Astron. Astrophys. 360, 878–886 (2000)

ASTRONOMY AND ASTROPHYSICS

The 0.1–100 keV view of NGC3998: an AGN origin for the LINER activity

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Received 14 April 2000 / Accepted 29 June 2000

Abstract. We present a *BeppoSAX* observation of the LINER nucleus of the S0 galaxy NGC3998. A long standing issue concerning LINER galaxies is the origin of their optical emission lines that could be due to either starburst or AGN-like activity. The broad band *BeppoSAX* spectral data of NGC3998 allow one for the first time to single out a power law component extending from 0.1 to 100 keV. This provides a strong indication for an AGN origin of the LINER activity in this galaxy. The value of the photon index ($\Gamma \sim 1.9$), the small amount of intrinsic absorption required by the X-ray spectrum ($N_H < 3 \times 10^{20}$ cm^{-2}) and the presence of a broad Hα component all suggest that the nucleus of NGC3998 might be an example of a low luminosity type 1 AGN. This hypothesis is also supported by the (2–10) keV and Hα luminosity values placed on the extension to low luminosities of the correlation observed for Seyfert galaxies and quasars, and by the possible presence of an OVII absorption edge in the spectral data. At variance with the properties commonly shown by more luminous type 1 AGNs is however the absence of rapid and strong flux variability, the lack of signs of reflection from cold material and the low ratio ($\sim 10^{-4}$) of the observed nuclear luminosity to the Eddington luminosity. So, accretion could be advection dominated in NGC3998, as already suggested for other low luminosity AGNs. The broad band spectral energy distribution of the nucleus, though, shows high UV emission that makes it more similar to that of high luminosity AGNs. A ~ 9.2 keV absorption feature has also been marginally detected in the X-ray spectrum; this could be produced by transmission through highly ionized material as recently suggested for a similar feature revealed by *BeppoSAX* with much higher significance in M81.

Key words: galaxies: active – galaxies: individual: NGC3938 – galaxies: nuclei – galaxies: Seyfert – X-rays: galaxies

1. Introduction

LINER galaxies are defined as those showing a low ionization nuclear emission line region (Heckman 1996). The latest and most sensitive survey to search for emission lines in the nuclear regions of nearby galaxies comprises a sample of 486 northern galaxies with $B_T \leq 12.5$ mag (Ho et al. 1997). In this sample LINERs make up a considerable fraction ($\sim 1/3$) of all galaxies. The true physical nature of LINERs is not known yet and they seem to form a heterogeneous class: some can be explained in terms of a starburst (e.g., Terlevich et al. 1992; Alonso-Herrero et al. 2000); some are more consistent with being photoionized by a low luminosity AGN, on the basis of the presence of a broad Hα component, of a pointlike UV source or a nonthermal X-ray source at the nucleus, and of the continuity of the X-ray properties with those of luminous Seyferts (Koratkar et al. 1995). The S0 galaxy NGC3998, classified as a LINER by Ho et al. (1997), likely falls in this second group of LINERs: a broad Hα component with log L$_{\mathrm{H}\alpha}$(erg s^{-1})=40.16 has been detected (Ho et al. 1997) and an unresolved nuclear source is present in the *HST* FOC images, most prominent in the UV (Fabbiano et al. 1994). At the optical nucleus a compact (< 0.4 arcsec) nonthermal radio source has been found at 20 cm (Wrobel 1991). Finally, strong emission between 4.5μm and 15μm detected by ISOCAM (Knapp et al. 1996) gives evidence for a compact hot dust cloud in the central regions. A near infrared spectroscopic study shows a low [FeII]/Paβ ratio, on the basis of which NGC3998 is considered to host Seyfert-like activity more likely than starburst-like activity (Larkin et al. 1998).

In this paper we aim at testing further the hypothesis of the presence of a low luminosity AGN (LLAGN) as the source of the optical emission lines in NGC3998. This is achieved through a *BeppoSAX* observation that extends over three orders of magnitude in photon energy, from 0.1 to 100 keV. The large energy band coupled to a moderate spectral resolution (8% FWHM at 6 keV) is especially suited to measure the properties of the high energy continuum, to search for thermal components that could be due to a starburst, and to investigate the presence of Fe-K features. The general properties of NGC3998 are given in Table 1.

2. Previous X-ray observations of NGC3998

NGC3998 was first clearly detected in X-rays by the *Einstein Observatory*. Dressler & Wilson (1985) found an unresolved

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Table 1. General characteristics of NGC3998

Type[a]	RA (J2000)	Dec (J2000)	d [b] (Mpc)	Optical[c] classification	B_T^0 [a] (mag)	logL_B [d] ($L_\odot$)	D_{25} [e] (arcmin)	$N_{H,Gal}$ [f] (cm^{-2})
S0	$11^h57^m55\overset{s}{.}2$	$55°27'22''$	21.6	L1.9	11.49	10.26	2.7	9.7×10^{19}

[a] from de Vaucouleurs et al. (1991). B_T^0 is the total B magnitude, corrected for Galactic and internal extinction.
[b] distance from Tully (1988), based on $H_0 = 75$ km s^{-1} Mpc^{-1}.
[c] From Ho et al. (1997), L=LINER.
[d] total B-band luminosity, derived using the indicated distance and B_T^0.
[e] Isophotal major axis diameter at $\mu_B = 25.0$, from de Vaucouleurs et al. (1991).
[f] Galactic neutral hydrogen column density along the line of sight (Murphy et al. 1996).

Table 2. Observation log

Sequence Number	Date	Exposure time[a] (ks) LECS	MECS	PDS	Count Rate[b] (ct/s) LECS	MECS	PDS
40901001	1999 Jun 29	24.5	76.5	37.8	0.099±0.002	0.145±0.001	0.23±0.04

[a] On-source net exposure time. The LECS exposure time is considerably shorter than the MECS one, because the LECS can operate only when the spacecraft is not illuminated by the Sun.
[b] Background subtracted source count rates, with photon counting statistics errors. Extraction radii are 8 and 3 arcmin, and energy bands are 0.1–4 and 1.65–10.5 keV, respectively for the LECS and MECS data.

