The BeppoSAX View of the X-Ray Active Nucleus of NGC 4258

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THE BeppoSAX VIEW OF THE X-RAY ACTIVE NUCLEUS OF NGC 4258

F. Fiore,1,2,3 S. Pellagrini,4 G. Matt,5 L. A. Antonelli,1 A. Comastri,6 R. della Ceca,7 E. Giallongo,1 S. Mathur,8 S. Molendi,9 A. Semiginowska,3 G. Trinchieri,7 and B. Wilkes3

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ABSTRACT

BeppoSAX observed the Seyfert 1.9 galaxy NGC 4258 in 1998 December, when its 2–10 keV luminosity was about 10^{44} ergs s^{-1}. Large amplitude (100%) variability is observed in the 3–10 keV band on timescales of a few tens of thousands of seconds, while variability of ~20% is observed on timescales as short as 1 hr. The nuclear component is visible above 2 keV only, being obscured by a column density of (9.5 ± 1.2) x 10^{22} cm^{-2}; this component is detected at up to 70 keV with a signal-to-noise ratio of ≥3 and with a strong power-law energy spectral index of α_{E} = 1.11 ± 0.14. Bremsstrahlung emission for the 2–70 keV X-ray luminosity, as expected in advection-dominated accretion flow models with strong winds, is ruled out by the data. The ratio between the nuclear radio (22 GHz) luminosity and the X-ray (5 keV) luminosity is consistent with that of radio-quiet quasars and Seyfert galaxies. X-ray variability, spectral shape, and radio/X-ray and near-IR/X-ray luminosity ratios suggest that the nucleus of NGC 4258 could be a scaled down version of a Seyfert nucleus and that the X-ray nuclear luminosity can be explained in terms of Comptonization in a hot corona. The soft (E ≤ 2 keV) X-ray emission is complex. There are at least two thermal-like components with temperatures of 0.6 ± 0.1 keV and ≥1.3 keV. The cooler (L_{0.1–2.4 keV} = 10^{40} ergs s^{-1}) component is probably associated with the jet, resolved in X-rays by the ROSAT HRI (Cecil et al. 1994). The luminosity of the second component, which can be modeled equally well by an unobscured power-law model with α_{E} = 0.2 ± 0.8 and with a steep power-law energy spectral index of α_{E} = 0.2 ± 0.2, is L_{0.1–2.4 keV} = 7 × 10^{38} ergs s^{-1}, consistent with that expected from discrete X-ray sources (binaries and supernova remnants) in the host galaxy. Observations of NGC 4258 and other maser active galactic nuclei (AGNs) show strong nuclear X-ray absorption. We propose that this large column of gas might be responsible for shielding the regions of water maser emission from X-ray illumination. So a large column density absorbing gas may be a necessary property of masering AGNs.

Subject headings: galaxies: individual (NGC 4258) — galaxies: Seyfert — X-rays: galaxies

1. INTRODUCTION

The nearby (distance 7.2 ± 0.3 Mpc; Herrnstein et al. 1999) bright (B_{0} = 8.5) SABbc galaxy NGC 4258 (M106) is spectroscopically classified as a Seyfert 1.9 galaxy (Ho, Filippenko, & Sargent 1997; they find [O III]/Hβ = 10.3, and [S II]/Hα = 0.94). Wilkes et al. (1995) find relatively broad (1000 km s^{-1}) emission lines that are strongly polarized (5%–10%), supporting the existence of an obscured active nucleus in this galaxy. Further support to this case comes from high-resolution observations of the water maser in the galaxy nucleus. Miyoshi et al. (1995) discovered a highly inclined thin disk between 0.13 and 0.25 pc. The inclination of the disk is estimated to be 82.1 ± 1° (Herrnstein et al. 1999; the inclination of the galaxy is 70°; Ho et al. 1997). The aspect ratio of the disk is extremely small, ≤0.2% (Herrnstein et al. 1999). The Keplerian rotation curve traced by the water maser requires a central binding mass, presumably in the form of a supermassive black hole, of (3.9 ± 0.1) × 10^{7} M_{☉} (Herrnstein et al. 1999). To date, this is the strongest evidence for a supermassive black hole in a galaxy and the best measurement of its mass. The implied Eddington luminosity is ~5 × 10^{35} ergs s^{-1}. Therefore, pending an accurate estimate of the observed nuclear luminosity, it is possible in this case to tightly constrain the L/L_{edd} ratio of the active nucleus.

