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LETTER

Letter to the Editor

The nature of the hard X-ray power-law tail in M 87

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Abstract. Spatially-resolved spectroscopy of the elliptical galaxy M 87 with the MECS instrument on board BeppoSAX demonstrates that the hard X-ray power-law tail, originally discovered by ASCA (Matsumoto et al. 1996; Allen et al. 1999), originates in the innermost $2'$. Our results are consistent with it being produced in an Accretion Dominated Flow, although a substantial jet contribution cannot be ruled out. An origin from a Seyfert-like nucleus is disfavored by our data. As a by-product of this result, we present an analysis of the thermal emission coming from the center of the Virgo cluster, which exhibits a strong positive radial temperature gradient, along with a radial decrease of the iron abundance.

Key words: accretion, accretion disks – galaxies: nuclei – galaxies: individual: M 87 – galaxies: clusters: individual: Virgo – X-rays: galaxies

1. Introduction

The first suggestion that Active Galactic Nuclei (AGN) are fueled by accretion onto supermassive black holes is thirty years old (Lynden-Bell 1969). The measure of 10^6–$10^9 \mathrm{M}_\odot$ black hole masses in the nuclei of several nearby galaxies (see Ho 1998 for a review) has raised the question of why most of them are not active. A possible solution is provided by the so called Advection Dominated Accretion Flows (ADAF; Rees 1982; Narayan & Yi 1995; Fabian & Rees 1995). In this class of accretion solutions, the accreting gas is so tenuous that it cannot cool efficiently, the viscous energy is stored in the protons as thermal energy and eventually advected onto the nuclear compact object. The ADAF are therefore characterized by small radiative efficiency and accretion rates ($\dot{\mathrm{m}} \equiv \dot{\mathrm{M}}/\dot{\mathrm{M}}_{\mathrm{Edd}} < 10^{-1.6}$; Narayan & Yi 1995; Rees et al. 1982). At low $\dot{\mathrm{m}}$ the hard X-ray emission is mainly due to a bremsstrahlung emission from a population of $\sim$100 keV electrons, and is therefore much harder than that expected by a standard two phase optically-thick disk/corona scenario (Haardt & Maraschi 1993), which is believed to be at work in X-ray bright AGN.

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The recent discovery of power-law, hard X-ray tails in the ASCA spectra of several elliptical galaxies and LINERS, with photon indices in the range 0.6–1.5 (Allen et al. 1999, A99; Guainazzi & Antonelli 1999) has provided the first X-ray observational support to the ADAF picture. The brightest object in the A99 sample is the elliptical galaxy M 87 ($\mathrm{z} = 0.0043$), at the center of the Virgo cluster, which exhibits a $20''$ long radio and optical jet (Biretta et al. 1991). A difference by a factor of five in the flux detected by *Spacelab 2* (Hanson et al. 1990) and Ginga (Tanako & Koyama 1991), suggested a variation of the hard X-ray M 87 core emission. Actually, high-resolution images with the ROSAT/HRI (Neumann et al. 1997; Harris et al. 1997) led to the discovery of two soft X-ray, strongly variable (up to a factor of two) sources, coincident with the nucleus and the so called "knot A", $12''$ away from the nucleus. The ASCA data were analyzed by several authors. Reynolds et al. (1997) and Buote et al. (1999) did not find any firm evidence for a power-law hard X-ray tail, with upper limits on its 2–10 keV flux of 8×10^{-12} erg cm^{-2} s^{-1}. An analysis of the same ASCA data by Matsumoto et al. (1996) and A99 yielded, however, a positive detection, with a comparable flux and a rather poorly constrained spectral index ($\Gamma = 1.4\pm^{0.4}_{0.5}$; A99). Reynolds et al. (1999) used RXTE data to set an upper limit of 4×10^{-12} erg cm^{-2} s^{-1}. The major difficulty in detecting the power-law component is related to the presence of the intense thermal emission from the core of the Virgo cluster. The fact that this thermal emission is coming from a multi-temperature gas (A99; Buote et al. 1999), most likely characterized by a radial temperature and abundance gradient (Matsumoto et al. 1996; D'Acri et al. 1998) further complicates matters.