IPC source centered on the optical position of NGC3998. Subsequent observations by *GINGA* performed in 1988 (Awaki et al. 1991) revealed the presence of a power law with photon index $\Gamma = 2.0 \pm 0.1$ in the 2–10 keV band. *ASCA* pointed NGC3998 in 1994 (Ptak et al. 1999); the spectrum over 0.4–10 keV was fitted by a power law of $\Gamma = 1.90^{+0.04}_{-0.05}$ absorbed by cold material of column density $N_H \sim 9 \times 10^{20}$ cm^{-2}, roughly nine times larger than the Galactic value. No significant line emission was found, and fits with the line center energies fixed at 6.4 or 6.7 keV gave 90% confidence upper limits on the equivalent widths of these lines between 0.2 and 0.4 keV. A simultaneous fit of the $ASCA$ and $ROSAT$ PSPC data found a thermal component of $kT \sim 0.2$ keV (and $Z \sim 0.02 Z_\odot$) plus a power law absorbed by an even higher N_H. A search for ionized oxygen absorption edges using power law fits gave upper limits of 0.2 on the optical depths $\tau_{OVII}(0.74$ keV) and $\tau_{OVIII}(0.87$ keV) (Ptak et al. 1999).

3. X-ray data analysis

NGC3998 was observed by $BeppoSAX$ on June 29, 1999 (the journal of the observation is given in Table 2). In this paper we use data from three Narrow Field Instruments: the Low Energy Concentrator Spectrometer (LECS, Parmar et al. 1997), the Medium Energy Concentrator Spectrometer (MECS, Boella et al. 1997), and the Phoswich Detector system (PDS, Frontera et al. 1997). HPGSPC data (Manzo et al. 1997) are not considered since the source is too faint to be detected. The LECS and MECS are grazing incidence telescopes with position sensitive gas scintillation proportional counters in their focal planes. The MECS has a field of view of $56'$ diameter, and works best in the range 1.65–10.5 keV (Boella et al. 1997). The LECS operates at softer energies (0.1–4 keV), and has a field of view of $37'$ diameter. The PDS is a collimated instrument operating in rocking mode (half of the time on the source and half on the background direction) that covers the 13–300 keV energy band. It has a triangular response with FWHM of $\sim 1\overset{\circ}{.}3$.

The cleaned and linearized data produced by the *BeppoSAX* Science Data Center have been reduced and analysed using the standard software (XSELECT v1.4, FTOOLS v4.2, IRAF-PROS v2.5, and XSPEC v10.0). For the MECS, we used the event file made by merging the data of the units 2 and 3 properly equalized (on May 6, 1997 a technical failure caused the switch off of unit 1). The PDS data reduction was performed using the SAXDAS software package (v.1.3.0, Fiore et al. 1999).

3.1. Spatial analysis and extraction regions

The centers of the X-ray emission in the LECS and MECS images were found to be well within $1'$ from the optical center of the galaxy given in Table 1. Therefore, within the positional accuracy allowed by $BeppoSAX$ data, the X-ray centers coincide with the nucleus of NGC3998.

For a point source, the PSF of the MECS includes ~ 80% of the photons of energies ≥ 1.5 keV within a radius of $2\overset{'}{.}7$ (Boella et al. 1997). The PSF of the LECS is broader than that of the MECS below 2 keV, while it is similar to it above 2 keV. Due to these instrumental characteristics and given the optical size of the galaxy (Table 1), NGC3998 is not resolved by $BeppoSAX$. For the spectral analysis counts have been extracted from a circle of $3'$ radius for the MECS and of $8'$ radius for the LECS. The larger radius adopted for the LECS is motivated by its larger PSF at softer energies. In the $Einstein$ IPC image the profile of NGC3998 is consistent with the instrumental PSF (Fabbiano 1996). So, the presence of other significant emission compo-

Table 3. Results of the spectral analysis

Model	N_H (10^{20} cm^{-2})	Γ	Edge E (keV)	Edge τ	χ^2/ν
A. pow:	$2.4^{+0.6}_{-0.4}$	$1.86^{+0.03}_{-0.04}$			126/131
B. pow+edge	$2.7^{+0.5}_{-0.5}$	$1.89^{+0.03}_{-0.04}$	$0.77^{+0.08}_{-0.11}$	$0.37^{+0.23}_{-0.22}$	118/129
C. pow+edge+edge§:	$2.5^{+0.5}_{-0.5}$	$1.87^{+0.03}_{-0.04}$	$9.2^{+0.8}_{-0.8}$	$0.3^{+0.6}_{-0.2}$	111/127

N_H is the column density of neutral hydrogen in addition to $N_{H,Gal}$ given in Table 1.
ν is the number of degrees of freedom of the fit.
§ The first edge is the 0.77 keV edge; in the fitting with model C it maintains the same energy and absorption depth as in model B.

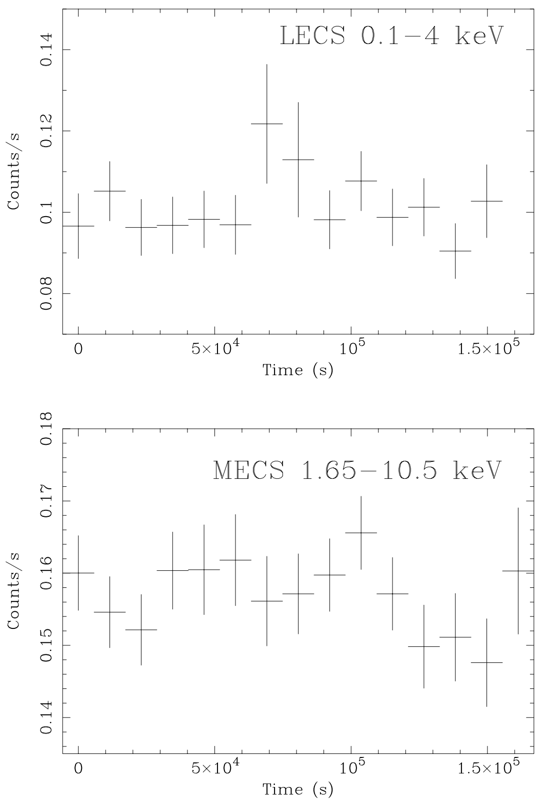

Fig. 1. The *BeppoSAX* light curves of NGC3998 in the 0.1–4 keV band (top; LECS data, counts from a circle of $8'$ radius) and in the 1.65–10.5 keV band (bottom; MECS data, counts from $3'$ radius). Time bins of 11520 seconds have been used; these correspond to 2 satellite orbits per bin.

nents in addition to the nucleus (as a hot interstellar medium) could not be investigated.

