations (Chanan 1979). Preliminary results from the first six months of the CAL survey of active galaxies will be presented below. A few representative objects of interest will be discussed briefly. Simple statistical tests will be applied to determine whether X-ray properties can be used to understand the differences and similarities between the various classes of active galaxies. Particular emphasis will be placed on the quasars in our sample. Our results for the quasar survey will be compared with those discussed by Tananbaum et al. (1979). Finally, the implications of the discovery of a large number of quasars will be briefly discussed. (Cosmological parameters of $q_o = 0$ and $H_o = 50$ km (s Mpc)$^{-1}$ are used throughout.)

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2. X-RAY ACTIVE GALAXIES

2.1. Seyfert Galaxies

Four out of four type I Seyferts observed have been detected: 3C120, NGC3227, NGC3516, and X Comae. Four additional Seyferts were discovered serendipitously (see Table 1). They range in 0.5-4.5 keV X-ray luminosity from $L_x = 10^{41.2}$ erg s^{-1} to $L_x = 10^{44.0}$ erg s^{-1}. These values are somewhat lower than the 2-10 keV X-ray luminosities reported by Tananbaum et al. (1978) and Elvis et al. (1978). Two of these Seyferts, 3C120 and NGC3227, were identified as X-ray sources prior to the launch of the Einstein Observatory. While the flux that we measure for 3C120 agrees well with previously published values for the source (e.g., Tananbaum et al. 1978), NGC3227 appears to have varied. If we adopt a photon spectral index of $\alpha = -2$, consistent with our data, the 0.5-4.5 keV luminosity of the Ariel V measurement (Elvis et al. 1978) is approximately an order of magnitude greater than $L_x = 1.8 \times 10^{41}$ erg s^{-1} obtained with the IPC on 20 May 1979. Source confusion with three nearby distant clusters (not detected in the IPC observation) is not likely to explain the discrepancy.

2.2. N Galaxies

Five N galaxies have been detected: 3C109, 3C227, PKS1417-190, RN73, and 3C445. One of these, 3C445, was suggested as an X-ray source by Marshall et al. (1979) on the basis of HEAO-1 data. They measured a 2-10 keV luminosity of 4.5×10^{44} erg s^{-1}, two orders of magnitude greater than the 0.5-4.5 keV luminosity measured by the IPC on 25 May 1979. Their measurement included emission from the Abell cluster 2440 (D = 4, R = 0) which appears $\sim$ 5 times brighter than 3C445 in the IPC measurement. With the cluster contribution removed, however, long-term time variability for the source remains a possibility.

The 0.5-4.5 keV X-ray luminosity of these N galaxies can be large, exceeding 10^{45} erg s^{-1} in the case of 3C109, placing it well within the quasar class. 3C109 is also notable as the only active galaxy in our sample to show large absorption: $N_H = 10^{22}$ cm^{-2}. In all other cases where sufficient numbers of photons were detected for spectral analysis, the absorption is $< 3 \times 10^{21} cm^{-2}$.

2.3. BL Lacs

Seven BL Lacs have been detected: OB81, 0109+225, 0235+164, 0735+178, 4C20.29, AP Libra, and I Zw186. All of these are new X-ray detections; this nearly doubles the number of detected members of this class (see Schwartz et al. 1979). Where absorption redshifts have been measured, the luminosties calculated on the basis of the most distant measured redshifts are within the range from 10^{43} to 10^{46} erg s^{-1}, comparable to those values obtained previously for other BL Lacs and quasars. A factor of 2 variation in the flux has been observed in the

