PROBING AGN WITH MASERS AND X-RAYS-SAX PROPOSALS

NASA Grant NAG5-7064

Final Report

For the Period 1 March 1998 through 31 May 2001

Principal Investigator
Dr. Belinda J. Wilkes

September 2001

Prepared for:

National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this grant is Nicholas White 662.0, National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland 20771.

All work is now complete on this project and the final paper has appeared (see reference list below). The results confirm properties of the source from earlier observations as well as showing strong variability of the flux, but not the spectrum. The emission line is marginally resolved, but not sufficiently so to allow investigation of the velocity of the emitting material. They also show a high energy cut-off which occurs at intriguingly low energies and calls into question standard assumptions on typical cut-off energies. If this source is typical, standard modelling of the Cosmic X-ray Background will need to be revised.

Abstract of final paper, summarizing the results in detail:

> We have made BeppoSAX observations of the Seyfert 2/1.9 galaxy ESO103-G35, which contains a nuclear maser source and is known to be heavily absorbed in the X-rays. Analysis of the X-ray spectra observed by SAX in October 1996 and 1997 yields an energy index = 0.74+/-0.07, typical of Seyfert galaxies and consistent with earlier observations of this source. The strong, soft X-ray absorption has a column density, N_H of (1.79+/-0.09)E23 cmE-02, again consistent with earlier results. The best fitting spectrum is that of a power law with a high energy cutoff at 29+/-10 keV, a cold (E=6.3+/-0.1 keV, rest frame), marginally resolved (σ = 0.35+/-0.14 keV, FWHM ~(31 +/- 12)E03 km/s) Fe Kα line with EW 290 +100 -80 eV (1996) and a mildly ionized Fe K-edge at 7.37 +0.15 -0.21 keV, tau 0.24 +0.06 -0.09. The Fe Kα line and cold absorption are consistent with origin in a accretion disk/torus through which our line-of-sight passes at a radial distance of ~0.01 pc. The Fe K-edge is mildly ionized suggesting the presence of ionized gas probably in the inner accretion disk, close to the central source or in a separate warm absorber. The data quality is too low to distinguish between these possibilities but the edge-on geometry implied by the water maser emission favors the former. Comparison with earlier observations of ESO103-G35 shows little/no change in spectral parameters while the flux changes by factors of a few on timescales of a few months. The 2--10 keV flux decreased by a factor of ~2.7 between Oct 1996 and Oct 1997 with no detectable change in the count rate >20 keV (i.e. the PDS data). Spectral fits to the combined datasets indicate either a significant hardening of the spectrum (energy index ~0.5) or a ~constant or delayed response reflection component. The high energy cutoff (29+/-10 keV) is lower than the typical ~300 keV values seen in Seyfert galaxies. A significant subset of similar sources would affect current models of the AGN contribution to the cosmic X-ray background (CXRB) which generally assume a high energy cutoff of ~300 keV.

Publications to date on this project:

- SAX Observations of the Maser AGN ESO103-G35 Wilkes, B.J., Mathur, S., Fiore, F. & Antonelli, A. BAAS 30, 842

- SAX Observations of the Maser AGN ESO103-G35. Wilkes, B.J., Mathur, S., Fiore, D. & Antonelli, A. in `` Structure and Kinematics of Quasar Broad Line Regions"

eds. C.M. Gaskell, W.N. Brandt, D. Dultzin-Hacyan, M. Eracleous & M. Dietrich, ASP Conference Series, in press

- The BeppoSAX Observations of the Seyfert 1.9 Galaxy ESO103-G35, Antonelli, A., Wilkes, B.J., Fiore, F., Matt, G., Mathur, S. & Nicastro, F., in Proceedings of the 3rd Integral Workshop, Sicily, 14--18 Sept 1998, in press

- BeppoSAX Observations of the Maser Sy2 Galaxy: ESO103-G35 Wilkes, B.J., Mathur, S., Fiore, F., Antonelli, A., Nicastro,F., ApJ, 549, 248

THE ASTROPHYSICAL JOURNAL, 549:248–253, 2001 March 1

BEPPOSAX OBSERVATIONS OF THE MASER SEYFERT 2 GALAXY ESO 103-G35

BELINDA J. WILKES,[1] SMITA MATHUR,[1,2] FABRIZIO FIORE,[3,4] ANGELO ANTONELLI,[3,4] AND FABRIZIO NICASTRO[1]