3.2. Variability

Fig. 1 shows the LECS and MECS light curves extending over the whole observing period. The LECS data do not show significant variability. In the MECS data, no variability is evident in the first $\sim 10^5$ s of the observation, after which a variation of the order of ~ 12% on a timescale of 5×10^4 s is observed. If one considers though the whole observing period, the nuclear emission is consistent with being constant (as revealed by a χ^2 test to quantify how the observed MECS count rate differs from a constant average emission). Significant intensity variations have not been found previously from $GINGA$ (Awaki et al. 1991) and from $ASCA$ data (Terashima 1999).

The X-ray flux is somewhat more variable over long time scales. Between the $Einstein$ and $GINGA$ observations, over a ~ 9 yrs period, there was an increase of a factor of 3 in the 0.4–3.5 keV flux, from which Awaki et al. (1991) concluded that the scale of the X-ray emitting region should be < 3 pc, and the emission is not dominated by a hot interstellar medium. The (2–10) keV fluxes observed by $GINGA$ (in 1988), $ASCA$ (in 1994) and $BeppoSAX$ (in 1999) are respectively 1.5×10^{-11} erg cm^{-2} s^{-1}, 8.0×10^{-12} erg cm^{-2} s^{-1} and 1.2×10^{-11} erg cm^{-2} s^{-1} (Sect. 3.3.1).

3.3. Spectral analysis

The background spectra used for the spectral analysis were estimated from blank-fields event files, accumulated on different pointings of empty fields; the extraction regions used for them correspond in size and position to those of the source. Spectral channels corresponding to energies 0.1–4 keV, 1.65–10.5 keV, and 15–200 keV have been used respectively for the analysis of the LECS, MECS and PDS data. The original channels have been rebinned to sample the instrumental resolution with the same number of channels at all energies, and to have a significant detection with S/N> 3 in each bin. The spectral response matrices and effective area files released in September 1997 have been used in the fitting process. For the LECS data the response matrix of the January 2000 software release has been used. We fitted the models simultaneously to the LECS, MECS and PDS data. In the fitting two normalization constants were introduced to allow for known differences in the absolute cross-calibrations between the detectors (Fiore et al. 1999). The results of the spectral analysis are presented in Table 3. Everywhere in this paper quoted errors give the 90% confidence intervals for one interesting parameter ($\Delta\chi^2 = 2.71$).

3.3.1. Fitting results

A single power law component of photon index $\Gamma = 1.86^{+0.03}_{-0.04}$ can reproduce the data over the whole energy band of 0.1–100 keV (see Fig. 2 and model A in Table 3). The power law is ab-

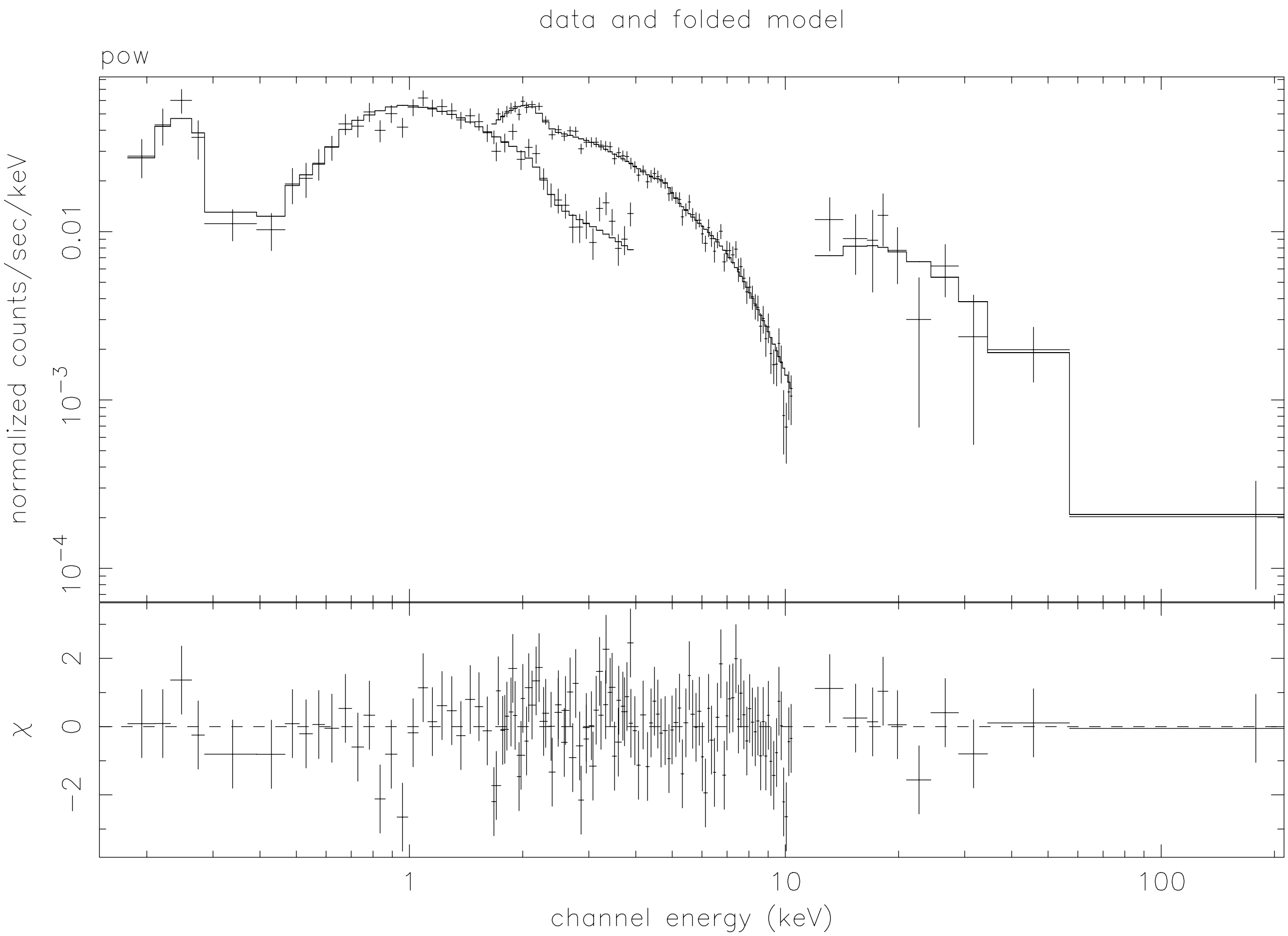

Fig. 2. *BeppoSAX* LECS, MECS and PDS observed spectra of NGC3998 (crosses) modeled with a power law of $\Gamma = 1.86$ (solid line; model A in Table 3). The residuals between the data and the model are plotted below.