TABLE 1

Active Galaxies Observed with the IPC on Board the Einstein Observatory

Name	Redshift	Log L_x (0.5–4.5 keV)* (ergs s^{-1})	Name	Redshift	Log L_x (0.5–4.5 keV)* (ergs s^{-1})
Seyfert Galaxies			Quasars		
1E0038+061	0.067	43.27	PHL957	2.69	<46.91
3C120	0.033	43.93	0237–234	2.223	47.16
NGC3227	0.0033	41.25	PKS0420–014	0.915	46.26
1E1059+73	0.085	43.18	4C05.34	2.877	<47.02
NGC3516	0.0093	41.58	KP0805.4	2.11	<46.50
X Comae	0.091	43.92	0906+015	1.018	46.02
1E1557+272	0.066	43.08	TON490	1.633	46.60
1E1705+607	0.077	43.14	3C273	0.158	45.88
			5C04.105	0.650	45.25
N Galaxies			5C04.127	1.373	<46.02
			W61972	1.922	46.54
3C109	0.306	45.23	W22722	1.770	<46.47
3C227	0.085	43.30	W21541	2.047	<46.67
PKS1417–190	0.119	44.50	OQ172	3.53	47.81
RN73	0.047	42.70	PKS1510–089	0.361	45.32
3C445	0.057	42.83	1E1526+286	0.45	45.20
			3C323.1	0.264	45.29
			TON256	0.131	44.53
BL Lacs			NAB1612+266	0.395	44.49
			4C39.46	1.082	<45.76
OB81	...	...	4C38.41	1.814	46.45
0109+225	...	...	KP1703.5	1.98	46.40
0235+164	0.852	45.90	3C351	0.371	44.96
0735+178	0.424	45.17	1729+501	1.111	<45.92
4C20.29	...	...	1E2215–037	0.24	44.49
AP Libra	0.050	43.17	PKS2216–038	0.901	45.80
I Zw186	0.055	44.16	MR2251–178	0.068	44.47

*At the source, H_0 = 50 km (s Mpc)$^{-1}$, q_0 = 0.

source AP Libra for two observations separated by five months. No short time scale (< 10^4 s) variability has yet been found for any of the BL Lacs.

2.4. Quasars

We have searched for X-ray emission from 27 quasars. Nineteen have been detected in X-rays ranging in redshift from z = 0.068 (MR2251-178) to z = 3.53 (OQ172). Two of these quasars, 3C273 and MR2251-178, were known to be variable X-ray sources prior to the launch of the Einstein satellite. Two were discovered serendipitously. Detailed discussion of these quasars will be presented elsewhere; we discuss 3C351 as a typical example of the investigations possible.

The quasar 3C351 has been observed five times over a span of six months. Figure 1 shows a plot of the 0.4-3.3 keV X-ray light curve;

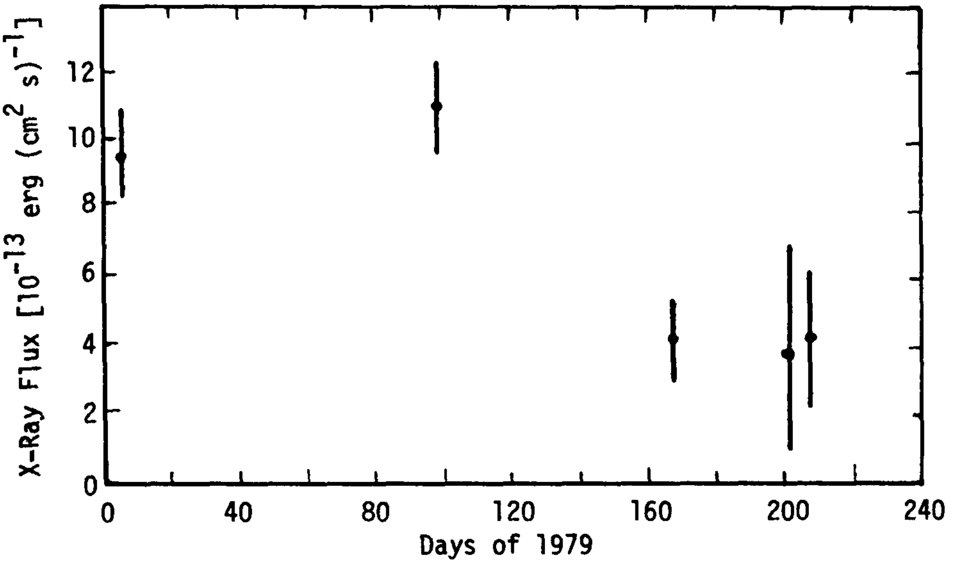

FIG. 1. - The 0.4-3.3 keV X-ray flux from 3C351 measured by the IPC as a function of time.

