THE ASTROPHYSICAL JOURNAL, 297:633–638, 1985 October 15

OBSERVATION OF SOFT X-RAY SPECTRA FROM A SEYFERT 1 AND A NARROW EMISSION-LINE GALAXY

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Received 1984 November 9; accepted 1985 April 18

ABSTRACT

We report soft X-ray spectral observations of the Seyfert 1 galaxy, Mrk 509, and the narrow emission-line galaxy, NGC 2992. Spectral analysis of the simultaneously obtained 0.2–40 keV pulse height data is presented. The absorbing column density N_H, in the line of sight to Mrk 509 is found to be consistent with no absorption intrinsic to the source. A two-component spectrum in Mrk 509 is required, under the assumption that the galactic obscuration is at least that measured on a large scale by 21 cm line surveys. The soft spectral component in Mrk 509 is interpreted as thermal emission from a hot gas. The X-ray spectrum of NGC 2992 is well described by a single-component power law with photon index, $\Gamma = 1.78$ and $N_H = 4 \times 10^{21}$ cm^{-2}. The N_H obtained in its line of sight is less than the value predicted from the reddening of Balmer lines but comparable to that predicted from the nonstellar optical continuum. A partial covering by "patchy" absorbers is indicated for NGC 2992. The covered fraction seems to be variable over a time scale of a few years.

Subject headings: galaxies: Seyfert — X-rays: sources — X-rays: spectra

I. INTRODUCTION

The Seyfert 1 galaxies and the narrow emission-line galaxies (NELGs) are well-known strong X-ray emitters. Petre *et al.* (1984), based on *Einstein Observatory* SSS data, reported that spectra of the 12 most luminous Seyfert 1 galaxies are generally consistent with a single power law of photon index $\Gamma \approx 1.7$ over the energy range 0.75–4.5 keV with no apparent intrinsic absorption. A similar spectral slope was earlier reported by Mushotzky *et al.* (1980) and Mushotzky (1982) for the 14 most luminous Seyfert 1 galaxies and 5 NELGs observed by the *HEAO 1* MED experiment over the energy range of 2–40 keV. Although the spectral slopes of Seyfert 1 galaxies and NELGs are indistinguishable from each other, the NELGs are inherently fainter and display evidence of cold gas with column densities exceeding 10^{22} cm^{-2} in the line of sight (Mushotzky 1982). Excess soft X-ray emission has been reported from only two Seyfert 1 galaxies so far: NGC 4151 (Holt *et al.* 1980) and E1615+061 (Pravdo *et al.* 1981) with only the latter showing an unusually steep spectrum ($\Gamma > 3$). A steep soft X-ray spectral component has also been reported from the low-luminosity active galactic nucleus of M81 (Elvis and Van Speybroeck 1982) and three high-luminosity quasars: E1821+643 (Pravdo and Marshall 1984), MR 2251−178 (Halpern 1984), and PG 1211+143 (Elvis, Wolkes, and Tananbaum 1985). Strong evidence for a similar component in a well-known Seyfert 1 galaxy, 3C 120, has also been reported by Petre *et al.* (1984).

In this paper we present observations made with the Low Energy Detectors (LED: 0.18–2.8 keV) of the *HEAO 1* A-2[2] experiment of one NELG, NGC 2992, and a Seyfert 1 galaxy, Mrk 509. NGC 2992 has been observed to contain a starlike nucleus with a broad Hα emission component (Véron *et al.* 1980), thus qualifying as a galaxy with a (strongly absorbed) Seyfert 1 nucleus. Mrk 509 is a Seyfert 1 nucleus that probably lies in an elliptical host galaxy (Adams 1977; Phillips *et al.* 1983). These galaxies have been previously recognized as strong and variable X-ray sources (Griffiths *et al.* 1979; Mushotzky *et al.* 1980; Marshall, Warwick, and Pounds 1981; Mushotzky 1982; Maccacaro, Perola, and Elvis 1982; Petre *et al.* 1984). We present the spectral analysis of the pulse height data obtained simultaneously from the LED and the higher energy (2–40 keV) X-ray detectors on board the *HEAO 1*.