Received 2000 June 28; accepted 2000 October 23

ABSTRACT

We have made *BeppoSAX* observations of the Seyfert 2/1.9 galaxy ESO 103-G35, which contains a nuclear maser source and is known to be heavily absorbed in the X-rays. Analysis of the X-ray spectra observed by *BeppoSAX* in 1996 October and 1997 October yields a spectral index $\alpha_E = 0.74 \pm 0.07$ ($F_\nu \propto \nu^{-\alpha_E}$), which is typical of Seyfert galaxies and consistent with earlier observations of this source. The strong, soft X-ray absorption has a column density N_H of $1.79 \pm 0.09 \times 10^{23}$ cm^{-2}, again consistent with earlier results. The best-fitting spectrum is that of a power law with a high-energy cutoff at 29 ± 10 keV, a cold ($E = 6.3 \pm 0.1$ keV, rest frame), marginally resolved ($\sigma = 0.35 \pm 0.14$ keV, FWHM $\sim 31 \pm 12 \times 10^3$ km s^{-1}) Fe Kα line with EW 290^{+100}_{-80} eV (1996), and a mildly ionized Fe K edge at $7.37^{+0.15}_{-0.21}$ keV, $\tau = 0.24^{+0.06}_{-0.09}$. The K$\alpha$ line and cold absorption are consistent with origin in an accretion disk/torus through which our line of sight passes at a radial distance of $\sim$50 pc. The Fe K edge is mildly ionized, suggesting the presence of ionized gas, probably in the inner accretion disk close to the central source or in a separate warm absorber. The data quality is too low to distinguish between these possibilities, but the edge-on geometry implied by the water maser emission favors the former. Comparison with earlier observations of ESO 103-G35 shows little or no change in spectral parameters while the flux changes by factors of a few on timescales of a few months. The 2–10 keV flux decreased by a factor of $\sim$2.7 between 1996 October and 1997 October with no detectable change in the count rate greater than 20 keV (i.e., the Phoswich Detector System data). Spectral fits to the combined data sets indicate either a significant hardening of the spectrum ($\alpha_E \sim 0.5$) or an approximately constant or delayed response reflection component. The high-energy cutoff (29 ± 10 keV) is lower than the typical $\sim$300 keV values seen in Seyfert galaxies. A significant subset of similar sources would affect current models of the active galactic nucleus contribution to the cosmic X-ray background which generally assume a high-energy cutoff of $\sim$300 keV.

Subject headings: galaxies: active — galaxies: individual (ESO 103-G35) — galaxies: nuclei — galaxies: Seyfert — X-rays: galaxies — masers

1. INTRODUCTION

The subparsec masing disk recently found to be orbiting a $\sim 10^7$ solar mass black hole in the Seyfert 2 galaxy NGC 4258 provides the most compelling evidence to date for the existence of a massive black hole in the nucleus of a galaxy (Miyoshi et al. 1995). The disk is edge-on, the X-ray spectrum is heavily absorbed (Makishima et al. 1995), and an active nucleus is visible in polarized light (Wilkes et al. 1995). Nearly all active galactic nuclei (AGNs) which contain maser sources and have X-ray observations show strong X-ray absorption consistent with an edge-on disk, suggesting that they generally harbor active nuclei in their cores. This is consistent with the generally accepted scenario that many Seyfert 2 galaxies are edge-on Seyfert 1 galaxies (Antonucci & Miller 1985). The combined power of the high-resolution radio observations and the X-ray spectrum to study the structure of the disk, both along the line of sight and in the plane of the sky, makes these objects potential keys to our understanding of the inner regions of active galaxies.

The Seyfert 1.9/2 galaxy ESO 103-G35 is a strong X-ray source, originally discovered by *HEAO 1*/A2 (H1834−653; Marshall et al. 1979; Piccinotti et al. 1982). It was identified as a Seyfert 1.9 galaxy at a redshift of 0.0133 by Phillips et al. (1979), although later spectra have shown no evidence for broad lines (Morris & Ward 1988), leaving its classification in some doubt. It has been observed extensively in the X-rays. *EXOSAT* observations revealed strong, soft X-ray absorption ($N_H \sim 2 \times 10^{23}$ cm^{-2}) which showed a factor of 2 variation over 90 days (Warwick, Pounds, & Turner 1988), providing some of the first evidence for variable absorption in a Seyfert nucleus. *Ginga* observations revealed an equivalent width $\sim$330 eV Fe Kα emission line whose origin was not clear given the presumed (but not confirmed) presence of a flaring source within the *Ginga* beam during a portion of this observation (Warwick et al. 1993). The continuum spectrum was consistent with that reported by *EXOSAT*.

ASCA observations confirmed and extended the earlier studies, reporting a cold, resolved Fe Kα emission line and a mildly ionized Fe K edge (Turner et al. 1997; Forster, Leighly, & Kay 1999). While flux variations up to a factor of a few are common on short timescales, no significant spectral or absorption variations have been detected.

Recent radio measurements have revealed water maser emission in the form of a single line at +100 km s^{-1} (Braatz, Wilson, & Henkel 1997) with respect to the AGN redshift. Owing to the large negative declination ($\delta \sim -65°$) of this source, higher resolution and sensitivity observations to further study this maser are difficult at present. However, the combination of water maser emission and the strong, absorbed X-ray source suggest a strong parallel with NGC 4258 and motivated our observations with *BeppoSAX* to

[1] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138.
[2] Ohio State University.
[3] *BeppoSAX* Science Data Center, via Corcolle 19, I-00131 Roma, Italy.
[4] Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monteporzio, Italy.

obtain an X-ray spectrum simultaneously over a wide energy band (1–200 keV). The moderate spatial resolution ($\sim 2'$) of *BeppoSAX* facilitates identification of any nearby, contaminating sources and so avoids the confusion present in the *Ginga* data. Here we present an analysis of the *BeppoSAX* X-ray data.

2. OBSERVATIONS AND ANALYSIS

ESO 103-G35 was observed with *BeppoSAX* at two epochs: 1996 October and 1997 October (see Table 1). Data were obtained with both gas scintillator proportional counter (GSPC) detectors: low- and medium-energy concentrator spectrometers (LECS and MECS, respectively; Parmar, Smith, & Bavdaz 1990) and with the Phoswich Detector System (PDS; Frontera et al. 1991). The source was clearly detected and unresolved in all three detectors, and no nearby source of comparable strength was seen.