The BeppoSAX scientific payload (Boella et al. 1997a) is well suited to investigate this issue in better detail, because the hard X-ray spatial resolution provided by the Medium Energy Concentrator Experiment (MECS; Boella et al. 1997b) is sharper than that provided by any other mission flown before *Chandra*. The results of a BeppoSAX observation of M 87 are reported in this *Letter*.

2. Observation and data reduction

M 87 was observed by BeppoSAX on 1996 July 14. In this *Letter*, only data from the MECS will be considered. The MECS (still composed of three units at the moment of the BeppoSAX observation of M 87) is an imaging scintillation proportional counter, with sensitive bandpass between 2 and 10.5 keV. The energy resolution is 8% at 6 keV, and varies as $\mathrm{E}^{-0.5}$. The 80% of the energy power is enclosed within $2'.5$–$2'.75$. The PSF does not significantly depend on the azimuthal angle, as - for instance - that of ASCA. The Low Concentrator Spectrometer was switched off, whereas the High Pressure Gas Scintillation Proportional Counter did not detect any emission from M 87. In the Phoswitch Detector System (PDS; Frontera et al. 1997) a positive detection was registered, with a net background-subtracted count rate of $0.28 \pm 0.06\ \mathrm{s}^{-1}$. However, the Seyfert 2 galaxy NGC 4388 is located about $75'$ from the M 87 core. A 1998 PDS observation of NGC 4388 measured a count rate of $\simeq$2 s^{-1} (M.Cappi, private communication). Given the triangular response of the PDS collimator (1.3° Half Width at Zero Intensity) the PDS detection of M 87 is likely to be substantially contaminated by NGC 4388. We will therefore not consider these data any further.

Data were reduced according to standard criteria, as in Guainazzi et al. (1999). The total exposure time after data screening was 24.9 ks. Background spectra were extracted from blank sky fields, accumulated at the BeppoSAX Science Data Center during the first three years of the operative life of BeppoSAX. The background subtraction does not strongly affect the results presented in this *Letter*, accounting for at most 10% of the 9 keV count rate, and for a rapidly decreasing fraction at lower energies. The total background subtracted count rate in the innermost $4'$ is $0.964 \pm 0.008\ \mathrm{s}^{-1}$.

In this *Letter*: uncertainties and are given at the 90% confidence level for one interesting parameter ($\Delta\chi^2 = 2.71$); $\mathrm{H}_0 = 50$ Mpc s^{-1} km^{-1} is assumed; energies are quoted in the source rest frame, unless otherwise specified; errors on the best-fit values take into account a residual 0.8% systematics in the gain calibration. At a distance of M 87, $1'$ corresponds to 7 kpc.

3. Spatially-resolved spectroscopy

We extracted spectra from the innermost $2'$ around the M 87 core, and in annuli with inner–outer radii of $2'$–$4'$, $4'$-$6'$ and $6'$–$8'$. Response matrices appropriate for each spectrum were created with the program EFFAREA included in the SAXDAS data analysis package (Molendi et al. 1999). Several authors have pointed out the importance of fully accounting for the complex temperature structure of the thermal emission and for possible variations in individual elemental abundances ratios (A99; Buote et al. 1999), especially to investigate the presence of non-thermal hard X-ray tails. Following their approach (which allows us also a direct comparison with ASCA), we fitted each spectrum with a model constituted by two optically thin plasma emissions (the `mekal` implementation in XSPEC is used throughout this *Letter*). The cooler component, which emerges below $\simeq$2 keV in ASCA, is not required by our fits. We have therefore constrained its temperature, $\mathrm{kT_{soft}}$ in the range 0.74–0.84 keV (A99), and assumed solar abundances.