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II. OBSERVATIONS

The *HEAO 1* A-2 experiment has been described in detail by Rothschild *et al.* (1979). It consists of six multiwire, multilayer gas proportional counters sensitive over the 0.18–60 keV band. The X-ray data reported here were taken in the pointed mode of observation by the low-energy detector, LED 1, which is sensitive in the 0.18–2.8 keV band and has specially designed mechanical collimators with two fields of view: $1.^\circ58 \times 2.^\circ97$ and $2.^\circ92 \times 2.^\circ80$. The collimator design enabled us to infer the separate contributions from a source and the X-ray sky background when the detector was pointed at a single position in the sky. The total effective area for these observations is 381.9 cm^2. Aspect information acquired from an onboard star tracker was used to determine the position of the source in the detector collimator and to correct for drifts in the pointing direction of the spacecraft during the course of observation. However, since the source contribution was relatively small, data over long periods of observation were summed and only an average correction due to pointing errors was applied.

An average internal detector background, determined from the epochs when the LEDs were pointed towards dark Earth, was subtracted from the LED 1 data before the source and X-ray background contributions were inferred. This method was applied to both the scalar data and the pulse height analyzed (PHA) data.

The *HEAO 1* A-2 experiment was pointed at the following Seyfert and narrow emission-line galaxies: Mrk 509, NGC 6814, NGC 3783, NGC 4151, NGC 2992, and MCG 5-23-16. Table 1 summarizes the LED observations of these galaxies.

TABLE 1

LOW ENERGY DETECTOR OBSERVATIONS OF SEYFERT AND NARROW EMISSION-LINE GALAXIES

Object	Data of Observation (*HEAO* A-2 Pointings)	Exposure (s)	LED 1 counts s^{-1} [a]	
			0.15–0.28 keV	0.45–2.8 keV
Mrk 509	1978 May 8	1760	1.38 ± 0.3	1.43 ± 0.18
NGC 2992	1978 May 24	2620	<0.75	0.90 ± 0.14
NGC 3783	1978 Jan 5	819	<0.9	<0.9
NGC 4151	1977 Dec 6	1230	<0.9	0.8 ± 0.2
NGC 6814	1978 Apr 28	450	<1.5	<0.6
MCG 5-23-16	1978 May 12	1475	<1.5	<1.2

NOTE.—Field of view: $\sim 1\overset{\circ}{.}5 \times 3\overset{\circ}{.}0$.

[a] Upper limits are 3 σ everywhere; errors are only 1 σ.

Significant detection was only made of Mrk 509 and NGC 2992. NGC 4151 was marginally detected (4 σ) in the 1 keV band.

Mrk 509 was observed by the *HEAO 1* A-2 detectors in the pointed mode on 1978 May 8. The observations started at 1737 UT and lasted for ~ 5 hr. After rejecting data obtained while the electron contamination was high and the spacecraft was in the Sun, useful data for 1760 s were obtained. Using the procedure described above, X-rays were detected in the 1 keV band (0.44–2.8 keV) from the source with a rate of 1.43 ± 0.18 counts s^{-1} in the front layer of LED 1. The count rates mentioned here refer the smaller field of view of LED 1. The source was detected at the same strength even when the data were divided into four nearly equal intervals. This implies that the X-ray emission from this galaxy was constant during the observations. Simultaneous observations of this galaxy with the higher energy (2–40 keV) *HEAO 1* A-2 detectors have already been reported by Mushotzky *et al.* (1980).

HEAO 1 A-2 detectors were pointed at NGC 2992 for ~ 2 hr starting at 0912 UT on 1978 May 24 and useful data for 2620 s were obtained. X-rays were detected from this galaxy in both the front layer (count rate = 0.90 ± 0.14 counts s^{-1}) and the second layer of LED 1 (count rate = 0.65 ± 0.07 counts s^{-1}). The source was detected at the same strength in those bands even when the data were divided into two equal time intervals. Mushotzky (1982) reported simultaneous observations of NGC 2992 with the higher energy (2–40 keV) *HEAO 1* A-2 detectors. NGC 4151 was also observed simultaneously with the higher energy *HEAO 1* A-2 detectors (Mushotzky *et al.* 1980).