The evaluation of the nuclear luminosity and the spectrum is not an easy task because the nucleus is highly obscured. Wilkes et al. (1995) discovered a faint blue highly polarized nuclear continuum, but the uncertainty on the optical nuclear luminosity is large (2 orders of magnitude, depending on the nature of the scattering region). Similar uncertainties are found using the intensity of the emission lines. Chary & Becklin (1997) found a ”nuclear” emission at 2 μm, in excess of that expected from the galaxy profile value, of 4.5 mJy, corresponding to a luminosity vL_v (ν) of about 10^{41} ergs s^{-1}. The nucleus is not detected in VLBA radio maps. Herrnstein et al. (1998) report upper limits to the 22 GHz flux and luminosity of 0.22 mJy and vL_v (ν) = 3 × 10^{35} ergs s^{-1}, respectively. Conversely, a double, twisted radio jet is visible on scales from milliarcseconds to a few arcminutes (the latter scale corresponds to a few kiloparsec at the galaxy distance). The jets are visible in optical and X-ray images too. In particular, Cecil, Wilson, & De Pree (1995) resolved the jets in ROSAT HRI observations and measured a 0.1–2.4 keV luminosity of 6.5 × 10^{39} ergs s^{-1}. They also detected an unresolved “nuclear” emission of comparable luminosity (see also...
Vogler & Pietsch 1999), confirming previous *Einstein* results (Fabbiano, Kim, & Trinchieri 1992). *ASCA* spectra (Makishima et al. 1994; Ptak et al. 1999; Reynolds, Nowak, & Maloney 2000) resolve at least two distinct components: a thermal component that dominates the spectrum up to 2–3 keV and a highly absorbed power law that dominates the spectrum above this energy. The *ASCA* power-law energy index is $\alpha_L \sim 0.8$, and the neutral absorbing column is in the range $N_H = (0.9-1.5) \times 10^{23}$ cm$^{-2}$ (see Reynolds et al. 2000 for details). The 2–10 keV flux observed by *ASCA* varied between $3 \times 10^{-12}$ and $1 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ (Reynolds et al. 2000) during several observations performed between 1993 May and 1999 May; when corrected for intrinsic absorption, it was in the range ($6 \times 10^{-12}$ to $1 \times 10^{-11}$) ergs cm$^{-2}$ s$^{-1}$ (Lasota et al. 1996). These 2–10 keV nuclear luminosities can be explained either by a standard accretion disk with a very small accretion rate or by radiatively inefficient accretion models, such as the advection-dominated accretion flow model (ADAF; e.g., Narayan & Yi 1995). The radio/X-ray spectral energy distribution (SED) has been interpreted in terms of emission from an ADAF with a critical accretion rate (Lasota et al. 1996; is the viscosity parameter in units of 0.1) or $n_0 \sim 0.012n_1$ (Gammie et al. 1999; their modeling also includes the near-IR data and the 22 GHz upper limit). In ADAF models the radio luminosity comes from synchrotron emission, and the X-ray comes from the combined contributions of a high-temperature ($kT \gtrsim 100$ keV) thermal bremsstrahlung and Comptonization of the synchrotron photons. Lasota et al. (1996) point out that this representation is not unique because of the substantial uncertainties in the optical-UV and X-ray data and because of the difficulty in distinguishing an ADAF from thermal Comptonization using only the X-ray spectral shape. Both Lasota et al. (1996) and Gammie et al. (1999) do not account in their models for the strong wind expected from the inner accretion disk (Blandford & Begelman 1999; Di Matteo et al. 2000). The wind carries a significant fraction of the mass, energy, and angular momentum. In particular, it drastically reduces the synchrotron emission in the radio band and the Compton emission in the optical-UV and X-ray bands (Di Matteo et al. 2000). In both modelings, the near-IR (NIR) luminosity is generated by a standard geometrically thin disk, external to the ADAF transition radius.

*BeppoSAX*, with its good sensitivity over a broad (0.1–200 keV) band, can help in separating the different X-ray spectral components and can provide a strong constraint on the nuclear power-law spectral index and on the high-energy cutoff (predicted by both ADAF models and thermal Comptonization models). It can help in the understanding of whether the NGC 4258 nucleus hosts a "normal" AGN (although of low luminosity) or rather an ADAF. *BeppoSAX* observed NGC 4258 for about 100 ks on 1998 December 19–22. The nuclear component was in a high state in comparison with most *ASCA* observations. This, together with the broad band (the source is detected with a signal-to-noise ratio of $\gtrsim 3$ up to about 70 keV) allows us to tightly constrain the flux and spectral shape of the nuclear hard component.

The paper is organized as follows: § 2 presents the data and gives information on their reduction, § 3 presents a variability analysis, § 4 presents the spectral analyses and the broadband radio/X-ray spectral indices, and § 5 discusses the main results on the hard nuclear component and low-energy components.

### 2. Observation and Data Reduction

The observations were performed with the *BeppoSAX* Narrow Field Instruments LECS (0.1–10 keV; Parmar et al. 1997), MECS (1.3–10 keV; Boella et al. 1997), HPGSPC (4–60 keV; Manzo et al. 1997), and PDS (13–200 keV; Frontera et al. 1997). LECS and MECS are imaging gas-scintillation proportional counters, the HPGSPC is a collimated high-pressure gas-scintillation proportional counter, and the PDS consists of four phoswich units. The PDS is operated in the so-called rocking mode, with a pair of units pointing to the source while the other pair monitor the background $\pm 210''$ away. The units on- and off-source are interchanged every 96 s. We report here the analysis of the LECS, MECS, and PDS data; the HPGSPC data are very noisy owing to high HPGSPC background. The MECS observations were performed with units 2 and 3 (on 1997 May 6 a technical failure caused the switch-off of MECS unit 1); these data were combined after gain equalization. The LECS is operated during dark time only; therefore, LECS exposure times are usually smaller than MECS ones (by a factor of 3 for NGC 4258). Table 1 gives the LECS, MECS, and PDS exposure times and count rates.