clear evidence for a factor of 2 to 3 change in the flux is apparent. O'Dell (1979) obtained UBVRJHK photometry of this quasar in late March 1979. We plot his data in Figure 2 along with radio data from Miley and Hartsuijker (1978), infrared data from Neugebauer et al. (1979), and X-ray data obtained by the IPC on 8 April 1979. This quasar shows a steep infrared slope (1.4) which appears to continue into the X-ray regime in common with several other quasars.

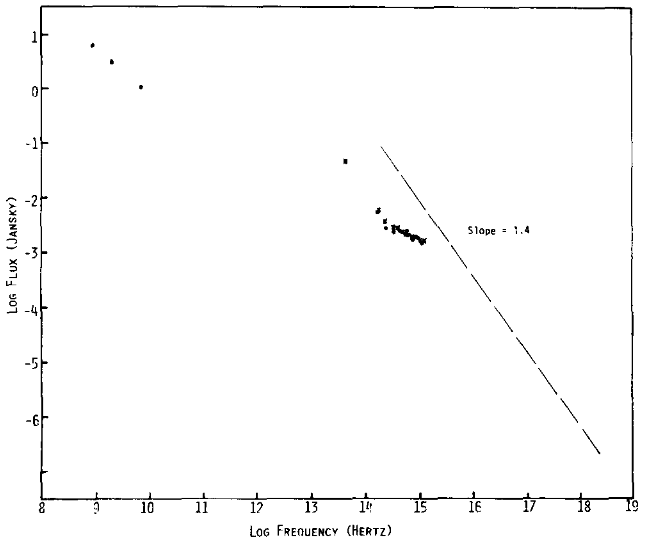

FIG. 2. - Multifrequency spectra of 3C351. Radio data are from Miley and Hartsuijker (1978), optical data (x) from Neugebauer et al. (1979) and (•) O'Dell (1979), and X-ray data from IPC measurements on 8 April 1979.

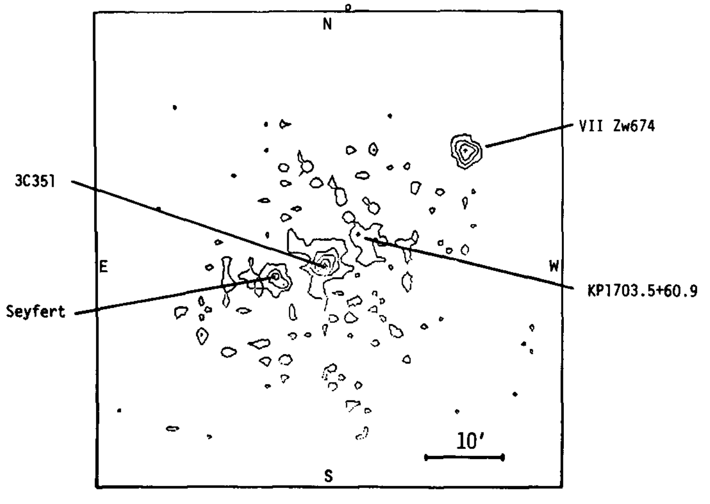

FIG. 3. - IPC map of the $1^{\circ} \times 1^{\circ}$ field centered on 3C351. A total of 4820 s of data acquired on 6 January 1979 and 8 April 1979 are summed to form this contour map. Contour levels are 9, 15, 22.7, 32.3, and 43.6 counts (64" x 64" pixel)$^{-1}$.