III. SPECTRAL ANALYSIS

We have carried out spectral fits to the pulse height data of Mrk 509 and NGC 2992 obtained from both the LED 1 and HED 3 detectors spanning the energy interval from 0.18–40 keV. The relative normalization factor between the two detectors was determined from the analysis of the X-ray pulse height data obtained from the Crab Nebula. The spectral analysis was started by fitting the pulse height spectra (shown in Fig. 1) to a simple model consisting of a uniformly absorbed, single-component power-law continuum. The results of these fits are summarized in Table 2A, which lists for each galaxy the best-fit normalization, photon spectral index Γ, the column density N_H, the 90% confidence ranges in Γ and N_H according to ${\chi_{min}}^2 + 6.2$ criterion (Lampton, Margon, and Bowyer 1976), the minimum value of χ^2, the number of degrees of freedom ν, and the soft X-ray flux observed. In general, this simple model provides accaptable fits to the pulse height data. However, the $N_H = 10^{19}$–10^{20} cm^{-2} implied for Mrk 509 is significantly lower than the Galactic absorption in the direction of this source ($l = 26°$, $b = 29\overset{\circ}{.}8$). The N_H value expected from the large-scale H I column density measurements of Heiles (1975) is 5×10^{20} cm^{-2}. When the N_H was fixed at 5×10^{20} cm^{-2}, the simple model above was not acceptable (99% level) as an explanation of the pulse height data. The fit is extremely poor in the 0.2–0.8 keV range where an excess X-ray flux is observed as shown in Figure 1 for Mrk 509, thus requiring the presence of a second soft component in the X-ray spectrum of Mrk 509. The results of spectral fitting to two-component (either both power laws or power law and thermal bremsstrahlung) are shown in Table 2B, which lists the best-fit parameters. The N_H was not allowed to vary below 5×10^{20} cm^{-2} in these fits. The change in the minimum χ^2 and the corresponding value of F-statistic (Bevington 1969) are also listed. Here the change in χ^2 is the decrease in the minimum value of χ^2 relative to that obtained for the simple model for the same N_H. Thus, the simple model for Mrk 509 can be rejected in favor of a two-component model at a confidence level exceeding 99%. The soft (0.18–1.0 keV) X-ray flux observed for this second component is 3.8×10^{-11} ergs cm^{-2} s^{-1}, implying an X-ray luminosity (L_x) = 2.1×10^{44} ergs s^{-1}, for a redshift of 0.036 and a Hubble constant (H_0) of 50 km s^{-1} Mpc^{-1}. A two-component model is not required to explain the pulse height spectrum of NGC 2992.

Analysis of *Einstein* SSS observations of NGC 2992 by Reichert *et al.* (1985) showed that a significant partial covering of the X-ray source in NGC 2992 is required. The partial covering model used by Reichert *et al.* (1985) consisted of two power-law components with the same spectral index, but different normalizations and absorbing columns. Spatially uniform absorption is assumed in front of both covered and uncovered components with respective column densities of $>2 \times 10^{22}$ cm^{-2} and $<10^{22}$ cm^{-2}. The fraction of the source covered is given by the ratio of the normalization of the highly absorbed component and the sum of the normalizations. The results of our fits to these models for NGC 2992 are shown in Table 2C, which lists the best-fit spectral index (as a free variable and also as constrained by the results of simple power-law fits), covering absorption column density and the covered fraction, the change in minimum χ^2 with respect to the simple single component model and the corresponding value of the F-statistic. The simple model appears to be rejected at a confidence level >99%. The soft X-ray flux observed from the uncovered component is 2.4×10^{-11} ergs cm^{-2} s^{-1} which corresponds to $L_x = 5.4 \times 10^{42}$ ergs s^{-1}, for the known redshift of 0.0073 of this galaxy ($H_0 = 50$ km s^{-1} Mpc^{-1}).