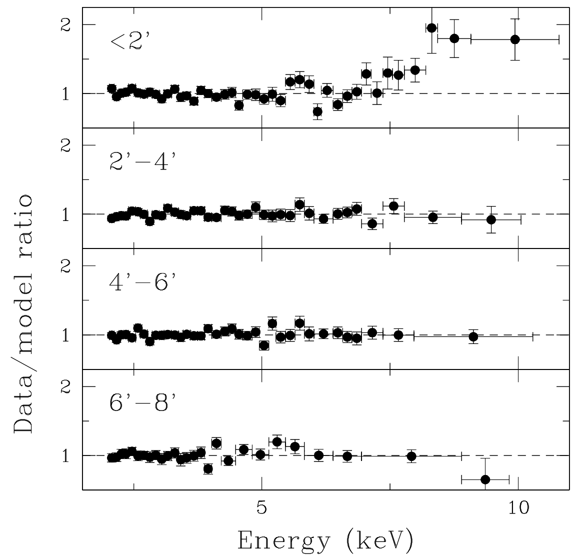

Fig. 1. Data/model ratio when a two temperature model is applied to the spectra extracted in annuli with bounding radii: $0'$-$2'$, $2'$-$4'$, $4'$-$6'$ and $6'$-$8'$, from top to bottom respectively. Each data point corresponds to a signal-to-noise ratio >3

Iron is the only element, whose abundance in the warmer thermal component can be determined by our data. We have fixed the relative abundances to the values reported in Buote et al. (1999) for all the elements to which the MECS is sensitive ($\mathrm{Z_{Si}}$:$\mathrm{Z_S}$:$\mathrm{Z_{Ar}}$:$\mathrm{Z_{Ca}}$ = 1.16 : 1.04 : 0.72 : 0.99), and assumed solar values for the remainders. None of the following results is substantially affected by variations of the relative abundances within the statistical uncertainties in Buote et al. (1999). The model is modified by Galactic photoelectric absorption ($\mathrm{N_H} = 2.5 \times 10^{20}$ cm^{-2}; Dickey & Lockman 1990). The results are summarized in Fig. 1 and Table 1. The addition of a power-law model is required only for the innermost spectrum. The $\Delta\chi^2$ for the addition of two interesting parameters is 17.2, significant at 98.5% confidence level, according to the F-test. Γ is only poorly constrained ($0.9\pm^{0.8}_{1.0}$). If Γ is fixed at 1.4 (1.7), $\Delta\chi^2 = 16.7$ (15.6), significant at more than 99.9% level. No further spectral complexity is required (if e.g. $\mathrm{kT_{soft}}$ is left free $\Delta\chi^2 < 0.1$). If in the initial two thermal components model both temperatures are left free to vary, the rôle of the hard tail is played by a hot plasma with $\mathrm{kT} = 17\pm^{\infty}_{13}$ keV, the temperature of the component dominating the 2–7 keV flux is only marginally affected ($1.77\pm^{0.11}_{0.21}$ keV), and a slightly better χ^2 is obtained (42.2/35 dof). The addition of a hard power-law tail to the other spectra yields no appreciable improvement in the quality of the fits and the upper limits on its normalizations are lower than the measure in the innermost spectrum at more than 90% confidence level for two interesting parameters ($\Delta\chi^2 = 4.61$; see Fig. 2). If a line corresponding to a fluorescent transition of neutral iron were present, with Equivalent Width against the power-law of 200 eV (as typically observed in Seyfert 1 galaxies, Nandra et al. 1997), we would expect the measured centroid of the K_α line in the innermost spectrum to be lower than in the others by about 130 eV, if the neutral line is narrow, and 90 eV,

Table 1. Best-fit parameters and results for the spatially-resolved MECS spectra (inner-outer radii of the extraction annuli are indicated in the top row). All parameters derive from the application of a two-temperature plasma emission plus power-law model in the 2–10.5 keV band (details in text), except E_c, which is the best-fit centroid of a Gaussian profile used to fit the iron emission line complex. In the latter case, the fit is performed in the 5–10.5 keV energy band, and the continuum is approximated by a single temperature bremsstrahlung

	$0'$-$2'$	$2'$-$4'$	$4'$-$6'$	$6'$-$8'$
kT^a	$1.86^{+0.40}_{-0.11}$	$2.31^{+0.07}_{-0.05}$	2.49 ± 0.11	$2.9^{+0.2}_{-0.3}$
Z_{Fe}	$0.71^{+0.19}_{-0.18}$	$0.57^{+0.08}_{-0.09}$	$0.49^{+0.09}_{-0.19}$	$0.29^{+0.13}_{-0.10}$
$\Delta\chi^2_{po}$ [b]	17.2	0.3	0.0	0.0
E_c [a]	$6.70^{+0.05}_{-0.04}$	6.67 ± 0.03	$6.66^{+0.05}_{-0.04}$	$6.70^{+0.09}_{-0.08}$
χ^2/dof	43.4/33	37.2/33	36.7/33	43.8/29

[a] in keV
[b] for the addition of the power-law to the two-temperature thermal model

if broad (*i.e.*: intrinsic width $\sigma = 500$ eV). Such variations are actually not observed.