sorbed by cold material exceeding the Galactic column density by $N_H \sim (2-3)\times 10^{20}$ cm^{-2}. This value is in agreement with a recent VLA estimate of the column density of diffuse HI emission in the central regions of NGC3998 ($N_H \sim (1-5)\times 10^{20}$ cm^{-2}, M. Verhejien private communication). It is also more than 3 times lower than that found from $ASCA$ data (Ptak et al. 1999; Sect. 2). However the spectral analysis based on $ASCA$ SIS+GIS data is limited to energies higher than 0.4 keV; also, the $ASCA$ SIS is likely to overestimate the column density due to possible remaining uncertainties in its low energy response (Cappi et al. 1998).

Next we searched for absorption edges, by adding them to the fit with a power law. Two possible cases were found. The first one is located at $0.77^{+0.08}_{-0.11}$ keV, with absorption depth $\tau = 0.37^{+0.23}_{-0.22}$ (model B; Fig. 3); within the errors it corresponds to the K-edge of OVII at 0.74 keV. An upper limit of 0.5 can be placed on the absorption depth of the OVIII edge at 0.87 keV. The second possible absorption feature is located at 9.2 ± 0.8 keV with $\tau \sim 0.3^{+0.6}_{-0.2}$ (model C; see also Fig. 4). The edge energy corresponds to the K-edge of FeXXVI at 9.29 keV, or to iron at a higher ionization level than FeXXII within the 90% confidence interval. According to the F-test these two edges are statistically significant at 98.5% and 98% confidence levels respectively (i.e., 2.5σ and 2.3σ), so their evidence is quite marginal. In Fig. 5 we plot the spectrum modeled with model C in Table 3.

A search for emission lines gave no clear detections. Some excess emission is present between 7–8 keV (Fig. 2); when fitted with a narrow gaussian line it gives a line center of $7.4^{+0.3}_{-0.2}$ keV and an equivalent width EW=106^{+110}_{-73} eV. The addition of this line is significant at 94% confidence level only (1.9σ) according to the F-test. The addition of a line centered at 6.4 keV, produced by Kα emission from an iron state less than or equally ionized as FeXVII, does not give any improvement of the fit, and the upper limit on the EW of this line is 40 eV.

As mentioned in Sect. 2, combining $ASCA$ with $ROSAT$ data a thermal component of $kT \sim 0.2$ keV was found. So we tried also the fit with a model consisting of model C in Table 3, with the edge at 0.77 keV replaced by a thermal component (described by the mekal model, which gives the thermal emission from an optically thin hot plasma). The cold absorption of the thermal component is fixed at the Galactic value, because it does not differ from $N_{\rm H,Gal}$ when left free. The best fit of the thermal component gives $kT \sim 0.15$ keV and $Z \sim Z_{\odot}$; the power law has $\Gamma \sim 1.90$ and an intrinsic $N_H \sim 10^{21}$ cm^{-2}, that is ~ 4 times higher than in model C. The thermal component flux,

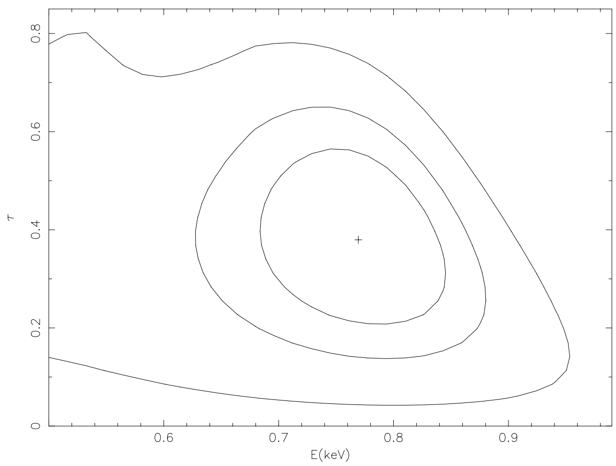

Fig. 3. The 68%, 90% and 99% confidence contours for two interesting parameters for the energy and absorption depth of the edge due to oxygen (from the fitting model C in Table 3).

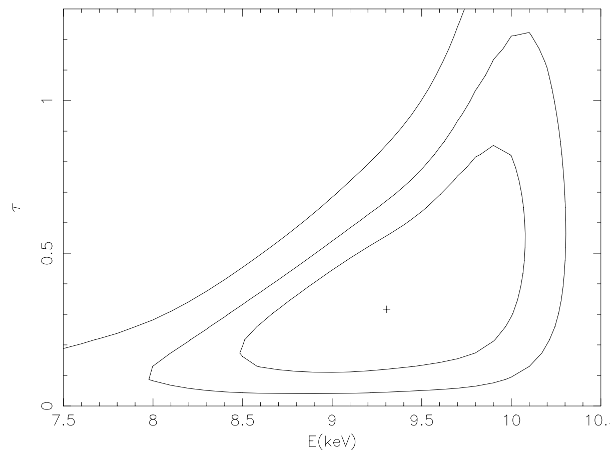

Fig. 4. The 68%, 90% and 99% confidence contours for two interesting parameters for the energy and absorption depth of the edge located at 9.2 keV (from the fitting model C in Table 3).