TABLE 2

SUMMARY OF SPECTRAL FITS

A. SINGLE POWER-LAW SPECTRA

Source	Normalization[a]	Γ	N_H[b]	χ^2_{min}/ν	Soft (0.2–2.0 keV) X-Ray Flux[c]
Mrk 509	1.20×10^{-2}	1.72(1.68–1.76)	0.04(0.01–0.11)	27/28	5.0
	1.25×10^{-2}	1.75	0.5	52/29	...
NGC 2992	2.7×10^{-2}	1.78(1.75–1.82)	4.0(0.28–0.48)	42.2/34	2.4

B. TWO-COMPONENT SPECTRUM—SOURCE: MRK 509

FIRST COMPONENT			SECOND COMPONENT					EXCESS SOFT (0.2–1.0 keV) FLUX[c]
Normalization[a]	Γ	N_H[b]	Normalization[a]	Γ or kT	N_H[b]	$\Delta\chi^2$	F[d]	
1.0×10^{-2}...........	0.64(1.6–1.7)	0.5	5.4×10^{-3}	Γ = 4.5(3.8–4.9)	0.5	31	37	3.8
1.0×10^{-2}...........	0.64(1.6–1.7)	0.5	4.9×10^{-1}	kT = 0.2(0.18–0.30)	0.5	24	25	3.8

C. PARTIALLY COVERED MODELS—SOURCE: NGC 2992

Γ	N_H[b,e]	Covered Fraction	$\Delta\chi^2$	F[d]
1.96.........	112	0.26–0.42	9.2	8.9
1.83.........	56	0.13–0.34	5.1	4.9

[a] Units: photons cm^{-2} s^{-1} keV^{-1}.
[b] Units: 10^{21} cm^{-2}.
[c] Units: 10^{-11} ergs cm^{-2} s^{-1}.
[d] $F = \Delta\chi^2/\chi^2_\nu$, where χ^2_ν is the minimum reduced χ^2 for the two-component or partially absorbed model.
[e] Best-fit absorbing column for covered component.

When the hard X-ray flux of NGC 4151 was extrapolated using the spectral parameters derived from simultaneous observations of Mushotzky *et al.* (1980), it failed to account for the observed flux by a factor of ~100. The observed soft X-ray flux requires the N_H to be as low as 5×10^{21} cm^{-2} as compared to the value of 10^{23} cm^{-2} determined by Mushotzky *et al.* (1980). The excess soft X-ray flux could have been due to leaky absorber or partial covering model as has been postulated earlier by Holt *et al.* (1980); however, lack of spectral information prevents us from calculating the covered fraction of the source in NGC 4151.

No evidence for intrinsic absorption has been found for Mrk 509 either in the present experiment or in the previous observations with the *Einstein* SSS by Petre *et al.* (1984). Therefore, a partial covering model seems to be inapplicable to Mrk 509.

No acceptable fits could be obtained for the broad-band pulse height data of Mrk 509 and NGC 2992, using thermal bremsstrahlung (exponential plus Gaunt factor) models.

IV. LONG-TERM INTENSITY VARIABILITY

The soft X-ray emission from Mrk 509 and NGC 2992 might be variable as reported by Petre *et al.* (1984) for Mrk 509 and by Maccacaro *et al.* (1982) for NGC 2992, as well as E1615+061 (Pravdo *et al.* 1981) and E1821+643 (Pravdo and Marshall 1984). Although Mrk 509 and NGC 2992 were scanned at intervals of 6 months, soft X-ray emission was not detected from them during the scanning observations. The nondetection by the LEDs during scans is, however, consistent with their observed intensity during pointing observations. Therefore, we do not find evidence for variability of soft X-ray emission from Mrk 509 and NGC 2992. NGC 2992 was observed with the IPC at three different epochs by Maccacaro, Perola, and Elvis (1982). The found that its soft X-ray luminosity increased from $10^{42.3}$ to $10^{42.7}$ ergs s^{-1} over a period of 6 months with a near simultaneous increase in the hard X-ray luminosity measured by the MPC, from $10^{42.7}$ to $10^{43.2}$ ergs s^{-1}. The soft and hard X-ray luminosities of NGC 2992 measured with *HEAO 1* are comparable to the maximum value reported by Maccacaro, Perola, and Elvis (1982).