Counts were extracted from a 4′ circle in both LECS and MECS detectors and background counts subtracted, estimated from the background file appropriate for this extraction radius provided by the *BeppoSAX* Data Center (SDC) as of 1998 March. The resulting net source count rates for the energy ranges over which the instrument calibration is reliable are listed in Table 1. The PDS data were background-subtracted as part of the data reduction pipeline.

The spectra were analyzed with the XSPEC spectral fitting package (Arnaud 1996) using the calibration files provided by the SDC (1998 March). The data from all three instruments were fitted simultaneously. Following the recommendation of the SDC, we constrained the PDS normalization to be 0.85 times that of the MECS. We first fitted the data with an absorbed power-law model (Table 2, fit 1). The best-fit value of the column density ($z = 0$) $N_H = (2.07 \pm 0.007) \times 10^{23}$ cm^{-2} is significantly larger than the Galactic column density toward the source ($N_H \lesssim 3 \times 10^{20}$ cm^{-2}). The absorbed power-law fit showed a clear excess in both data sets at the position of the Fe Kα emission line (~ 6.4 keV). Addition of a Gaussian emission line resulted in an acceptable fit (Table 2, fit 2, Fig. 1) with an χ^2_ν of 1.16 (239 degrees of freedom, dof). The emission-line equivalent width (EW) is 240^{+80}_{-60} eV, and it is marginally resolved. However, the residuals at high energies show an excess suggestive of curvature. We therefore applied first a high-energy cutoff to

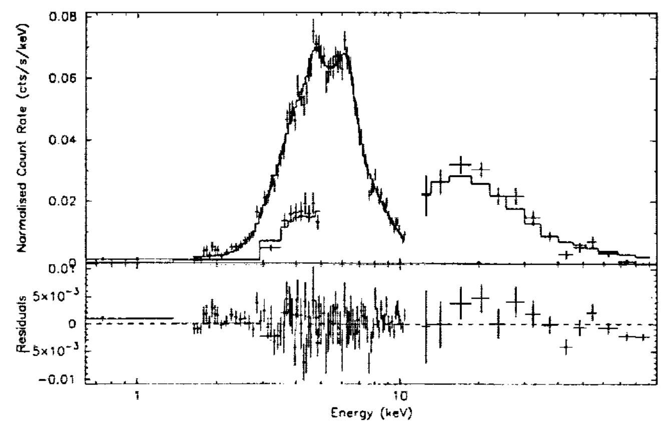

FIG. 1.—Best-fitting power law plus Gaussian emission-line model for the epoch 1996 *BeppoSAX* data for ESO 103-G35 over the energy range 0.6–100 keV (Table 2, fit 2). The figure shows the data and best-fit model folded through the instrument response with the residuals in the lower panel.

TABLE 1

OBSERVATIONAL DETAILS FOR THE *BEPPOSAX* OBSERVATION OF ESO 103-G35

Start Date–End Date	Instrument	Exposure Time (ks)	Energies (keV)	Count Rate (counts s^{-1})
1996 Oct 3–1996 Oct 4	LECS	10.238	0.1–5.0	0.031 ± 0.002
	MECS	50.615	1.7–10.5	0.306 ± 0.003
	PDS	21.029	15–200	0.75 ± 0.04
1997 Oct 14–1997 Oct 15......	MECS	14.312	1.7–10.5	0.122 ± 0.003
	PDS	5.9	15–200	0.73 ± 0.11

TABLE 2

RESULTS OF SPECTRAL FITS TO THE 1996 DATA SET

Fit: Model[a]	1: PL	2: PL+Gauss	3: PL+HighEcut+Gauss	4: PL+Refl+Gauss
N_H ($\times 10^{23}$ cm^{-2})......	2.07 ± 0.07	1.92 ± 0.08	1.79 ± 0.09	1.97 ± 0.09
F_ν (1 keV)[b].............	0.024	0.019 ± 0.003	0.015 ± 0.002	0.024 ± 0.005
α_E	0.94 ± 0.05	0.87 ± 0.05	0.74 ± 0.07	1.00 ± 0.12
Energy (keV)	...	6.33 ± 0.10	6.30 ± 0.10	6.34(fr)
σ (keV)	...	0.32 ± 0.14	0.35 ± 0.14	0.30(fr)
EW (Fe Kα) (eV)	...	240^{+80}_{-60}	290^{+100}_{-80}	210^{+60}_{-40}
$E_{\rm cutoff}$ (keV)	...	...	29 ± 10	...
$E_{\rm fold}$ (keV)	...	...	40^{+30}_{-20}	...
cos i ($R = 1$)	...	...	...	$0.2^{+0.4}_{-0.2}$
χ^2_ν(dof)	2.05(103)	1.51(99)	1.28(96)	1.46(101)
Flux (2–10 keV)[c]	2.57	2.56	2.57	2.55

NOTE.—All errors are quoted at 90% confidence.

[a] PL: Power law; Gauss: Gaussian emission line; HighEcut: a high-energy exponential cutoff; Refl: reflection component.

[b] In photons cm^{-2} s^{-1} keV^{-1}.

[c] In units of 10^{-11} ergs cm^{-2} s^{-1}.