Table 4. Fluxes and luminosities

Energy band (keV)	0.1–2	2–10	10–100
Flux[a] (10^{-11} erg cm^{-2} s^{-1})	0.94	1.20	2.11
Luminosity[b] (10^{41} erg s^{-1})	9.3	6.7	12

[a] observed
[b] corrected for the total (intrinsic plus Galactic) column density of absorbing material derived for model C in Table 3.

when corrected for absorption, is roughly one sixth of the total unabsorbed 0.1–2 keV flux (i.e., 2.6×10^{-12} erg cm^{-2} s^{-1}, corresponding to a luminosity of 1.4×10^{41} erg s^{-1}). The addition of this soft thermal component gives a smaller improvement of the fit than the addition of the 0.77 keV edge ($\chi^2/\nu = 107/125$; χ^2 decreases by 6 for two additional free parameters, temperature and normalization, while the addition of the edge at 0.77 keV produces a decreases by 8 for two additional free parameters).

Finally, we searched for the presence of a reflection component, even though a simple power law seems to be a good representation of the continuum up to 100 keV (Figs. 2 and 5). So, we tried the fitting with a power law spectrum that undergoes reflection from neutral or ionized material, with solar abundance (models pexrav and pexriv in XSPEC). In both cases there is no improvement with respect to the fitting with a simple power law. At the best fit the subtended solid angle of the reflecting material $\Omega/2\pi = 0$, and $\Omega/2\pi < 0.21$ at 90% confidence.

Fluxes and luminosities derived for model C are given in Table 4.

4. Discussion

4.1. A LLAGN at the nucleus of NGC3998

A power law of $\Gamma \sim 1.9$ gives a good representation of the whole $BeppoSAX$ spectrum of NGC3998 from 0.1 to 100 keV. Thermal components, that could be expected if the nuclear activity revealed by the optical emission lines was starburst-triggered, are not found to be significant here. A very soft thermal component of $kT \sim 0.1 - 0.2$ keV could be present, but it can well be replaced by an absorption edge due to oxygen, as discussed in Sect. 3.3.1 (see also Sect. 4.3).

The power law component that well reproduces the (0.1–100) keV spectrum is usually related to the presence of an AGN, so this LINER galaxy most likely hosts a LLAGN, confirming previous suggestions (Sect. 1). The amount of cold absorption revealed by the X-ray spectrum is small ($N_H < 3 \times 10^{20}$ cm^{-2}); it is consistent with the Galactic value plus a possible contribution from diffuse HI emission intrinsic to NGC3998 (Sect. 3.3.1). The absence of a large absorbing column density and the value of the photon index close to that found for Seyfert 1's (Nandra et al. 1997) make this LLAGN similar to Seyfert 1's. Note that NGC3998 is classified as a LINER 1.9, i.e., as an object with a weak, broad component of Hα emission (comprising $\sim$ 37% of the flux of the entire Hα+[NII] blend, and with a width of FWHM≈ 2150 km s^{-1}, Ho et al. 1997). Recently Barth et al. (1999) have found that the broad Hα component of NGC3998 is not polarized, consistent with the hypothesis (coming from X-ray observations) that we are viewing its "broad line region" directly.

NGC3998 has though also some X-ray properties that make it different from Seyfert 1's. These usually show signs of reflection from optically thick material (an accretion disk or a torus) as a 6.4 keV emission line and a broad bump peaking at 10–20 keV (Nandra et al. 1997). These features are not present in NGC3998. This is similar to what found for M81, another LLAGN detected up to 100 keV by $BeppoSAX$, with an X-ray spectrum similar to that of Seyfert 1's in power law shape and absence of high absorption (Pellegrini et al. 2000). Also, as many other LLAGNs (Ptak et al. 1998) NGC3998 departs from the trend of increased variability with decreasing luminosity shown by brighter Seyfert galaxies (Turner et al. 1999).