V. DISCUSSION

Mrk 509 has been observed in the optical and UV bands by Wu, Boggess, and Gull (1983) and its UV–optical (1200 Å–10 μm) power-law spectrum has been found to be significantly steeper than the Γ = 1.64 power law for >2 keV X-rays, suggesting that spectral steepening must occur somewhere in the extreme UV-soft X-ray region in order to join the UV and X-ray continua. We have now observed that this steepening does indeed occur at energies less than 0.8 keV, and that both the soft and hard X-ray spectral components of Mrk 509 have no intrinsic absorption. The present data, therefore, exclude the possibility that our line of sight to the active galactic nucleus of Mrk 509 passes through the disk of a host or an intervening normal spiral galaxy.

Observation of a steep soft X-ray component from Mrk 509 places this well-known Seyfert galaxy in the same class as the Seyfert galaxy E1615+061 (Pravdo *et al.* 1981), quasars E1821+643 and PG1211+143 (Pravdo and Marshall 1984; Elvis, Wolkes, and Tananbaum 1985), and BL Lacertae–type objects, with the differences that soft X-rays are not the dominant emission and that strong variability is not observed. Steep, low-energy X-ray spectra in BL Lac type objects have been interpreted either as the high-frequency energy loss tail of a synchrotron component from relativistic jets (Marscher 1980) or due to a synchrotron self-Compton (SSC) process (Jones, O'Dell, and Stein 1974). However, lack of strong radio emission and optical or radio polarization from Mrk 509 makes the above-mentioned emission processes doubtful candidates for explaining the steep, soft X-ray component.