4. Discussion

A hard X-ray power-law tail is statistically required only in the MECS spectrum corresponding to the innermost $2'$ from the M 87 core. In Fig. 2 we show the power-law normalization versus photon index iso-χ^2 contours. Although the strong correlation between these parameters prevents us from setting any meaningful constraints on them singularly, the 2–10 keV flux is well bounded to be lower than 6×10^{-12} erg s^{-1} cm^{-2} (at 90% confidence level for two interesting parameters). This is about a factor 1.5 lower than that reported by A99, confirming the variability observed by Reynolds et al. (1999). If this tail indeed originates in a low $\dot{m}$ ADAF ($\Gamma = 1.4$) the corresponding bolometric X-ray luminosity is 7.4×10^{42} erg s^{-1}. This implies $L/L_{Edd} \lesssim 2 \times 10^{-5}$, and $\dot{m} \sim 10^{-3}$ assuming a viscosity parameter $\alpha = 0.3$ (Esin et al. 1997; Reynolds et al. 1997) and a black hole mass of $3 \times 10^9 M_\odot$ (Macchetto et al. 1997). A simple relation between the radio and X-ray output is observed in low-luminosity active nuclei (Franceschini et al. 1998), and can be explained from basic physical principles (Yi & Boughn 1999). The ADAF 5 Ghz power predicted from our measure ($\sim 1.2 \times 10^{40} m_7^{8/5} \dot{m}^{6/5}$; Yi & Boughn 1998) is only a factor of a few lower than observed (Franceschini et al. 1998), a remarkable agreement given the simplicity of the model.

Other interpretations are, however, not ruled out by our data. We have reanalyzed a public M 87 ROSAT/HRI observation, which was performed about one week before the BeppoSAX one. We followed the reduction and analysis described in Harris et al. (1997) to extract the fluxes from both the core and the knot A. In Fig 2 we superpose the locus of the spectral index versus normalization pairs corresponding to the ROSAT/HRI fluxes and the BeppoSAX contour plots for the same quantities, assuming that the same power-law extends from 0.1 to 10 keV and is

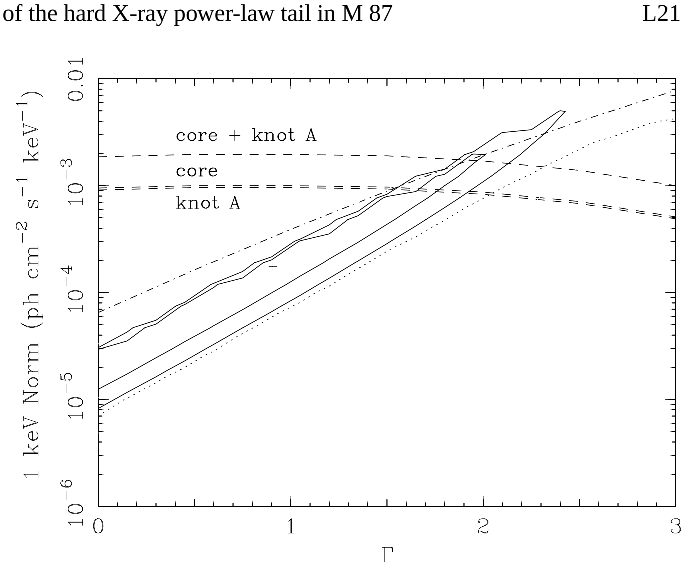

Fig. 2. *Solid lines*: iso-χ^2 power-law normalization versus photon index contours plot (at 68%, and 90% for two interesting parameters) in the innermost $2'$ around the M 87 core; *dotted line*: 90% normalization upper limit as a function of Γ for the $2'$–$4'$ spectrum. Similar curves for the more external spectra are not shown for the sake of clarity; *dot-dashed lines*: iso 2–10 keV flux curve for 5×10^{-12} erg cm^{-2} s^{-2}; *dashed lines*: locus of the points corresponding to the M 87 ROSAT/HRI quasi-simultaneous observation fluxes. The core and "knot A" sources are shown separately and summed