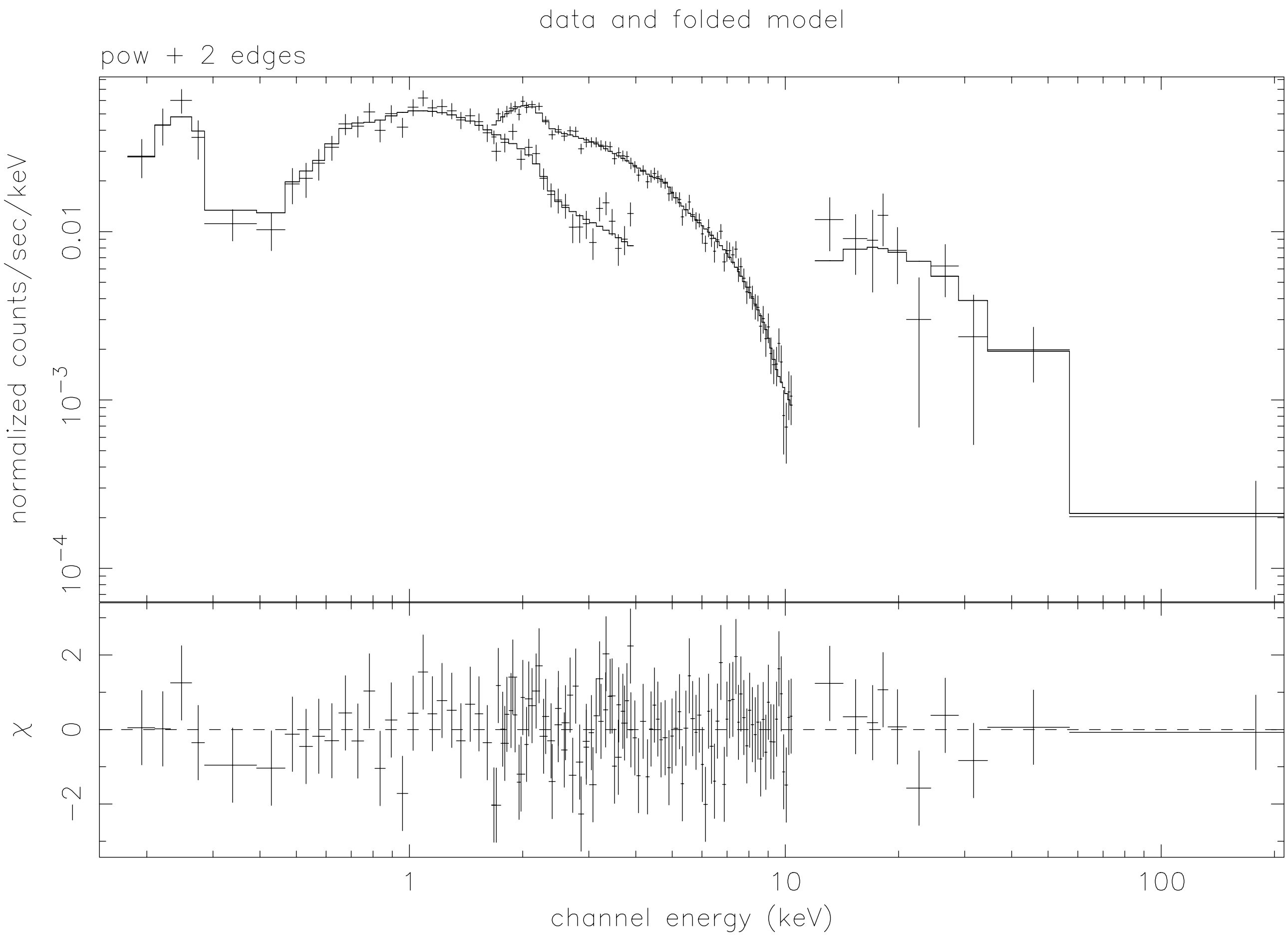

Fig. 5. *BeppoSAX* LECS, MECS and PDS observed spectra of NGC3998 (crosses), modeled with a power law plus two absorption edges (model C in Table 3). The residuals between the data and the model are plotted below.

A further comparison with the properties of more luminous AGNs can be made considering the correlation between L(2–10 keV) and L(Hα) observed for luminous Seyfert galaxies and quasars (Ward et al. 1988; Koratkar et al. 1995). The L(2–10 keV) value derived here and the L(Hα) value given by Ho et al. (1997) place NGC3998 on the extension to low luminosity values of this correlation. So a LLAGN could be at the same time the dominant source of X-ray emission and the ionizing source responsible for the optical LINER emission lines. Terashima (1999) suggests that this could be the case for all LINER galaxies with a broad Hα component.

4.2. Origin of the X-ray continuum emission

In this section we investigate the origin of the X-ray continuum emission by making use of three more ingredients: the mass of a putative central black hole ($M_{\rm BH}$), the total luminosity output of the nucleus of NGC3998 (L_{bol}), and its observed broad-band spectral energy distribution (SED). It is currently believed that all spheroids (early-type galaxies and bulges of spirals) host central massive black holes (Kormendy & Richstone 1995). Magorrian et al. (1998) showed that on average $M_{\rm BH} = 0.005\,M_{\rm Spheroid}$, where the spheroid mass can be estimated from its luminosity $L_{\rm B}$ ($M_{\rm Spheroid} = 5\times10^{9}(L_{\rm B}/10^{9}L_{\odot})^{1.2}$ $M_{\odot}$, Richstone et al. 1998). When adopting a bulge luminosity of $L_{\rm B} = 1.05\times10^{10}L_{\odot}$ for NGC3998 (Ho et al. 1997), one derives $M_{\rm BH}\sim 4\times10^{8}\,M_{\odot}$. To estimate L_{bol} we sum to L(0.1–100 keV) the optical and UV luminosities calculated by Fabbiano et al. (1994) from an HST FOC pointing ($L_{opt,UV} > 4.5\times10^{41}$ erg s^{-1} after rescaling for the distance adopted here[1]). This gives $L_{bol}\gtrsim 3.2\times10^{42}$ erg s^{-1}, which implies an Eddington ratio $L_{bol}/L_{Edd}\gtrsim 6\times10^{-5}$ [here $L_{Edd} = 0.1\dot{M}_{Edd}c^{2} = 1.25\times10^{38}M_{\rm BH}(M_{\odot})$ erg s^{-1}]. So accretion is taking place at a highly sub-Eddington rate, and/or the radiative efficiency of accretion is very low. In the first hypothesis, the nucleus of NGC3998 could be emitting as a scaled-down version of brighter Seyfert nuclei, where X-ray emission with a power law shape arises from inverse Compton scattering, by a hot optically thin plasma in a corona, of UV/soft X-ray pho-

[1] More precisely the “optical” and “UV” luminosities derived from these HST FOC observations actually correspond to three bands, centered on 5080, 3400 and 1720Å, and of width respectively 722, 704 and 678Å. Moreover, these luminosities are not corrected for internal extinction, and the two UV images are overexposed at the nucleus, so that only lower limits to the point source fluxes could be established (Fabbiano et al. 1994).