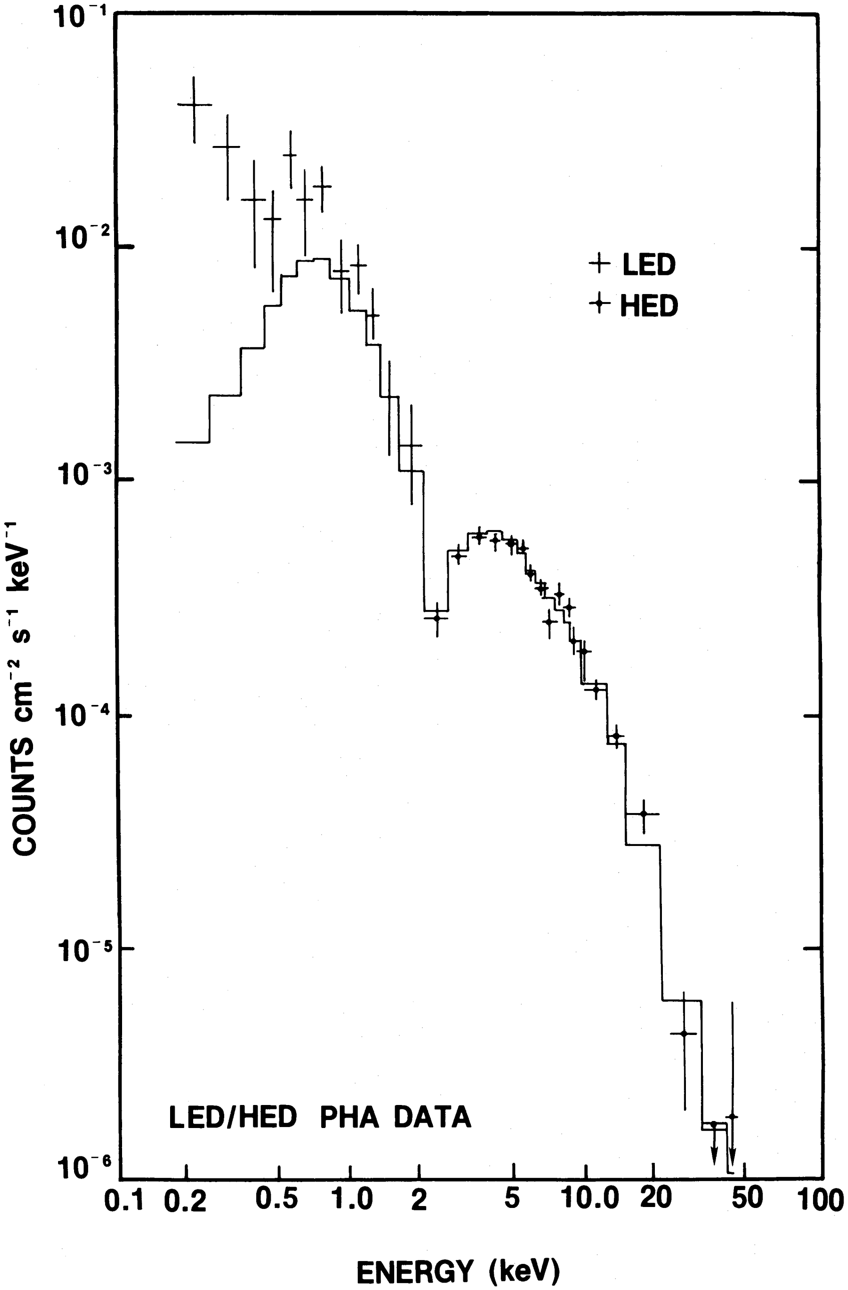

FIG. 1*a*

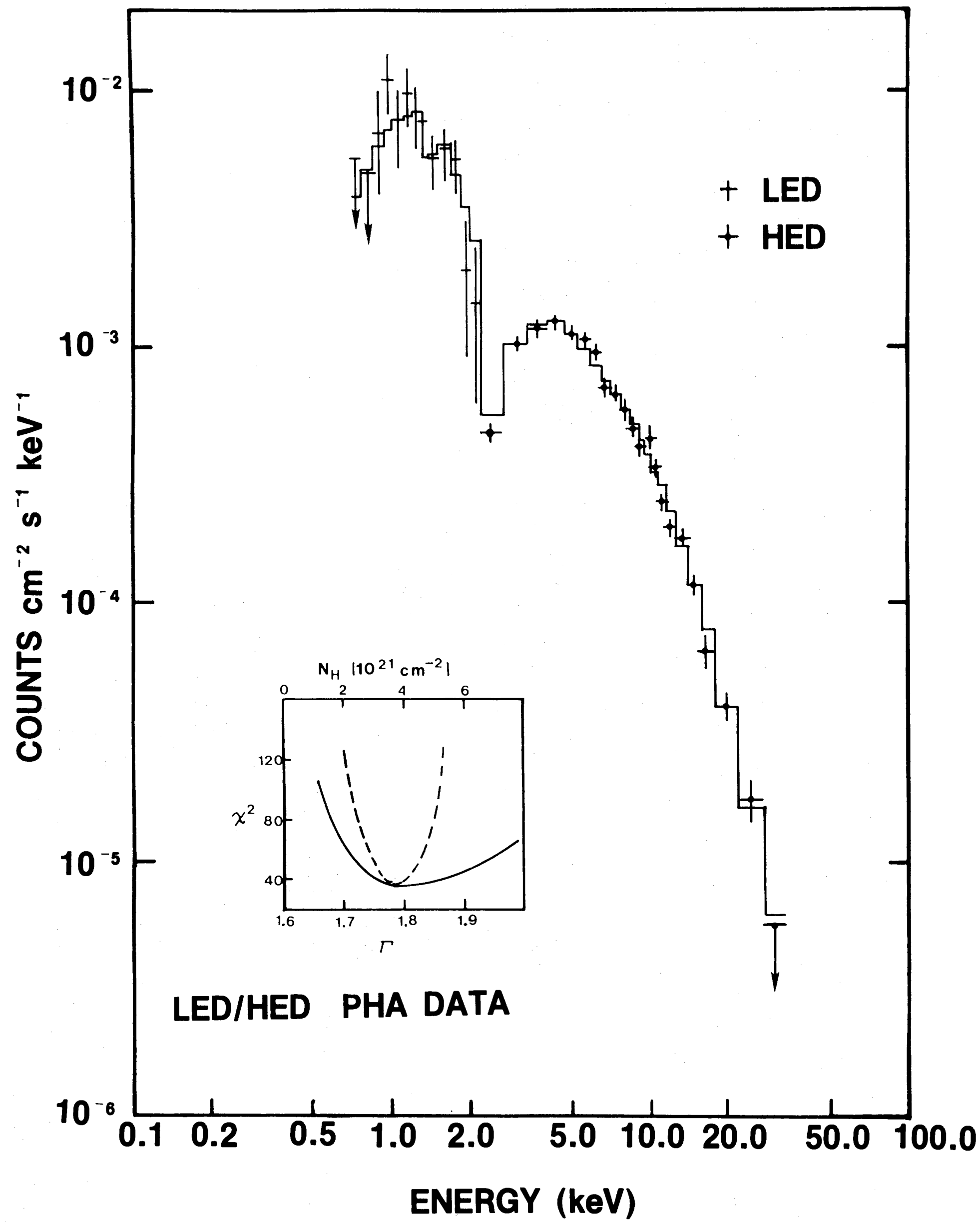

FIG. 1*b*

FIG. 1.—(*a*) The pulse height spectrum from LED and HED observations of Mrk 509. The histogram shows the predicted count rates for the uniformly absorbed, single power-law model with best-fit Γ and normalization, and with fixed $N_H = 5 \times 10^{20}$ H atoms cm^{-2}. (*b*) The pulse height spectrum of NGC 2992 from LED and HED observations. The histogram shows the predicted count rates from the best-fit uniformly absorbed, single power-law model. The inset shows the variation of χ^2 with the photon spectral index Γ and N_H.

TABLE 3

ESTIMATES OF EQUIVALENT HYDROGEN ABSORBING COLUMNS IN NGC 2992

Method	N_H (10^{21} cm^{-2})	Reference
21 cm radio (Galactic)	0.6	1
Continuum	5.3	2
	2.5	3
Narrow-line (Hα/Hβ etc.)	9.8	4
	11.0	5
	10.5	2
	4.5	6
Broad-line (Hα/Hβ)	12.0	7
X-ray cut-off	4.0	8

REFERENCES.—(1) Heiles 1975. (2) Ward *et al.* 1980. (3) Glass 1981. (4) Ward *et al.* 1978, (5) Shuder 1980. (6) Malkan 1983. (7) Maccacaro *et al.* 1982. (8) This work.

Instead, soft X-ray emission from Mrk 509 could be of a completely different origin such as a thermal emission from a hot gas associated with the galaxy. An outflowing system of highly ionized gas, covering much of the Mrk 509 galaxy has been observed recently (Phillips *et al.