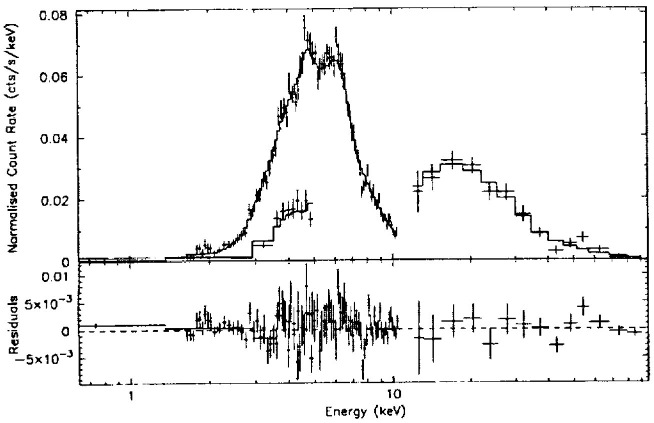

FIG. 2.—Best-fitting cutoff power law plus Gaussian emission line for the epoch 1996 *BeppoSAX* data of ESO 103-G35 over the energy range 0.6–100 keV (Table 2, fit 3). The figure shows the data and best-fit model folded through the instrument response with the residuals in the lower panel.

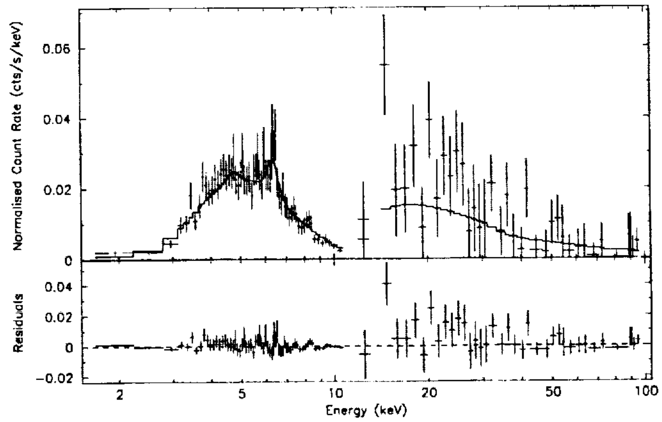

FIG. 4.—Best-fitting power law plus Gaussian emission-line model for the epoch 1997 *BeppoSAX*-MECS and PDS data of ESO 103-G35 over the energy range 0.6–100 keV (Table 3, fit 5). The figure shows the data and best-fit model folded through the instrument response with the residuals in the lower panel.

the power law (Table 2, fit 3) and then a reflected component with no high-energy cutoff (Table 2, fit 4). The former resulted in a significantly improved χ^2_ν (*F*-test yields 0.01% significance level). The results are displayed in Figures 2 and 3, respectively.

The 1996 *ASCA* data (Turner et al. 1997; Forster et al. 1999) showed an iron edge at about $7.37^{+0.26}_{-0.22}$ keV with $\tau = 0.47^{+0.16}_{-0.12}$, consistent with earlier observations (Warwick et al. 1993). Since systematic residuals are present around 7–8 keV in the best-fit spectrum (Fig. 2), we investigated the presence of excess iron absorption. We added an edge to the best-fit model described above and indeed found a greater than 99% improvement in the fit (*F*-test). The best-fit edge energy is $7.37^{+0.15}_{-0.21}$ keV, consistent with *ASCA* observations in 1996 March (Forster et al. 1999), with an opacity, $\tau = 0.24^{+0.06}_{-0.09}$, marginally ($\sim 2\ \sigma$) lower than the *ASCA* value. This absorption is likely due to the K edge of mildly ionized iron. However, our data quality is not good enough to fit a complex warm absorber model. We tried using the "absorbi" model in XSPEC but could not constrain the parameters.

The 1997 data set has a lower MECS count rate and shorter exposure time so that the data have a much lower

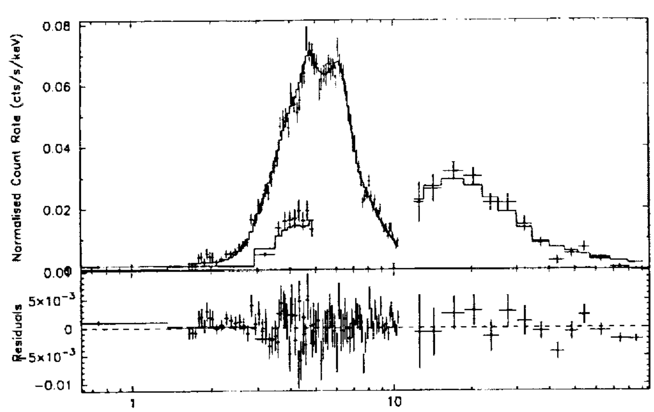

FIG. 3.—Best-fitting power law plus Gaussian emission line plus reflection model for the epoch 1996 *BeppoSAX* data of ESO 103-G35 over the energy range 0.6–100 keV (Table 2, fit 4). The figure shows the data and best-fit model folded through the instrument response with the residuals in the lower panel.

signal-to-noise ratio (see Table 1, Fig. 4). To quantify the amount of variation, we first fitted a simple absorbed power law plus Gaussian emission-line model to the MECS data only. The results are given as fit 5 in Table 3 and displayed in Figure 4. The flux decreased by a factor of ~ 2.7 over the year between the two observations. There is no evidence for spectral variability or for a variable absorbing column density. The emission-line strength is poorly constrained, $\mathrm{EW} = 250^{+150}_{-110}$ eV, and is consistent with either a constant flux or constant EW over the year. We therefore are unable to constrain the response time of the line-emitting material to the continuum variations. There is no evidence in this spectrum for the line to be broad, though once again the errors are sufficiently large that it remains consistent with the 1996 line width.