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High resolution imager (HRI) maps show that the X-ray emission from 3C351 is coincident to within 3" of the optical object. An IPC map of the region, including 4820 s of data accumulated on 6 January and 8 April 1979, provides some evidence for the presence of a diffuse $\sim$ 1' X-ray source around 3C351 (Figure 3). Hintzen and Scott (1978) have suggested that asymmetric radio morphology of sources such as 3C351 may indicate the presence of a cluster environment. Deeper observations of the field should detect the presence of hot cluster gas if it is as bright as $\sim$ 10% of the quasar.

The X-ray map is also noteworthy due to the presence of at least two other strong sources in the field. One of them is a newly identified Seyfert galaxy at z = 0.077 (Chanan 1979). The other has been tentatively identified with VII Zw674, a compact Zwicky galaxy. Optical spectra obtained for this object by Margon (1979) show it to have a normal spectrum, devoid of emission lines. Finally, at least one quasar candidate KP1703.5+60.9 (z = 1.98), discussed by Sramek and Weedman (1978), may be responsible for the emission to the northwest of 3C351.

3. STATISTICAL PROPERTIES OF THE CLASSES OF OBJECTS

While it is clear from the highly variable nature of the X-ray and optical emission of active galaxies that single-epoch, multi-frequency spectral observations are extremely important toward understanding the nature of these powerhouses, observational constraints imposed by satellite operations make this a difficult ideal to achieve. On the other hand, given the large number of these objects which can be detected in the X-ray regime, statistical studies of a good sample can provide useful clues to their true nature as well as their evolution.

Class averages and correlation coefficients (ρ) have been calculated to try to relate the various X-ray active galaxies to one another and to their properties in other regions of the electromagnetic spectrum. Correlations between the X-ray flux (2 keV), the optical flux (2500 Å), the infrared flux (10 μ), the radio flux (1.4 GHz), the U-B and B-V colors, the radio slope, the infrared slope, the redshift, and the L_x/L_o ratio were checked. For all the CAL active galaxies there is good correlation $\{\rho = -0.61\ (5.1\ \sigma)\}$ between the optical and the X-ray fluxes (see Figure 4). The X-ray and infrared fluxes appear to correlate well as do the optical-to-X-ray continuation slope and the infrared (1-10 μ) slope ($\sim$ 1.3), but only a small fraction of the sources in the sample have been measured in the infrared (Neugebauer et al. 1979). There is, however, no correlation between the X-ray flux and the radio flux measured at 1.4 GHz. Possible correlation between X-ray flux and the central radio flux may exist, but only a fraction of the radio sources has been resolved thus far. When only the detected quasars in the sample were considered, a significant correlation $\{\rho = -0.52\ (2.1\ \sigma)\}$ was found for the relationship between the logarithm of the X-ray flux and the logarithm of the redshift z. The value of ρ remained the same, but the significance improved to 3.7 σ when all 50 of the known X-ray quasars