* 1983). The quasar MR 2251−178, which also shows a soft X-ray excess (Halpern 1984), has an emission-line spectrum similar to that of Mrk 509 and has high-excitation gas out to 150 kpc from the ionizing quasar (Bergeron *et al.* 1983). Similar ionized gas has also been observed surrounding the nucleus of a well-known Seyfert 1 galaxy, 3C 120, which also showed a strong evidence for the existence of a steep, soft X-ray component (Petre *et al.* 1984). Assuming that the observed soft X-ray component in Mrk 509 is due to thermal emission from a hot gas, the observed temperature of $\sim 2.3 \times 10^6$ K and X-ray luminosity $(L_x) \approx 2.1 \times 10^{44}$ ergs s^{-1} imply a volume emission measure $(n_e^2 V) = 5.8 \times 10^{67}$ cm^{-3} (Tucker 1975). This emission measure is a factor $\sim 10^2$–10^4 higher than what is expected on the basis of typical values of the radius ($\sim 10^{17}$ cm) and density (10^6–10^7 cm^{-3}) of the intercloud gas in the broad line region of an AGN (Krolik and London 1983). It is, therefore, more likely that the hot gas responsible for soft X-ray component is much more extensive than the broad-line region and could be associated with the highly ionized gas covering Mrk 509. Assuming an extent, R, of 50 kpc for this hot gas in Mrk 509, we derive an electron density $n_e = 6.1 \times 10^{-2} (R/50 \text{ kpc})^{-3/2}$ cm^{-3}.