Surprisingly, the PDS data in the 1997 data set show a count rate similar to the 1996 value (Table 1). We fitted the combined MECS + PDS data for 1997. An absorbed power law plus Gaussian line fit to the combined data set shows a flatter slope (see Table 3, fit 6) and gives an acceptable χ^2 value. The resulting spectral index ($\alpha_E \sim 0.5$) is much flatter than in 1996 and would imply a significant hardening of the spectrum as the flux decreases. Since there is no other evidence for spectral variability in ESO 103-G35, we seek an alternative interpretation.

Partial covering of a hard continuum source can be ruled out by the lack of variability in the PDS data. However, since the PDS data would be dominated by any reflected component, an alternative interpretation of this pattern of variability is that of a reflected component which remains constant while the power-law component varies. Fit 7 (Table 3) shows the best-fitting power law plus reflection plus Gaussian line model to the MECS + PDS 1997 data set. This gives a marginally better fit, but the data are not of sufficiently high quality to provide strong constraints on the parameters. For this to be realistic, the reflecting medium must respond to a change in incident continuum with some delay or be seeing a constant continuum which is invisible to us. This latter could occur, for example, if the flux variation were due to absorption by material between us and the reflecting material. However, the spectrum shows no evidence for a variation in the column density to support this scenario. The most likely explanation is that of a reflected

TABLE 3

RESULTS OF SPECTRAL FITS TO THE 1997 DATA SET

Fit: Model[a]	5: PL+Gauss[b]	6: PL+Gauss	7: PL+Refl+Gauss
N_H ($\times 10^{23}$ cm^{-2})......	2.02 ± 0.28	$1.68^{+0.23}_{-0.21}$	1.78
F_ν(1 keV)[c]...............	$0.008^{+0.0078}_{-0.0034}$	$0.003^{+0.002}_{-0.001}$	0.006
α_E	0.9 ± 0.3	$0.49^{+0.19}_{-0.17}$	0.93
Energy (keV)	$6.45^{+0.11}_{-0.19}$	$6.43^{+0.11}_{-0.25}$	6.42
σ (keV)	<0.3	<0.4	<0.4
EW (Fe Kα) (eV)	250^{+150}_{-110}	260^{+180}_{-110}	193
R ($\cos i = 0.45$).........	...	...	4^{+7}_{-3}
χ^2_ν (dof)..................	0.66(65)	0.87(96)	0.78(94)
Flux (2–10 keV)[d]	0.95	0.98	0.97

NOTE.—All errors are quoted at 90% confidence.
[a] PL: Power law; Gauss: Gaussian emission line; Refl: reflection component.
[b] MECS data only.
[c] In photons cm^{-2} s^{-1} keV^{-1}.
[d] In units of 10^{-11}ergs cm^{-2} s^{-1}.

component, undetectable in the earlier data set and with a delayed response to continuum variations. With only two data points, we cannot be sure whether further continuum variations occurred during the period in between our observations to which the reflected component is responding. Thus we cannot place any meaningful constraints on the distance of the reflecting region from the continuum source.

3. DISCUSSION

3.1. *Absorption*

The *BeppoSAX* observations confirm the presence of a large column density of neutral absorbing material ([$N_H = (2.0 \pm 0.1) \times 10^{23}$] cm^{-2}) in the X-ray spectrum of ESO 103-G35. The column density measured here is consistent with the higher column density reported in the *EXOSAT* data (Warwick et al. 1988), as well as that from more recent *ASCA* data (Forster et al. 1999; Turner et al. 1997). There is no evidence for variation in this absorbing column between the 1996 and 1997 observations. Figure 5 and Table 4 show a compilation of N_H measurements over a 13 yr period (1984–1997). They are generally consistent with one another, the largest deviation[5] is $\sim 2\,\sigma$ in 1991.

Absorbing material with column densities $\sim 10^{23}$ cm^{-2} is typically seen in the subset of Seyfert 2 galaxies which show evidence for a hidden Seyfert 1 (Turner et al. 1997; Awaki 1997). It is consistent with a line of sight passing through an edge-on, optically thick accretion disk/torus of neutral material such as is commonly believed to be present in Seyfert galaxies (Antonucci & Miller 1985). The presence of water maser emission in ESO 103-G35 (Braatz et al. 1997) indicates that our line of sight intersects the accretion disk/torus accurately edge-on. In the absence of warps in the disk/torus, the X-ray absorption measures its full column density.

We also detect excess absorption due to ionized iron, most likely due to Fe II–Fe XV, consistent with earlier *Ginga* and *ASCA* results. The observed opacity $\tau = 0.24^{+0.06}_{-0.09}$ is

[5] Apart from the rapid change reported by Warwick et al. (1988) which may have been because of a spurious source in the *Ginga* data (§ 1).