Standard data reduction was performed using the SAXDAS software package version 2.0, following Fiore, Guainazzi, & Grandi (1999). In particular, data are linearized and cleaned from Earth occultation periods (we accumulated data for Earth elevation angles greater than $5'$) and unwanted periods of high particle background (satellite passages through the South Atlantic Anomaly and periods with magnetic cutoff rigidity greater than 6 GeV c$^{-1}$). The internal background of the LECS, MECS, and PDS during the accepted periods is relatively low and stable (variations of at most 30% during the orbit) owing to the low inclination of the satellite orbit (3'95). LECS and MECS spectra were extracted from regions with radii of 8' and 3', respectively. These radii maximize the signal-to-noise ratio below 1 keV in the LECS and above 2 keV in the MECS. Background spectra were extracted in detector coordinates from high Galactic latitude "blank fields" (98.11 issue), using

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Exposure (ks)</th>
<th>Band (keV)</th>
<th>Count Rate ($10^{-2}$ counts s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LECS ......</td>
<td>33.3</td>
<td>0.1–4</td>
<td>$3.00 \pm 0.11$</td>
</tr>
<tr>
<td>MECS ......</td>
<td>99.4</td>
<td>1.7–10</td>
<td>$7.25 \pm 0.09$</td>
</tr>
<tr>
<td>PDS ......</td>
<td>46.9</td>
<td>13–130</td>
<td>$0.121 \pm 0.024$</td>
</tr>
</tbody>
</table>

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regions equal in size to the source-extraction region. We have checked that the mean level of the background in the LECS and MECS “blank field” observations is comparable to the mean level of the background in the NGC 4258 observations, using source-free regions at various positions in the detectors.

The PDS data have been reduced using the variable rise-time threshold technique to reject particle background (see Fiore, Guainazzi, & Grandi 1999). This technique reduces the total 13–200 keV background to about 20 counts s⁻¹ and the 13–80 keV background to about 6 counts s⁻¹ (instead of 30 and 10 counts s⁻¹, respectively, obtained using the standard fixed rise-time threshold technique). The PDS rocking mode provides a very reliable background subtraction. This can be checked looking at the spectrum between 200 and 300 keV, where PDS sensitivity to X-ray photons is small, and therefore the source contribution is negligible; after background subtraction we obtain 0.0085 ± 0.012 counts s⁻¹, consistent with the expected value of 0. The net (background subtracted) 13–130 keV on-source signal is 0.121 ± 0.024 counts s⁻¹. The source is detected with a signal-to-noise ratio of ≳3, up to ∼70 keV. The 13–130 keV PDS count rate is ≳5 times the systematic uncertainty in the PDS background subtraction, equal to 0.020 ± 0.015 (Guainazzi & Matteucci 1997). Confusion in the PDS collimator field of view (1.4 FWHM) ultimately limits our capability to constrain the high-energy spectrum. We have carefully checked for any possible contaminant in a region of 1.5° radius around NGC 4258 (using NED, SIMBAD, AGNs, clusters, cataclysmic variables, radio and X-ray source catalogs) and find no obvious bright, hard X-ray source. Of course there is the possibility of a bright “unknown” source in the PDS field of view. However, the chance of finding a bright source in any given 2°², the PDS beam area, is small. The *HEAO 1 A*-4 all sky catalog (Levine et al. 1984) lists just seven high Galactic latitude sources in the 13–80 keV band, down to a flux of $2 \times 10^{-10}$ ergs cm⁻² s⁻¹ (10 mcrab). The 13–80 keV flux is about 20 times smaller than this figure and so, assuming a log $N$–log $S$ slope of −1.5, we expect a chance coincidence rate of 2%.

3. VARIABILITY

Figure 1 shows the MECS 3–10 keV light curve in bins of 2850 s. Variability of a factor of about 2 is evident on half-day timescales, as well as smaller amplitude variations (10%–20%) on timescales as short as 1 hr. Shorter timescale variations of similar amplitude cannot be sampled owing to the limited sensitivity of the MECS instrument. In this regard, the source behaves similarly to the brighter and better studied X-ray Seyfert galaxies (e.g., NGC 4051, NGC 5506; Green et al. 1993; Nandra et al. 1997).

Figure 2 shows the MECS 3–5 keV and 5–10 keV light curves (on the same scale) together with their ratios. The light curves are not background subtracted (the internal plus cosmic background is about 3% and 6% of the mean total count rate in the two bands, and therefore it is negligible). The two MECS light curves present similar but not identical variations, and in fact, their hardness ratio shows small (≤20%) variations. Unfortunately, the statistic is not good enough to perform an accurate spectral variability study. To this purpose, high-throughput instruments, like those on board the *Chandra* and *XMM-Newton* satellites, are needed. In any case, the spectral variations are expected to be small enough to allow us to safely use time-integrated counts. We therefore concentrate hereafter on the time-averaged properties of the spectrum.