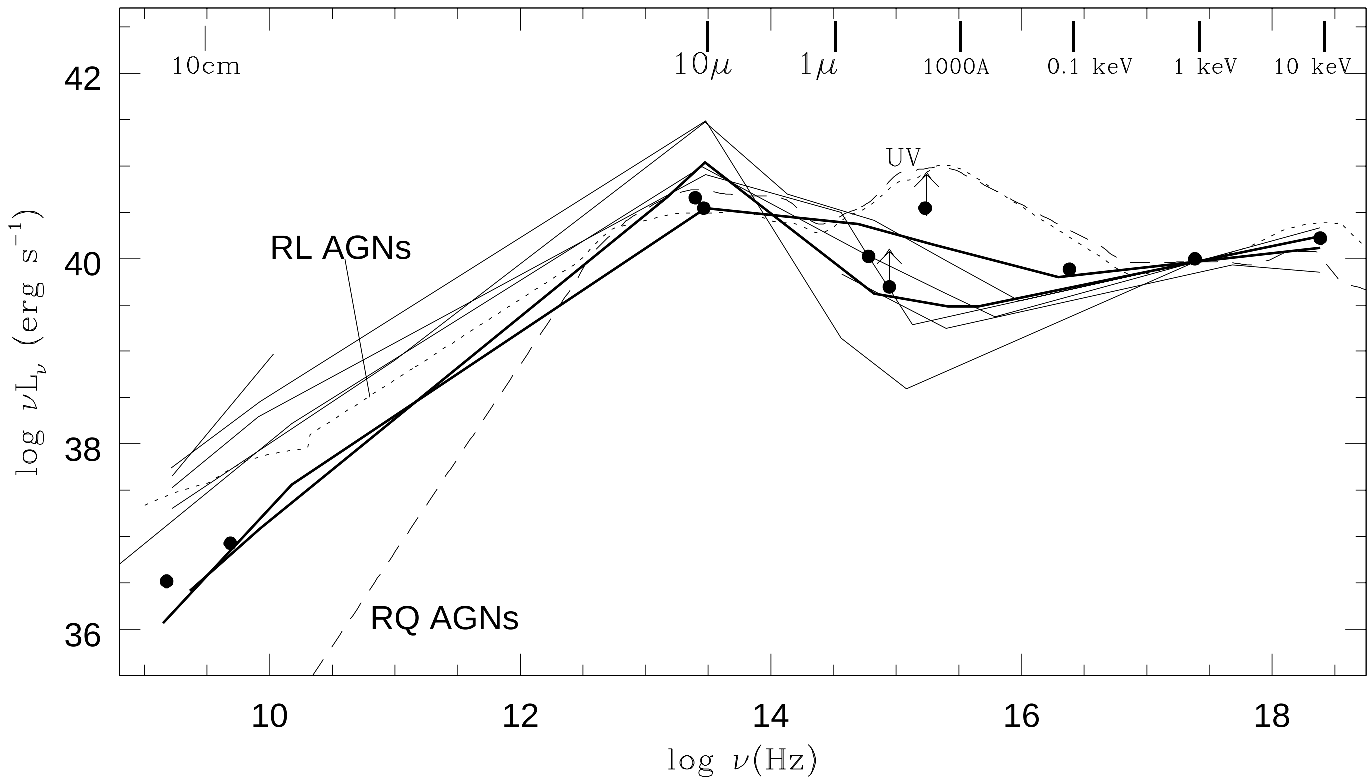

Fig. 6. The SED of NGC3998 (points) compared with the SEDs (solid lines) of the LLAGNs derived by Ho (1999) and the average SEDs of radio loud and radio quiet AGNs (Elvis et al. 1994); all SEDs are normalized to the 1 keV luminosity of M81. Thicker lines evidence the SEDs of M81 and NGC4579, which have been modeled with accretion through ADAF + standard disk by Quataert et al. (1999). The references for the NGC3998 points are Wrobel (1991) and Gregory & Condon (1991) in the radio, Knapp et al. (1992) in the $IRAS$ 10μ and 12μ bands, Fabbiano et al. (1994) in the optical and UV (HST FOC bands centered at 5080, 3400 and 1720Å), and this paper in the X-rays. ISO observations established that most of the $IRAS$ flux density at 10 and 12μ is nuclear in origin (Knapp et al. 1996).

tons produced by an accretion disk (see, e.g., Svensson 1996). This would agree with the similarities with the X-ray properties of Seyfert 1's pointed out in the previous section. In the second case, i.e., if the radiative efficiency is very low, an advection dominated accretion flow (ADAF) is a viable solution[2] (Narayan & Yi 1995). In fact this alternative origin for the X-ray continuum has been recently proposed for three LLAGNs: M81 and NGC4579 (Quataert et al. 1999) and NGC4258 (Gammie et al. 1999).

What can be inferred about the origin of the continuum emission based on the observed SED? Does it resemble more that of higher luminosity AGNs or that of the LLAGNs that have been modeled with ADAFs? The SEDs of the nuclei of a few LLAGNs (Ho 1999) are plotted in Fig. 6 together with the average SEDs of higher luminosity AGNs (Elvis et al. 1994). All the LLAGNs show similar SEDs, characterized by the absence of a bump in the optical-UV region. The SED of the nucleus of NGC3998 is similar to those of the other LLAGNs from the radio to the IR, but then it is remarkably different because of its higher UV luminosity at 1720Å. So, an ADAF modeling as done for M81 and NGC4579 (whose SEDs are evidenced in Fig. 6) is likely to be unable to reproduce the SED of NGC3998.

The high UV luminosity of the nucleus of NGC3998 makes the shape of its SED closer to that of brighter AGNs (Fig. 6). In fact the optical and UV fluxes of NGC3998 in Fig. 6 are not corrected for internal extinction, and the UV ones are also affected by saturation (see footnote 1). In the hypothesis that NGC3998 is just a scaled-down version of "normal" AGNs, and so that it contains a standard disk accreting with a normal efficiency ($L_{bol} = \epsilon \dot{M} c^2$, where the efficiency ϵ ranges from 0.06 to 0.4, Shakura & Sunyaev 1973), we can estimate the frequency at which the disk emission should peak by using a multicolor black body model for the disk (Frank et al. 1992). This gives[3] logν(Hz)$\sim$ 14.3, in the IR. In order to have the

[2] The ADAF regime also requires that the accretion rate falls below a critical value $\dot{M}_{crit} \approx \alpha^2 \dot{M}_{Edd}$, where $\alpha \approx 0.3$ is the viscosity parameter. This condition is easily satisfied in the case of the nucleus of NGC3998, given its low Eddington ratio.

[3] The calculation assumes L(2–10 keV)$\sim 0.2 L_{opt,UV}$ (as derived for Seyfert 1's, Mushotzky et al. 1993), from which $L_{opt,UV} \sim 3 \times 10^{42}$ erg s^{-1}. This value is $\sim$ 7 times larger than the lower limit on $L_{opt,UV}$ given previously. This limit, in addition to being uncorrected for extinction and suffering for saturation in the UV, refers only to the HST FOC bands and so does not cover the whole bump region. A correction for the reddening based on the observed Hα/Hβ ratio (Ho et al. 1997) gives unreddened luminosities higher by a factor of ~ 4 at 5080Å and $\sim$ 7 at 3400Å. This correction has in fact been applied

peak frequency at logν(Hz)~ 15.2, where a peak in the UV region of the SED could be present, we have to assume that $M_{\rm BH}$ has been largely overestimated (the peak frequency is proportional to $(\dot{M}/\dot{M}_{Edd})^{1/4}M_{\rm BH}^{-1/4}$). This could be the case, since the average relation given by Magorrian et al. (1998) is considered to overestimate $M_{\rm BH}$ due to the modeling procedure that produced it (van der Marel 1999). Also, this relation shows a considerable scatter, of a factor of ~ 100 in $M_{\rm BH}$ at fixed $L_{\rm B}$. Only if $M_{\rm BH}\sim 10^7 M_{\odot}$, though, the peak frequency would be around logν(Hz)~ 15.2.