TABLE 4

COMPILATION OF SPECTRAL PARAMETERS FOR EARLIER OBSERVATIONS OF ESO 103-G35

Satellite	Instrument	Date	Flux (2–10 keV)[a]	N_H[b]	α_E	References	Error (%)
EXOSAT......	ME	247/1983	1.81 ± 0.10	$2.28^{+1.37}_{-0.98}$	$0.90^{+0.96}_{-0.34}$	1	90
	ME	110/1984	2.18 ± 0.07	$2.47^{+0.81}_{-0.65}$	$1.54^{+0.71}_{-0.56}$	1	90
	ME	124/1985	2.46 ± 0.09	$2.37^{+0.90}_{-0.72}$	$1.23^{+0.78}_{-0.60}$	1	90
	ME	214/1985	2.68 ± 0.18	$0.71^{+0.73}_{-0.42}$	$0.24^{+0.76}_{-0.31}$	1	90
	ME	225/1985	1.90 ± 0.11	$0.81^{+0.54}_{-0.39}$	$0.57^{+0.76}_{-0.44}$	1	90
	ME	247/1985	1.22 ± 0.10	$1.67^{+1.95}_{-1.01}$	$1.08^{+1.82}_{-0.54}$	1	90
Ginga	LAC	268/1988	2.1 ± 0.7	$1.76^{+0.41}_{-0.31}$	$0.76^{+0.19}_{-0.17}$	2	90[c]
	LAC	102/1991	1.9 ± 0.3	$3.55^{+0.72}_{-0.56}$	$0.84^{+0.08}_{-0.11}$	3	90[d]
ASCA	SIS+GIS	246/1994	0.9 ± 0.4	$1.565^{+0.288}_{-0.173}$	$0.37^{+0.33}_{-0.21}$	4	90[d]
	SIS+GIS	246/1994	1.42 ± 0.05[e]	$2.16^{+0.40}_{-0.35}$	$0.89^{+0.35}_{-0.40}$	5	90
	SIS+GIS	269–270/1995	2.36 ± 0.13[e]	$1.68^{+0.54}_{-0.48}$	$0.31^{+0.59}_{-0.57}$	5	90
	SIS+GIS	078/1996	2.38 ± 0.06[e]	$2.16^{+0.26}_{-0.25}$	$1.08^{+0.29}_{-0.28}$	5	90

[a] In units of 10^{-11} ergs cm^{-2} s^{-1}.
[b] In units of 10^{23} cm^{-2}.
[c] Average of quoted error on normalization.
[d] Based upon quoted error in slope.
[e] Errors from photon statistics only.

REFERENCES.—(1) Warwick et al. 1988; (2)Warwick et al. 1993; (3) Smith & Done 1996; (4) Turner et al. 1997; (5) Forster et al. 1999.

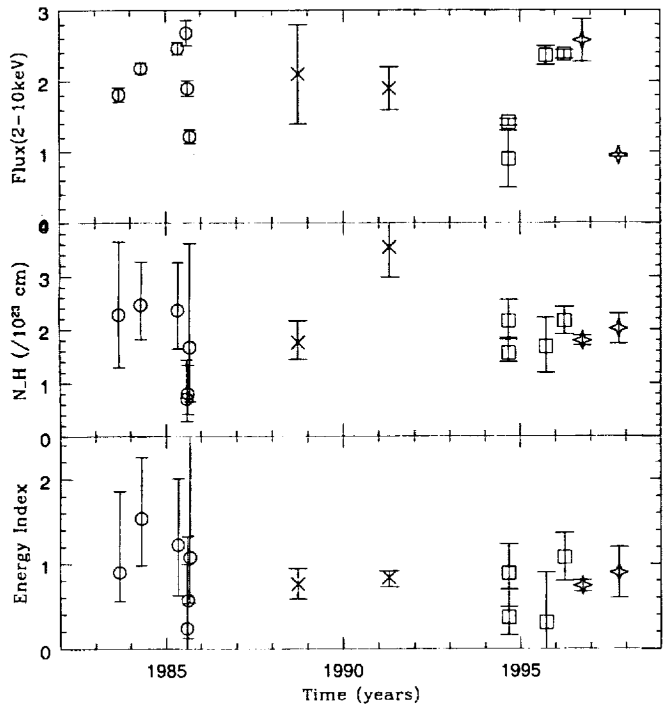

FIG. 5.—Time history of the broadband (2–10 keV) flux (in units of 10^{-11} ergs cm^{-2} s^{-1}), absorbing column density, and energy spectral index of ESO 103-G35 from 1983 to 1997. Significant flux variability is present on timescales of a few months while the spectral index remains constant within the errors. The absorbing column has varied on short timescales in the past but in general remains fairly constant as well. The different data sets are indicated as follows: *circle*: *EXOSAT*, *cross*: *Ginga*, *square*: *ASCA*, *star*: *BeppoSAX*.

somewhat lower than the *ASCA* value (Turner et al. 1997; Forster et al. 1999). While our data quality is insufficient to constrain a full warm absorber model, the presence of the edge requires ionized material along our line of sight. Given the accurately edge-on geometry, the ionized material most likely lies within the inner regions of the accretion disk/torus close to the central continuum source. One possible alternative would be a warp in the disk/torus so that our line of sight does not pass through the full geometric size of the disk. A sufficiently strong warp would allow the possibility of a separate warm absorber above or below the accretion disk/torus at a position closer to the central source than the intersection of the warped disk with our line of sight.

3.2. *Spectral Shape*

The best-fitting model is a cutoff power law with slope $\alpha_E = 0.74 \pm 0.07$ (Table 2, fit 3), a cutoff with energy of 29 ± 10 keV, and *e*-folding energy 40^{+30}_{-20} keV. This model shows a resolved Fe Kα emission line at 6.3 ± 0.1 keV and equivalent width 290^{+100}_{-80} eV. Figure 5 shows the lack of significant variation in spectral parameters over a 13 yr period.