4. SPECTRAL ANALYSIS

Spectral fits were performed using the XSPEC 9.0 software package and public response matrices, as from the 1998 November release. LECS and MECS spectra were rebinned following two criteria: (1) sampling of the energy resolution of the detectors with four channels at all energies whenever possible and (2) obtaining at least 20 counts per energy channel. Constant factors have been introduced in the fitting models in order to take into account the intercalibration systematics between the instruments. The expected factor between LECS and MECS is about 0.9 (0.7–1.1), and the expected factor between the PDS and MECS is 0.8 (0.7–0.9; see Fiore et al. 1999). We assume the MECS as a reference instrument in all spectral fits. The energy ranges used for the fits are 0.1–4 keV for the LECS (channels 11–400), 1.65–10 keV for the MECS (channels 37–213), and 13–100 keV for the PDS. Errors quoted in this paper are

![Figure 1](image1.png)

**Figure 1.** *BeppoSAX* MECS 3–10 keV light curves of NGC 4258 in bins of 2850 s (half satellite orbit). Errors represent the 1σ confidence interval.

![Figure 2](image2.png)

**Figure 2.** *BeppoSAX* MECS 3–5 keV and 5–10 keV light curves of NGC 4258 in bins of 22,800 s (corresponding to about 4 satellite orbits per bin; upper and middle panels). The 5–10 keV/3–5 keV count ratio as a function of time (lower panel).
90% confidence intervals for one interesting parameter ($\Delta \chi^2 = 2.71$).

Figure 3 shows that the 0.1–100 keV spectrum (LECS + MECS + PDS) is highly complex. A strong cutoff below 4 keV is clearly visible, as is a faint emission-line feature between 6 and 7 keV. The large excess visible between 0.7 and 1 keV is likely due to iron L emission from an optically thin plasma. The analysis of the high-energy spectrum is presented in § 4.1 ($E > 2.5$ keV). The thermal component(s) dominating the spectrum below ~2 keV are discussed in § 4.2.

4.1. The Hard Nuclear Component

The intensity of the hard component is strongly reduced by photoelectric absorption below 2–3 keV. For the sake of simplicity, we exclude the LECS data and limit the fit to the MECS + PDS data above 2.5 keV when considering the nuclear component. The MECS + PDS spectra were fitted with a power-law model plus photoelectric absorption. The agreement between the data and this simple model is acceptable (see Table 2). Thanks to the broad energy band, the power-law spectral index and the column density of the absorbing gas are well constrained \[ \alpha_F = 1.11 \pm 0.14, \quad N_H = (0.95 \pm 0.12) \times 10^{23} \text{ cm}^{-2} \]. Figure 4 shows the ratio between the MECS and PDS data and the best-fit model.

The observed 2–10 keV flux is $8.0 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$, while the flux corrected for intrinsic absorption is $(1.52 \pm 0.15) \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$. The uncertainty on the unabsorbed flux is mostly due to the uncertainty on the absorbing column. The 2–10 keV nuclear (unobscured) luminosity is $(1.0 \pm 0.1) \times 10^{41}$ ergs s$^{-1}$. The broadband 0.1–100 keV luminosity of the hard component is $4.5 \times 10^{41}$ ergs s$^{-1}$.

![Figure 3](image_url)

**Figure 3.** BeppoSAX LECS, MECS, and PDS 0.1–100 keV spectra of NGC 4258, fitted with a single power-law model in the full 0.1–100 keV band. Note the strong cutoff below 4 keV and the large excess between 0.7 and 1 keV likely due to iron L emission from an optically thin plasma.

4.2. The Low-Energy Spectrum

The inclusion of a narrow line is significant at the 98% confidence level according to the $F$-test. The line energy (6.57 ± 0.20 keV) is consistent with Kα emission from both neutral and helium-like iron. The equivalent width (85 ± 65 eV) is not well constrained. It is consistent with, but somewhat lower than, that of Seyfert 1 and Compton-thin Seyfert 1.9–2 galaxies (Matt 2000). Assuming neutral iron, the observed equivalent width is consistent with that expected from transmission through a column density of about $10^{23}$ cm$^{-2}$ (Ghisellini, Haardt, & Matt 1994). The inclusion of a high-energy cutoff is not significant. The 90% confidence level lower limit to the cutoff energy is 30 keV.

We have also fitted the MECS and PDS data with a thermal bremsstrahlung model (Table 2). The $\chi^2$ is significantly worse than for the power-law model fit. We then fitted the data with a power-law plus bremsstrahlung model (fixing the temperature of the bremsstrahlung to 100 keV), to put a limit on the flux of an additional spectral component with its shape predicted by ADAF models with strong winds. The 90% limits on the 2–10 keV unabsorbed flux and on the 0.1–100 keV luminosity of this component are $4 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ and $1.5 \times 10^{41}$ ergs s$^{-1}$, respectively, about one-third of the total 0.1–100 keV nuclear luminosity.