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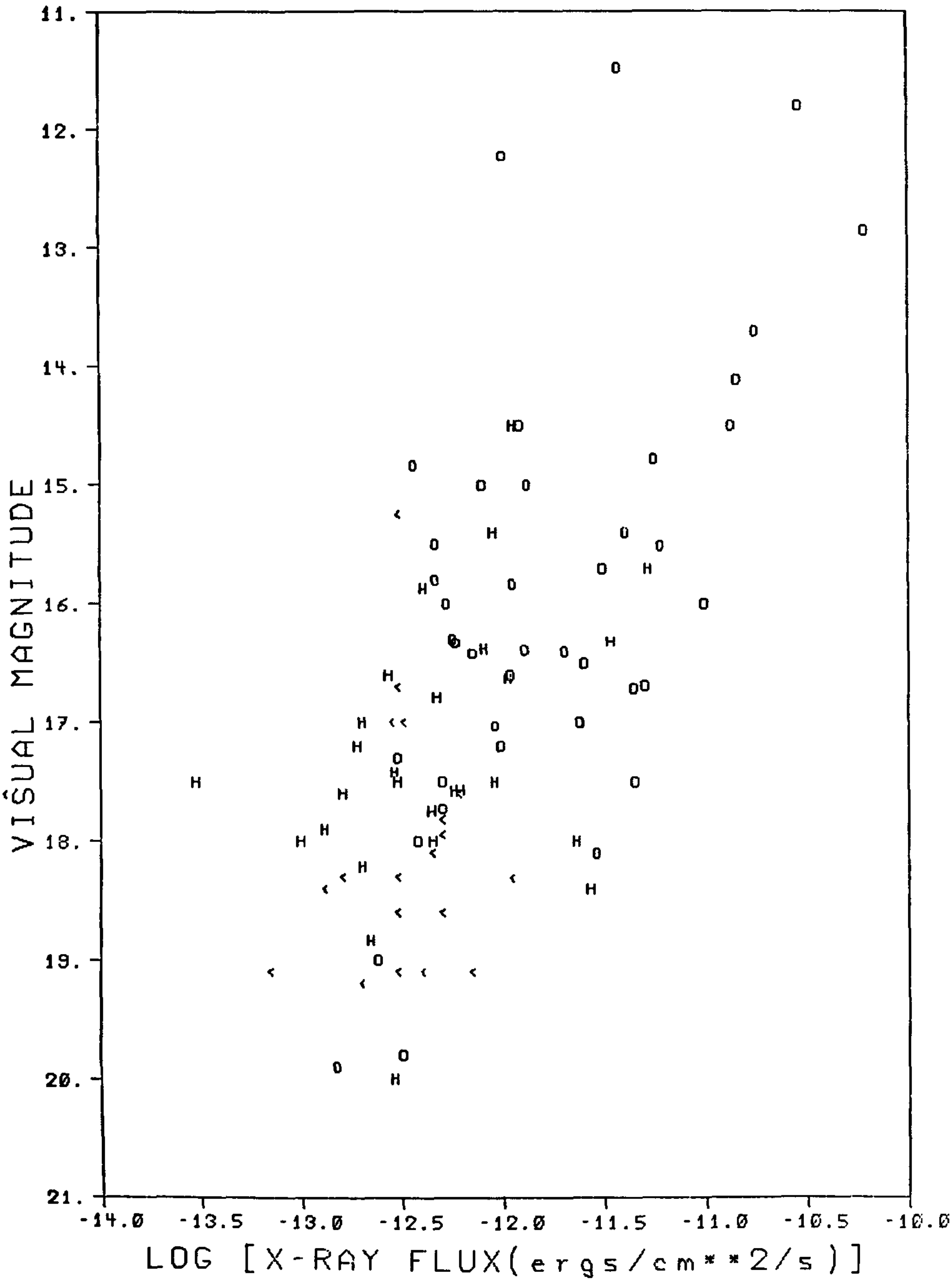

FIG. 4. - Visual magnitude versus log 0.5-4.5 keV X-ray flux for sample of 86 active galaxies. Those with z > 0.5 are shown as H, those with z < 0.5 are shown as 0, and those with only X-ray upper limits are shown as <.