In the hard X-ray, where the effects of the large absorbing column are negligible, the scenario of Seyfert 2 galaxies being edge-on Seyfert 1s predicts that both classes of galaxy look similar. Hard X-ray and γ-ray data for radio-quiet Seyfert 1 galaxies typically show a power-law spectrum with spectral index $\alpha_E \sim 0.9$, similar to that reported here for ESO 103-G35 but extending to energies greater than 100 keV (Gondek et al. 1996) rather than ~ 30 keV. This hard X-ray spectrum can be explained by emission from an optically thin, relativistic, thermal plasma in a disk corona or by a nonthermal plasma with a power-law injection of relativistic electrons (Gondek et al. 1996). The lower high-energy cutoff suggests this component has a higher optical depth in ESO 103-G35. In addition, the X-ray spectra of radio-quiet Seyfert 1 galaxies typically include a contribution from Compton reflection in warm material which is superposed on the underlying power law in the energy range 10–100 keV (Gondek et al. 1996). The 1996 observation favors a cutoff power law over a reflection model, suggesting that this latter component is, at most, weak in ESO 103-G35 in its brighter state. However, the relatively strong hard flux in the otherwise lower luminosity 1997 data set suggests the presence of a reflection component in 1997. Since the reflection model includes a large number of parameters, it is not possible to constrain them usefully. However, if we assume an isotropic source situated above the accretion disk, no high-energy cutoff, and solar abundances, we deduce an inclination angle for the disk in the range 50°–90°, consistent with ESO 103-G35 being a Sy1.9/2 in unified models and with the accurately edge-on geometry implied by the presence of water maser emission.

3.3. *Luminosity Variation*

Figure 5 shows the historical light curve of ESO 103-G35 since 1983, including the current *BeppoSAX* observations (1997). It is clear that flux variations of factors of a few are common on timescales of months. The variation seen by *ASCA* and *BeppoSAX* between 1994 and 1997 shows a slow rise and rapid fall quite similar to that seen by *Ginga* between 1983 and 1985. The flux level in the 1996 observation [$F(2\text{–}10\ \mathrm{keV}) = 2.57 \pm 0.07 \times 10^{-11}$ ergs cm^{-2} s^{-1}] indicates a luminosity $L_X \sim 2 \times 10^{43}$ ergs s^{-1} ($H_0 = 50$, $q_0 = 0$).

3.4. Fe *Kα Emission Line*

The emission line is cold (6.3 ± 0.1 keV) but consistent with being mildly warm and marginally resolved (Table 2). Adopting an MECS instrument energy resolution of (σ) 0.21 keV at 6.3 keV (*BeppoSAX* Observers' Handbook), the intrinsic width of the line is estimated to be 0.28 ± 0.12 keV, which yields an FWHM of $\sim (31 \pm 12) \times 10^3$ km s^{-1} for the Fe Kα line. This indicates an origin in neutral, high-velocity material. The EW, 290^{+100}_{-80} eV, is within the wide range of observed values for Seyfert 2 galaxies and is consistent with fluorescence in the cold absorber, the accretion disk/torus, which is attenuating the observed X-ray continuum (Awaki et al. 1991; Turner et al. 1997).

The emission line in the second data set is not well constrained. It is consistent with constant flux or with constant equivalent width over the 1 year period so we cannot determine if any response to the continuum variation has occurred. From the $\sigma = 0.32$ keV (Table 2), the FWHM of the line is about 30,000 km s^{-1}.

If the line width is dynamic, indicating a virial velocity around the $10^7\ M_\odot$ black hole, then the radial distance to the emitter is about 50 pc. We note that an alternative interpretation of the broad Fe Kα line is that of a mix of neutral and ionized material. This would be consistent with the earlier suggestion (§ 3.1) of ionized material in the inner regions of the accretion disk/torus being responsible for the ionized Fe K edge. Fits to the 1994 *ASCA* data set with three narrow lines covering a range of ionization were statistically indistinguishable from those with a broadened, neutral line (Turner et al. 1997).

3.5. *The High-Energy Cutoff*

BeppoSAX, with its high-energy response, has provided information on the high-energy spectrum of a number of AGN for the first time. The dispersion and errors in the observed values of high-energy cutoff of AGN are high, but values typically range from 100–400 keV (Matt 1999). The high-energy spectrum of AGN is a critical parameter for matching both the turnover at ~ 30 keV and the high-energy source counts when modeling the cosmic X-ray background. Successful models generally adopt a value of 300 keV and require strong evolution in the number of absorbed AGN with redshift (Gilli, Risaliti, & Salvati 1999). However, the high-energy cutoff determined from our *BeppoSAX* data for ESO 103-G35 (29 ± 10 keV) is significantly lower, calling into question the validity of the modeling to date. More realistic modeling of the distribution of AGN spectral properties, including the high-energy cutoff, is required to make an accurate assessment of the AGN contribution to the CXRB (Yaqoob 2000).

4. CONCLUSIONS

ESO 103-G35 is an X-ray–bright Sy 1.9/2.0 galaxy containing one of strongest water maser sources known, implying that it is viewed accurately edge-on. The presence of cold molecular material along the line of sight to the active nucleus supports this picture. The amount of X-ray absorption has been approximately constant over the past 15 years and, at 2×10^{23} cm^{-2}, it is typical of Seyfert 2 galaxies and consistent with a line of sight passing through the edge-on accretion disk/torus also responsible for the maser emission.