### Table 2

**Spectral Fits: 2.5–100 keV Band**

<table>
<thead>
<tr>
<th>Model</th>
<th>$N_H$ (10$^{22}$ cm$^{-2}$)</th>
<th>$\sigma_F$ or $kT$ (keV)</th>
<th>Line E (keV)</th>
<th>Line EW (eV)</th>
<th>$\chi^2$ (dof)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power law</td>
<td>9.5 ± 1.2</td>
<td>1.08 ± 0.14</td>
<td>...</td>
<td>...</td>
<td>30.3 (40)</td>
</tr>
<tr>
<td>Power law + line</td>
<td>9.4 ± 1.2</td>
<td>1.11 ± 0.14</td>
<td>6.57 ± 0.20</td>
<td>85 ± 65</td>
<td>25.3 (38)</td>
</tr>
<tr>
<td>Bremsstrahlung</td>
<td>7.9$^{-0.7}_{+1.3}$</td>
<td>9.5$^{-1.1}_{+1.2}$</td>
<td>...</td>
<td>...</td>
<td>40.7 (44)</td>
</tr>
</tbody>
</table>
line. An additional absorbing column of density fixed to the Galactic value along the line of sight \((N_H = 1.16 \times 10^{20} \text{ cm}^{-2})\) has been included in the fit. The best-fit power-law spectral index and intrinsic absorption results were very close to the best-fit values found in § 4.1. In Table 3 we give only the parameters of the low-energy component.

The fit with a single thermal component is not completely satisfactory (see Fig. 5a), with rather large residuals between 0.5 and 1 keV. The LECS and MECS spectra have therefore been fitted with a two-temperature model plus the highly absorbed power law and the iron Kα line (Fig. 5b). The improvement in \(\chi^2\) is significant (\(\Delta \chi^2 = 21.6\) for three additional parameters, corresponding to a probability of 99.98%, according to the F-test; see Table 3). While the temperature of the cooler component is well constrained, for the hotter component we obtain a lower limit of about 1.3 keV. The metal abundance of the cooler component is constrained to be higher than 0.2 solar, while that of the hot component is constrained to be smaller than 0.9 solar. The results on the other parameters do not change upon fixing the metal abundances to the solar value. The results on these values are rather large, on the order of 50%. A slightly better fit is obtained by replacing the thermal “hot” component with an unobscured power law. In this case, the improvement in \(\chi^2\) is significant at the 99.998% confidence level (\(\Delta \chi^2 = 23.6\) for two additional parameters). Fixing the spectral index of the unobscured power law to that of the obscured nuclear component (so mimicking a partial covering model) produces \(\chi^2 = 89.6\), which is still acceptable. The covering fraction in this case is 0.935 ± 0.010.

4.3. Comparison with Previous ROSAT and ASCA Observations

The BeppoSAX 2–10 keV flux is about 2 times higher than in the 1993 May and 1999 May ASCA observations, although it is similar to that in the 1996 observations (Reynolds et al. 2000). The power-law index is consistent with the ASCA measurements. The column density measured by Makishima et al. (1994) is \((1.5 \pm 0.2) \times 10^{23} \text{ cm}^{-2}\), while Ptak et al. (1999) find a nominally lower value of \((0.5–0.7) \times 10^{23} \text{ cm}^{-2}\) with a typical statistical error of \((0.8–0.3) \times 10^{23} \text{ cm}^{-2}\) (see their Tables 5 and 7). Reynolds et al. (2000) report values of \((0.88–1.4) \times 10^{23} \text{ cm}^{-2}\). The BeppoSAX measurement is consistent with all ASCA measurements except that in the 1993 May observation.

The temperatures and abundances of the low-energy components are consistent with ASCA (Makishima et al. 1994; Ptak et al. 1999; Reynolds et al. 2000) and ROSAT (Pietsch et al. 1994; Cecil, Wilson, & De Pree 1995) determi-

<p>| TABLE 3 |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Model</th>
<th>(kT_1) (keV)</th>
<th>(kT_2) or (a_{E2}) (keV)</th>
<th>(A_1) ((A_{01}))</th>
<th>(A_2) ((A_{02}))</th>
<th>Flux(_1^\text{a}) ((10^{-12}\text{ ergs cm}^{-2}\text{s}^{-1}))</th>
<th>Flux(_2^\text{a}) ((10^{-12}\text{ ergs cm}^{-2}\text{s}^{-1}))</th>
<th>(\chi^2) (dof)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEKAL + Power law + line ...........</td>
<td>0.81 ± 0.07</td>
<td>...</td>
<td>0.11 ± 0.05</td>
<td>...</td>
<td>2.0</td>
<td>...</td>
<td>108.9 (92)</td>
</tr>
<tr>
<td>2 MEKAL + Power law + line ...........</td>
<td>0.6(^*) ± 0.07 (-0.20)</td>
<td>&gt;1.3</td>
<td>&gt;0.2</td>
<td>&lt;0.9</td>
<td>1.7, 03</td>
<td>1.1, 06</td>
<td>87.3 (89)</td>
</tr>
<tr>
<td>MEKAL + 2 Power law + line ...........</td>
<td>0.6 ± 0.1</td>
<td>0.2(^*) ± 0.2</td>
<td>&gt;0.2</td>
<td>...</td>
<td>1.6, 04</td>
<td>0.4, 20</td>
<td>85.3 (90)</td>
</tr>
<tr>
<td>MEKAL + 2 Power law + line* ...........</td>
<td>0.6 ± 0.1</td>
<td>1.05 ± 0.08</td>
<td>&gt;0.2</td>
<td>...</td>
<td>1.0, 02</td>
<td>1.3, 090</td>
<td>89.6 (91)</td>
</tr>
</tbody>
</table>

* 0.1–2.4 and 2–10 keV fluxes.