A spectral steepening similar to that observed for Mrk 509 is also expected to occur in the spectrum of NGC 2992, somewhere in the extreme UV to X-ray regime, in order to smoothly join the UV and X-ray continua. However, the soft X-ray spectrum of NGC 2992 is cut off at 0.7 keV, and therefore either such a component in NGC 2992 is relatively very faint or the steepening occurs in the extreme UV region.

Table 3 lists several estimates of the hydrogen absorbing columns obtained by various independent methods (references are listed in the table). All these methods except the first and the last are based on the estimate of optical extinction due to dust, which are then converted into N_H values according to the relationship $A_V = 4.0 \times 10^{-22} N_H$ mag (Jenkins and Savage 1974; Seaton 1979). If the simple single power-law model is accepted for the X-ray spectrum of NGC 2992, it indicates an absorption column density consistent with that obtained from measurements of the nonstellar optical continuum, suggesting that the X-ray emission may be produced in the same regions as the optical and infrared continuum emission. Our analysis of the pulse height spectrum of NGC 2992, however, shows that the partial covering model provides a better description of the spectrum of NGC 2992 than a simple model with single power law and absorption. The covered fraction of the X-ray source in NGC 2992 determined by us is about a factor of 2 lower than that estimated by Reichert *et al.* (1985). Thus, it appears that the covered fraction of the X-ray source in NGC 2992 has changed from the time of the *HEAO 1* observations to the time of the *Einstein* observations.

VI. SUMMARY AND CONCLUSIONS

We have analyzed the 0.2–40 keV X-ray spectra of a Seyfert 1 galaxy Mrk 509 and a narrow emission-line galaxy NGC 2992. Our analysis suggests the presence of a steep soft X-ray component in Mrk 509 in addition to the well-known $\Gamma = 1.7$ component found in other active galactic nuclei in the 2–40 keV energy range. No intrinsic absorption is found for either of the two components in Mrk 509. The soft X-ray component is interpreted as due to thermal emission from a hot gas probably associated with the highly ionized gas observed to be outflowing from the Mrk 509 galaxy. The X-ray spectrum of NGC 2992 does not show any steepening in the soft X-ray band and is consistent with a single power law ($\Gamma = 1.78$) with very low N_H (4×10^{21} cm^{-2}). A model with partial covering of the nuclear X-ray source, however, is preferred over that of a simple model with a single power law and absorption. If the partial covering model is correct, a variable covered fraction, varying over a time scale of a few years, seems to be indicated for NGC 2992. In the future, more sensitive soft X-ray observations of active galactic nuclei with high spatial and spectral resolution detectors (CCDs) would help in understanding the nature and origin of soft X-rays from these objects.

We thank Dr. R. F. Mushotzky for many useful suggestions and for providing the simultaneously obtained high-energy (HED 3) data for the galaxies studied in this paper. We thank G. M. Weaver for assistance with the data reduction. One of us (K. P. S.) would like to thank Drs. E. Feigelson and R. Bussard for helpful discussions. We thank an anonymous referee for his suggestions which have greatly improved the presentation of this paper.

This work was supported under NASA contract NAS 5-26809.

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