We observe a marginally resolved Fe Kα emission line whose width, if dynamic, implies a radial distance to the absorber of about 50 pc, similar to that expected for an obscuring torus. Alternatively, the width may be due to a range of ionization states in the emitting material consistent with the ionized Fe K edge at $7.37^{+0.15}_{-0.21}$ keV. The Fe Kα line strength (EW = 290^{+100}_{-80} eV) and width are consistent with origin in an accretion disk/torus through which our line of sight is passing. The presence of both cold and warm (ionized) absorbing (and emitting) material suggests that the inner parts of the torus/disk are mildly ionized while the outer parts are cold.

The flux level in the energy range 0.6–10 keV decreased by a factor of ~ 2.7 between 1996 October and 1997 October with no evidence for a change in spectral shape or absorption. However, the 10–50 keV flux did not change between the two observations, suggesting either a hardening of the hard continuum or the presence of a reflection component (undetectable at the higher flux level) which reacts to continuum changes with some delay. Given the paucity of data points, we are unable to place meaningful constraints on the distance of the reflecting material from the continuum source.

The 1996 data set shows a high-energy cutoff at 29 ± 10 keV. This is significantly lower than the values ~ 300 keV believed typical to date (Gondek et al. 1996; Matt 1999). The high-energy spectrum of AGN is critical for modeling the AGN contribution to the CXRB so that this result emphasizes the need to include a realistic distribution of cutoff energy in these models.

B. J. W. and S. M. gratefully acknowledge the financial support of NASA grants NAG 57-064 (*BeppoSAX*) and NAG 53-249 (LTSA).

REFERENCES

Antonucci, R. R. J., & Miller, J. S. 1985, ApJ, 297, 621
Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. Jacoby & J. Barnes (San Francisco: ASP), 17
Awaki, H. 1997, in ASP Conf. Ser. 113, Emission Lines in Active Galaxies: New Methods and Techniques, ed. B. M. Peterson, F.-Z. Cheng, & A. S. Wilson (San Francisco: ASP), 44
Awaki, H., Koyama, K., Inoue, H., & Halpern, J. 1991, PASJ, 43, 195
Braatz, J. A., Wilson, A. S., & Henkel, C. 1997, ApJS, 110, 321
Forster, K., Leighly, K. M., & Kay, P. E. 1999, ApJ, 523, 521
Frontera, F., et al. 1991, Adv. Space Res., 11(8), 281
Gilli, R., Risaliti, G., & Salvati, M. 1999, A&A, 347, 424
Gondek, D., Zdziarski, A. A., Johnson, W. N., George, I. M., McNaron-Brown, K., Magdziarz, P., Smith, D., & Gruber, D. E. 1996, MNRAS, 282, 646
Makishima, K., et al. 1994, PASJ, 46, L77
Marshall, F., Boldt, E., Holt, S., Mushotzky, R., Rothschild, R., Serlemitsos, P., & Pravdo, S. 1979, ApJS, 40, 657
Matt, G. 1999, in ASP Conf. Ser. 161, High Energy Processes in Accreting Black Holes, ed. J. Poutanen & R. Svensson (San Francisco: ASP), 149
Miyoshi, M., Moran, J., Herrnstein, J., Greenhill, L., Nakai, N., Diamond, P., & Inoue, M. 1995, Nature, 373, 127
Morris, S. L., & Ward, M. J. 1988, MNRAS, 230, 639
Parmar, A. N., Smith, A., & Bavdaz, M. 1990, in Observatories in Earth Orbit and Beyond, ed. Y. Kondo (Dordrecht: Kluwer), 457
Phillips, M. M., Feldman, F. R., Marshall, F. E., & Wamstekker, W. 1979, A&A, 76, L14
Piccinotti, G., Mushotzky, R. F., Boldt, E. A., Holt, S. S., Marshall, F. E., Serlemitsos, P. J., & Shafer, R. A. 1982, ApJ, 253, 485
Smith, D. A., & Done, C. 1996, MNRAS, 280, 355
Turner, T. J., George, I. M., Nandra, K., & Mushotzky, R. F. 1997, ApJS, 113, 23
Warwick, R. S., Pounds, K. A., & Turner, T. J. 1988, MNRAS, 231, 1145
Warwick, R. S., Sembay, S., Yaqoob, T., Makishima, K., Ohashi, T., Tashiro, M., & Kohmura, Y. 1993, MNRAS, 265, 412
Wilkes, B. J., Schmidt, G. D., Smith, P. S., Mathur, S., & McLeod, K. K. 1995, ApJ, 455, L13
Yaqoob, T. 2000, in Proc. Large Scale Structure in the X-Ray Universe, ed. M. Plionis & I. Georgantopoulos (Gif-sur-Yvette: Editions Frontières), 257

The Astrophysical Journal, 557:492, 2001 August 10

ERRATUM

In the paper "*BeppoSAX* Observations of the Maser Seyfert 2 Galaxy ESO 103-G35" by Belinda J. Wilkes, Smita Mathur, Fabrizio Fiore, Angelo Antonelli, and Fabrizio Nicastro (ApJ, 549, 248 [2001]), the size of the line-emitting region derived from the line width should read 0.01 pc and not 50 pc as currently listed in the abstract, § 3.4, and § 4.