\(^*\) The spectral indices of the obscured and unobscured power laws are linked together.
4.4. The Radio/X-Ray Nuclear Spectral Energy Distribution

As mentioned in § 1, the SED of NGC 4258 was compared with broadband ADAF models by Lasota et al. (1996) and Gammie et al. (1999). The fit of detailed ADAF models to the radio/X-ray SED is beyond the scope of this paper. Here we limit ourselves to considering the two broadband spectral ratios $R_{\text{RX}} = L(22 \text{ GHz})/L(5 \text{ keV})$ and $R_{\text{NIRX}} = L(2 \mu m)/L(5 \text{ keV})$, which are plotted in Figure 6. The NGC 4258 BeppoSAX and ASCA data have been combined with the Herrnstein et al. (1998) 22 GHz upper limit and with the Chary & Becklin (1997) 2 $\mu$m “nuclear” emission. The resulting ratios are compared with the analogous ratios built from the Di Matteo et al. (2000) ADAF plus wind best-fit models to the SEDs of six nearby elliptical galaxies. From Figure 6, we note that the $R_{\text{RX}}$ and $R_{\text{NIRX}}$ values for NGC 4258 are 2–4 orders of magnitude lower and higher, respectively, than the values in the ADAF plus wind best-fit models. A comparison can also be made with the ratios computed from the average SEDs of UV-excess-selected radio-quiet quasars (Elvis et al. 1994). In this case, we can include in $L(22 \text{ GHz})$ the emission slightly offset from the dynamical center found by Herrnstein et al. (1998; 3 and 0.5 mJy at 0.4 and 1 mas from the dynamical center, respectively). Even including this radio emission, the NGC 4258 radio/X-ray ratios are in the region occupied by radio-quiet AGNs.

Fig. 6.—Ratio between the 22 GHz luminosity and the 5 keV luminosity as a function of the ratio between the 2 $\mu$m luminosity and the 5 keV luminosity. Open diamond, area covered by the radio quiet quasar SEDs of Elvis et al. (1994); filled circle, NGC 4258 BeppoSAX observation; cross, NGC 4258 ASCA observations (average); and open circles, best-fit ADAF plus wind models to the six elliptical galaxies studied by Di Matteo et al. (2000). Note that while the X-ray and radio luminosities of the six models are very close to measured values, the NIR points come just from the models. Also note that the NGC 4258 points are computed using the 22 GHz upper limit on the nuclear emission. For a more complete comparison, the cross and the filled circle should be shifted upward by 1.2 to include the off-center 22 GHz detections of 3 and 0.5 mJy by Herrnstein et al. (1998).

5. DISCUSSION AND CONCLUSIONS

5.1. Origin of the Nuclear Emission

The nuclear luminosity $L$ (2–10 keV) of NGC 4258 during the BeppoSAX observation was about $10^{41}$ ergs s$^{-1}$, similar to the NIR 2 $\mu$m luminosity estimated by Chary & Becklin (1997). This is consistent with an extrapolation of the X-ray power law down to a few microns. On the high-energy side, the BeppoSAX data are not able to provide a strong constraint on the cutoff. However, BeppoSAX measured a cutoff energy of 100–200 keV in half a dozen Seyfert galaxies (Matt 2000 and references therein; see also Zdziarski et al. 2000 and references therein for GRO/OSSE results). It is therefore reasonable to assume that the nuclear power-law component can be extrapolated up to $\sim$200 keV. If this is the case, the 3 $\mu$m to 200 keV total nuclear luminosity is of the order of $10^{42}$ ergs s$^{-1}$. The uncertainty on this number strongly depends on the assumed NIR/X-ray spectral index (an uncertainty of 0.2 on this spectral index would imply a 50% uncertainty on the total luminosity). The nuclear NIR/X-ray luminosity is similar to the minimum bolometric luminosity implied by the Wilkes et al. (1995) detection of polarized flux. A nuclear NIR/X-ray luminosity of $10^{42}$ ergs s$^{-1}$ and a black hole mass of $(3.9 \pm 0.1) \times 10^7 M_\odot$ (Herrnstein et al. 1999) imply an Eddington ratio of $\approx 0.0002$. Although higher than the Eddington ratios estimated by Lasota et al. (1996) and Gammie et al. (1999), this is still in the ADAF regime (e.g., Narayan, Mahadevan, & Quataert 1998). We therefore discuss briefly in the following the applicability of ADAF models to the nuclear emission of NGC 4258.