4.3. Origin of the absorption edges

Two absorption edges could be present, superimposed on the continuum X-ray emission, at 0.77 keV and at ~ 9.2 keV. Although the evidence for these features is only marginal we briefly discuss the implications that would result from their existence because they are relevant for explaining the nature of this LINER nucleus. In fact the presence of absorption at low energies matches well with the similarity with type 1 AGNs already derived from the continuum properties (Sect. 4.1). K-shell absorption edges due to warm oxygen (OVII and OVIII) are characteristic of optically thin photoionized material commonly found along the line of sight to the nucleus of type 1 AGNs (the so called warm absorber). This material is supposed to be located at radii ranging from the broad line region ($R\sim 0.03$ pc) to the obscuring torus, but likely within ~ 10 pc of the primary continuum source (Reynolds 1997).

The second absorption feature could be produced by iron more ionized than FeXXII; so, it should correspond to absorbing material with a different ionization state (oxygen is fully ionized where iron is more ionized than FeXXII, Kallman & McCray 1982). Also a different column density is derived from the optical depths of the oxygen and iron edges ($N_H\sim 2\times 10^{21}$ cm^{-2} and $N_H\sim 2\times 10^{23}$ cm^{-2} respectively). So, if confirmed by future observations, these absorption features reveal the presence of distinct absorbing materials. Absorption at 8.6 keV from highly ionized iron has been clearly detected in the $BeppoSAX$ spectrum of the LLAGN M81. This was suggested to be produced in a transmitting medium located within the broad line region (Pellegrini et al. 2000). Similarly in NGC3998 the highly ionized iron would be located closer to the nucleus than the ionized oxygen [as is derived by calculating a rough constraint on the distance R of the absorbing material from the source of photoionizing radiation, following Reynolds & Fabian (1995) (see also Pellegrini et al. 2000); then $R<3\times 10^{16}$ cm for the highly ionized iron, and $R\lesssim 10$ pc for the ionized oxygen]. Further observations performed by higher sensitivity satellites with high spectral resolution such as XMM will soon shed light on the presence and the properties of the ionized absorption features that $BeppoSAX$ has discovered in M81 and perhaps also in NGC3998.

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to the SEDs of the LLAGNs in Fig. 6 by Ho (1999). With this higher $L_{opt,UV}$ value the Eddington ratio is 10^{-4}.

5. Summary and conclusions

The analysis of a $BeppoSAX$ observation of the LINER nucleus of NGC3998 reveals the following:

- A power law of photon index $\Gamma\sim 1.9$ well describes the 0.1–100 keV spectrum. This finding is a very strong indication for an AGN origin of the LINER activity in NGC3998. Since the intrinsic absorption is small [$N_H=(2-3)10^{20}$ cm^{-2}], the nucleus of NGC3998 might be an example of a low luminosity type 1 AGN. This hypothesis is supported also by the possible presence of an OVII absorption edge, which could be produced by a warm absorber, of a broad Hα component that polarization measurements indicate is seen directly, and by the L(2–10 keV) and L(Hα) values consistent with the correlation observed for more luminous Seyfert galaxies and quasars.
- A departure from the commonly observed properties of Seyfert 1's is represented by the absence of rapid flux variability, that is expected from an extrapolation of the trend shown by more luminous Seyfert 1's, and the absence of signs of reflection from cold material (an accretion disk or torus).
- A highly ionized absorption feature at ~ 9.2 keV has also been marginally detected. This could be produced by transmission through highly ionized material, as was suggested for a similar feature discovered by $BeppoSAX$ in the LLAGN M81.
- The bolometric luminosity of the nucleus of NGC3998, coupled to an estimate of the central black hole mass, indicate that accretion is taking place at a highly sub-Eddington rate, or that its radiative efficiency is very low. So accretion could be advection dominated as already suggested for other LLAGNs. The broad band spectral energy distribution, though, differs from those of the other LLAGNs that have been modeled with ADAFs, due to a high UV emission that makes it more similar to the energy distribution of high luminosity AGNs.

These observational results will have implications for models explaining the AGN/LINER connection. As a final consideration we compare the X-ray and optical properties of a few LLAGNs classified LINER 1.9 as NGC3998: NGC1097, NGC4203 (Iyomoto et al. 1996, 1998) and NGC1052 (Guainazzi & Antonelli 1999; Weaver et al. 1999). The first two have an X-ray continuum similar to that of NGC3998 in photon index and small or no intrinsic absorption, so could be interpreted as low luminosity type 1 AGNs. The X-ray spectrum of NGC1052 indicates instead that the nuclear emission is partially/totally obscured or Compton reflected by a screen of matter with high column density. So, galaxies with the same optical classification based on the detection of broad Hα wings (as in the catalog by Ho et al. 1997) might be very different in their X-ray properties. The latter seem to be more directly linked to the presence of a LLAGN, and to have in addition the advantage of indicating whether the nuclear emission is seen directly or through scattering/absorbing material. In this respect note also that the LINER 2 NGC4736, with no broad Hα component, actually hosts a LLAGN based on X-ray observations (Roberts et al. 1999). A large sample of LINERs with X-ray observations is needed to establish 1) the relationship between presence of a broad Hα component and of a LLAGN, and 2) whether a classification like that applied to Seyfert nuclei into type 1 and type 2, which have well defined optical and X-ray properties, can be extended also to the subset of LINERs that host a LLAGN.

Acknowledgements. We are grateful to T. Di Matteo, for comments concerning the possibility of an ADAF modeling for NGC3998, and to A.C. Fabian for useful discussions. F. Fiore and A. Parmar are thanked for help with the MECS and the LECS data analysis respectively. L.C. Ho kindly provided the data for Fig. 6. The referee is acknowledged for useful comments. This research has made use of SAXDAS linearized and cleaned event files (rev0) produced at the BeppoSAX Science Data Center. ASI and MURST (contract CoFin98) are acknowledged for financial support.

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