modified only by the Galactic photoelectric absorption (this plot is admittedly inspired to the Fig. 2 of Reynolds et al. 1999). If the hard X-ray power-law tail originates from one of the two HRI sources, its spectral index must be comprised between 1.5 and 2.0. If the tail is instead given by the sum of the two sources, the index of the superposed spectrum must be comprised between 1.8 and 2.2. These limits are not particularly demanding, being consistent with the flat hard X-ray spectrum required in the low $\dot{m}$ ADAF scenario, or with standard Seyfert-like spectra (Nandra et al. 1997). The lack of any significant emissions from neutral iron fluorescent transitions argues against the Seyfert scenario. The central $2'$ enclose much of the optical galaxy, the inner radio lobes and the jet. It is rather unlikely that such a luminous hard tail is produced by a collection of unresolved galactic sources, but a substantial contribution from a jet cannot be ruled out. The idea that M 87 may actually be a mis-aligned BLLac object was first suggested by Tsvetanov et al. (1998) on the basis of HST data. A complete characterization of the properties of the hard tail in M 87 is an open challenge for the forthcoming *Chandra* and XMM high resolution imaging capabilities.

4.1. The thermal structure of the Virgo cluster core

As a by-product of our analysis, in Fig. 3 we compare the M 87 "thermal structure" obtained with BeppoSAX, ASCA and RXTE. Preliminary results for the BeppoSAX data were reported by D'Acri et al. (1998). The BeppoSAX best-fit temperatures clearly increase with radius, whereas the iron abundance decreases. While the latter result reproduces the ASCA findings (Matsumoto et al. 1996), the former represents a much

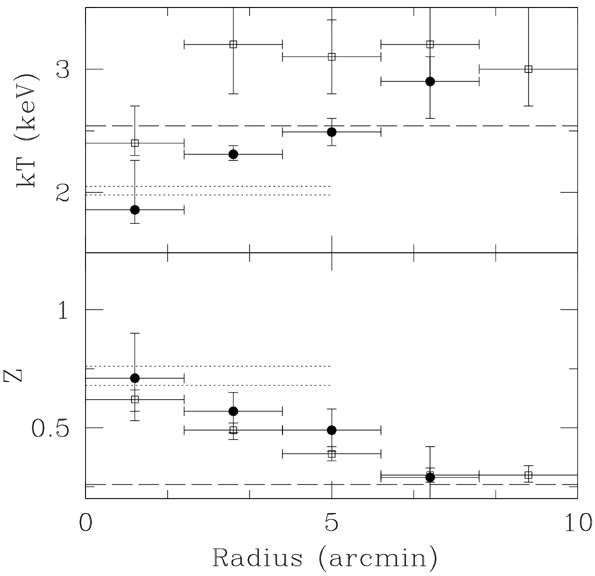

Fig. 3. Thermal plasma temperature (*upper panel*) and iron abundance (*lower panel*) as a function of radius according to the ASCA (Matsumoto et al. 1996; *empty squares*) and BeppoSAX (this *Letter*; *filled circles*) data. The spatially-averaged values obtained from an analysis of the ASCA innermost 5′ (A99; *dotted lines* bounded interval) and RXTE (Reynolds et al. 1999; *dashed line*) spectra are also shown

clearer evidence than the original Matsumoto et al. (1996) claim, and is consistent with a gradual change along the distance from the galaxy/cluster center. It is worth noting that the ASCA Matsumoto et al. (1996) temperature measures are systematically higher than the BeppoSAX ones. However, our spatially-averaged temperature and iron abundance are consistent with the multi-phase analysis of both A99 (see Fig. 3) and Buote et al. (1999). The relatively low abundance measured by RXTE is likely to be due to the contribution of the cluster emission at larger radii in the 1° PCA field of view.

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