The SEDs of ADAF models depend on a variety of parameters and assumptions (Narayan et al. 1998; Quataert & Narayan 1999; Di Matteo et al. 2000). Here we distinguish between two main families of models: (1) those in which strong winds efficiently deplete the emission region of emitting electrons and reduce the synchrotron radio emission together with the inverse Compton emission in X-rays (e.g., Di Matteo et al. 2000), and (2) those without winds. The observed 2.5–70 keV spectral index ($\alpha_E = 1.11 \pm 0.14$) is steeper than that expected in ADAF models, where the contribution of Comptonization is negligible, and the X-ray luminosity is mostly due to thermal bremsstrahlung with $kT = 100–200$ keV, i.e., $\alpha_E \approx 0.3$ at energies below 50–100 keV (case 1; see, e.g., Di Matteo et al. 2000). An additional $kT \approx 100$ keV bremsstrahlung component can contribute to at most one-third of the broadband X-ray luminosity of the main ($\alpha_E = 1.11$) power-law component (see § 4.1).

On the other hand, if the X-ray band is dominated by Comptonization as in case 2, the observed X-ray spectral index can easily be explained. In this case, we would expect either strong synchrotron emission in the radio band or strong infrared emission from the outer thin disk to provide enough soft photons for the inverse Compton scattering. We discuss these two possibilities in turn.
Strong synchrotron emission.—Given the X-ray luminosity observed by ASCA and the higher one observed by BeppoSAX, the Herrnstein et al. (1998) 22 GHz upper limit is barely consistent with the Gammie et al. (1999) ADAF models without wind. Furthermore, the observed radio/X-ray luminosity ratio is 2–3 orders of magnitude lower than in the nearby elliptical galaxies that are supposed to host an ADAF (see Fig. 6 and § 4.4). ADAF solutions with or without winds seem more radio loud than the NGC 4258 nucleus. Conversely, the radio/X-ray luminosity ratio is consistent with that found in radio-quiet AGNs (Elvis et al. 1994). We also note that the 3 mJy off-center detection at 22 GHz is consistent with the luminosity of a radio jet whose power is proportional to the optical luminosity of a standard accretion disk (as inferred from the optical emission lines; Falcke & Biermann 1999).

Strong infrared emission.—The NIR/X-ray ratio of NGC 4258 is similar to that of radio-quiet AGNs (see Fig. 6), while it is higher than that in the Di Matteo et al. (2000) ADAF models, with winds of 2–4 orders of magnitude. In fact, Gammie et al. (1999) associate the strong nuclear NIR luminosity detected by Chary & Becklin (1997) to emission from a thin disk extending down to 50 Schwarzschild radii (R_S = 2GM(c^2)). According to Gammie et al. (1999), the flow should become advection dominated and produce a geometrically thick configuration at this transition radius. The size of the X-ray emission region, and therefore the putative transition radius, can be constrained through X-ray variability studies. There are at least two relevant timescales here: the local dynamical timescale \( t_d = R^3/(32GM)^{1/2} \) and the causality timescale \( t_c = R/c \). Large variations on timescales of \( \sim 40,000 \) s are present in the 3–10 keV light curve of NGC 4258, as well as 10%–20% variations on shorter (\( \sim 1 \) hr) timescales. Associating the longer timescales to \( t_d \), as expected if the hard X-ray luminosity is mostly due to bremsstrahlung emission, produces an emission radius in units of \( R_S \) of \( r \lesssim 7 \). Associating the same timescale to \( t_c \), produces \( r \lesssim 100 \). These radii are still consistent with the ADAF transition radius of \( \sim (5–50)R_S \) suggested by Gammie et al. (1999). We note, however, that even if a transition radius as small as \( 5R_S \) may be mathematically correct, it is less than 2 times the last stable orbit in a Schwarzschild metric. Since the transition between a geometrically thin disk to a thick configuration is unlikely to be very sharp, this leaves little space for the putative hot-plasma region responsible for the X-ray emission. Reynolds et al. (2000) suggest that the size of the nuclear X-ray source may be as large as \( \sim 50R_S \) based on the limit on the width of the iron K\( \alpha \) line. However, a sizeable fraction of the line emission may well be produced by outer gas, like, e.g., the gas responsible for the X-ray absorption (see § 4.1).

In conclusion, ADAF models with strong winds can be ruled out for the nuclear emission of NGC 4258, based on both the measured X-ray spectral shape and the X-ray variability. ADAF models without strong winds may be applicable, but it is not clear if they are a viable physical solution (Blandford & Begelman 1999; Di Matteo et al. 2000). Moreover, they imply a radio/X-ray ratio barely consistent with the measured upper limit, and also their X-ray observed variability constrains the transition radius to being rather small \( \sim (20–100)R_S \).