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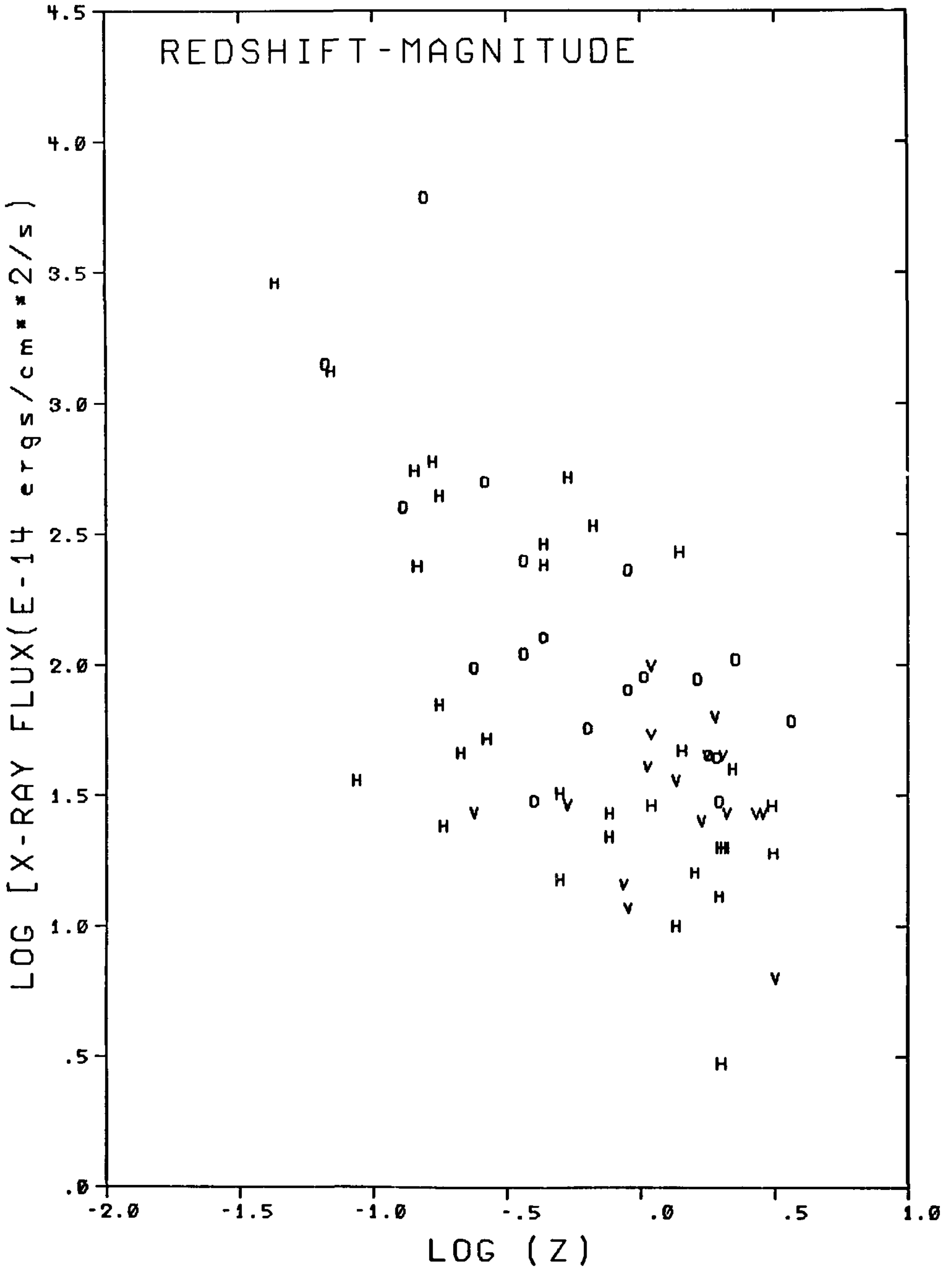

FIG. 5. - Log 0.5-4.5 keV X-ray flux versus log z for sample of 66 quasars. Those quasars measured by CAL are shown as O, those measured by Tananbaum et al. (1979) are shown as H, and those with only X-ray upper limits are shown as V.

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were considered (Figure 5). The large scatter in X-ray luminosities, however, makes it doubtful that they may be used as standard candles in cosmological tests. No other significant correlations were found.