The IR/X-ray Eddington ratio, the X-ray variability and spectral shape, and the radio/X-ray and NIR/X-ray luminosity ratios suggest that the nucleus of NGC 4258 is an AGN in a low state (see, e.g., Siemiginowska, Czerny, & Kostylyunin 1996) or a scaled-down version of a Seyfert nucleus. This is also consistent with the conclusions of Neufeld & Maloney (1995), who suggest that the low luminosity of NGC 4258 is the result of low accretion rate \( \sim 10^{-4}/M_\odot \) yr\(^{-1} \). In the model of Neufeld & Maloney (1995), the radiative efficiency is high, \( \sim 10\% \), in contrast to the low-efficiency ADAF models. The X-ray nuclear luminosity can be naturally explained in terms of Comptonization of soft photons in a hot corona (e.g., Haardt & Maraschi 1991; Haardt, Maraschi, & Ghisellini 1994). Witt et al. (1997) developed a model of accretion disk plus corona, introducing a coupling between the energy dissipated in the corona and the accretion rate. They found that if the viscosity mechanisms are the same in the disk and the corona, the corona does not form for accretion rates smaller than a critical value because Compton cooling wins against viscous heating in the corona. This critical value is \( m_\nu \approx 0.001 \) at small radii and increases with the radius. Under this condition, if the Eddington ratio of 0.0002 is linearly proportional to \( m_\nu \) and if the efficiency in the conversion of accretion power into radiation is \( \eta \sim 0.1 \), a corona should not form in the nucleus of NGC 4258. There are at least two ways out of this problem. First, the efficiency \( \eta \) is at least as small as 0.01. This may be the case if a large part of the accretion power is carried out by a different channel, e.g., kinetic energy in a wind (as also foreseen in the Witt et al. 1997 model). Second, the dissipation of accretion power and the viscosity mechanisms may be very different in the disk and in the corona, as in the case of local magnetic reconnection flares in the corona, envisaged by Haardt et al. (1994).

More theoretical work is clearly needed to understand if accretion rates as small as 0.0002 in Eddington units may power a low-luminosity version of a normal Seyfert galaxy nucleus, although this already seems the most likely and least demanding (in terms of complexity) scenario for NGC 4258.

5.2. Origin of the Low-Energy Component(s)

Makishima et al. (1994) and Ptak et al. (1999) found some support for a two-temperature model for the low-energy ASCA spectrum of this source. Using ROSAT HRI data, Pietsch et al. (1994) and Cecil, Wilson, & De Pre (1995) were able to resolve the soft X-ray emission into several components, the most relevant being a jet component. Cecil, Wilson, & De Pre (1995) and Makishima et al. (1994) also report the discovery of a hotter thermal component \( (kT \sim 4 \) keV). The BeppoSAX data confirm the presence of at least two components in addition to the obscured nuclear power law in the 0.1–10 keV spectrum of this source. One component must be thermal, given the strong iron L complex detected, and its best-fit temperature is \( kT \sim 0.6 \) keV. It can be attributed to shocks formed in the interaction of the jet with the interstellar matter (Cecil et al. 1995).

The shape of the second component is not well constrained by the BeppoSAX data. It is consistent with both thermal emission with temperature \( kT > 1.3 \) keV and a power law with energy index \( 0.2^{+0.8}_{-0.2} \). This component may consist of a fraction of 0.935 ± 0.010 of the nuclear power law spilling out from a nonuniform absorber. NGC 4258 is known to be highly polarized (Wilkes et al. 1995). This implies that there are lines of sight to the nucleus scattering photons toward us and providing an unobscured view. Such geometry mimics a partial covering of the nuclear...
5.3. Strong X-Ray Absorption and Water Maser Emission

The nuclear continuum of NGC 4258 varies on a timescale of 0.5 day (see § 3). Our data are not good enough to detect Fe K line variability. However, all the observations to date are consistent with Fe-like flux being constant over at least a few times $10^4$ s. We also find that the flux of the Fe line is consistent with its origin in the absorbing gas (§ 4.1). All this places the Fe line, and thus the absorber, at a distance of greater than $6 \times 10^{15}$ cm. The water maser emission in NGC 4258 originates at 0.13 pc from the nucleus. Thus the location of the X-ray absorber is consistent with being the same as that of the maser emission. Such an association between the X-ray absorber and maser emission is further corroborated by a general tendency of maser sources to show strong X-ray absorption; see, e.g., Braatz et al. (1997) and NGC 4945, Circinus galaxy, NGC 1068 (Matt et al. 2000 and references therein), ESO 103-G35 (Wilkes et al. 2001), and possibly NGC 3079 (Bassani et al. 1999).

In the models of Neufeld & Maloney (1995) for maser emission in NGC 4258, the X-rays from the nuclear AGN are shielded by gas of large column density. Such shielding helps in creating the layer of warm molecular gas in the midplane of the circumnuclear disk. The column density of the shielding gas in the Neufeld & Maloney (1995) model is $9 \times 10^{22}$ cm$^{-2}$, exactly what we measure in the present BeppoSAX observation. It is thus reasonable to assume that the large column density gas responsible for the nuclear X-ray absorption is also shielding the molecular gas. Neufeld & Maloney (1995) also note that if the circumnuclear disk is absolutely flat, i.e., not warped, then it would not be illuminated by the X-ray continuum. In this situation the temperature in the midplane of the disk would be too cold to excite water maser emission. Note that in such a geometry there would not be any X-ray absorption either.

All the above facts point toward a direct causal link between strong X-ray absorption and water maser emission. Illumination by X-ray continuum and subsequent shielding by a large column density gas seems to be required for maser emission, at least in some models. If such a scenario is correct, every maser-emitting AGN would show absorption in its X-ray spectrum.

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