Given the good correlation between the logarithms of the X-ray and optical fluxes, the X-ray luminosity in the 0.5-4.5 keV band may be usefully compared to the optical luminosity centered on 2500 Å at the source as defined by Schmidt (1968). The average L_x/L_o for our sample of 19 quasars is 0.55 ± 0.13 compared with a value of 0.78 ± 0.2 measured by Tananbaum et al. (1979). We note that the ratio L_x/L_o may have a high bias for both samples; the ratio found by Tananbaum et al. (1979) is dominated by the measurements for three radio-bright quasars, 3C47, 3C446, and PKS0537-286, the first two of which are known optical variables. These quasars, in addition to a similar quasar from our sample, PKS0420-014, may have been flaring at the time of their measurements. Both 3C446 and PKS0420-014 have flared by 2 to 3 optical magnitudes within the past year (Smith 1979). Given that a high percentage (24%) of observed quasars was not detected, the importance of a threshold effect (that is, the increased probability of detection when the quasar is flaring) and proper account of the effects of upper limits on the mean L_x/L_o for the total sample of quasars (Avni et al. 1979) should be emphasized. The L_x/L_o ratio was found to be independent of z for the total sample of 66 quasars studied. It was also found to be independent of the class of the object, with the possible exception of Seyferts which have low L_x/L_o.

TABLE 2

Summary of Survey of Active Galaxies and Quasars

Class	Number in Sample: Total Observed	Detected in X-Rays	New Objects	Log L_x (0.5–4.5 keV)* (ergs s^{-1})	Average L_x/L_o
Seyfert I	8	8	(4)	41.2–43.9	0.18
N Galaxy	5	5		42.7–45.2	0.60
BL Lac	7	7		43.2–45.9	0.40
Quasar	27	19	(2)	44.5–47.8	0.63
All Quasars	66	50	(7)	43.1–47.8	0.69

*At the source, H_0 = 50 km (s Mpc)$^{-1}$, q_0 = 0.

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4. DISCUSSION

Table 2 summarizes the range of properties exhibited by the active galaxies in our sample. There is good evidence for a continuity of high energy behaviour among all active galaxies. There is considerable overlap between the X-ray luminosities and X-ray-to-optical behaviour of these objects. All exhibit flux variability, often on a short time scale, indicating that the size of the emission region must be extremely small. Rapid time variability, on a time scale of hours, as reported by Tananbaum et al. (1979) can be used to set restrictive limits on the source parameters, for example, the mass of the black hole.

In the context of the synchrotron self-Compton model (Jones, O'Dell, and Stein 1974), one can understand the soft X-ray emission if one assumes that it arises from the tail of the optical synchrotron emission and that the first-order Compton emission occurs at higher X-ray energies. The reasonably good correlation found between the optical and the X-ray flux supports this view. Mushotsky et al. (1979) noted that such a scenario may plausibly account for the soft X-ray excess observed in several BL Lac objects. An alternative explanation in terms of thermal emission from hot gas with kT $\sim 5 \times 10^6$ K (Agrawal and Riegler 1979) may also account for the soft X-ray emission.

Derivation of a quasar luminosity function from X-ray studies can lead to important insights into the contribution of quasars to the diffuse X-ray background and the evolution of quasars. However, because the quasars thus far studied do not form a complete, independent sample, such a derivation is not yet possible. On the other hand, one may use the X-ray-to-optical relationship and the optical quasar counts to infer their contribution to the diffuse X-ray background. Following the analysis of Tananbaum et al. (1979), the average L_x/L_o ratio measured from our sample suggests that quasars can account for all the high latitude diffuse soft X-ray background if the optical quasar count given by Braccesi et al. (1979) holds to 20.6 magnitudes. Detailed analysis of the spectral information available from the IPC observations should allow us to estimate how much quasars contribute to the diffuse X-ray background in the region above the 4.5 keV energy limit of the IPC.

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