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Research Note

The ROSAT PSPC spectrum of the Seyfert 2 galaxy NGC 4388

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Abstract. The ROSAT PSPC spectrum of the Seyfert 2 galaxy NGC 4388 is analyzed, with the aim to better understand the nature of the extended (a few kpc) soft X–ray emission discovered by the ROSAT HRI. Fitting the spectrum with an optically thin thermal model we find evidence for a metal abundance significantly lower than solar. We therefore argue that the emission is due at least in part to another component, maybe unresolved emission from compact sources.

Key words: galaxies: individual: NGC 4388 – galaxies: Seyfert – X-rays: galaxies

1. Introduction

The Seyfert 2 galaxy NGC 4388 is a highly inclined ($i \sim 72°$) spiral in the Virgo Cluster (Phillips & Malin 1982). It shows many signatures of the presence of an obscured type–1 nucleus: a broad Hα emission line extended over a region of about 10", probably due to scattering from dust (Shields & Filippenko 1988); two extended ionization cones (Pogge 1988); hard X–ray emission (Hanson et al. 1990; Takano & Koyama 1991; Lebrun et al. 1992; Kurfess 1994), emerging from a $\sim 10^{23}$ cm^{-2} column of cold material, possibly the molecular torus predicted in unification models (Antonucci 1993).

The optical depth of this column is such to completely obscure the nucleus in soft X–rays. Any detected soft X–ray emission, therefore, should indicate the presence either of scattered nuclear radiation or an altogether different component. Matt et al. (1994, hereinafter M94) analyzed the ROSAT HRI data of NGC 4388, and discovered 0.1–2.4 keV emission, corresponding to a luminosity of about 3×10^{40} erg s^{-1}, extended over about 45" (or 4.5 kpc assuming a distance of 20 Mpc). The upper limit to an unresolved nuclear component is about 20% of the total flux. A simple photoionization equilibrium argument and the lack of any spatial correlation between the soft X–ray emission and the optical ionization cones led M94 to exclude scattering from the nuclear radiation as a plausible explanation for this extended emission. The two most viable alternatives suggested by M94 were: thermal emission from an optically thin plasma and/or integrated emission from unresolved compact sources.

To make a step forward, complementary spectral data are needed. We therefore analysed public archive ROSAT PSPC data of this source. A simple power law fit of the same data has been already published by Rush & Malkan (1996); however, a more detailed and comprehensive analysis is mandatory to try to understand the physical nature of the soft X–ray emission. Good spectral data from ASCA have been analysed in detail by Iwasawa et al. (1996, hereinafter Iw96); while the ASCA data are superior as far as spectral resolution is concerned (which is particularly important in analysing emission from an optically thin plasma), the ROSAT PSPC data provides a very useful extension to lower energies, covering also the carbon band, which is instead outside the ASCA energy range.

2. Data analysis and results

NGC 4388 was observed with the ROSAT PSPC between June 14 and July 7 1993 for a total observing time of 11650 s. The data were analyzed with the MIDAS/EXSAS software package (Zimmermann et al., 1992). All channels below 11 and above 235 have been eliminated from the analysis due to instrumental uncertainties. Source detection and position determination have been estimated by means of the EXSAS maximum likelihood detection algorithm. Following this procedure we have detected 31 sources in the field. The most important are NGC 4388 (close to the center of the field), and the two elliptical galaxies M84 and M86, located at the top of the image just inside the window support ring. The contribution of each detected source in the inner part of the PSPC window have been subtracted by eliminating, from the events table, a circular region centered on the source with a radius defined by the radial brightness profile. In

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particular, for M86 and M84 a radius of 700 and 400 arcsec respectively has been used.

As the X–ray emission of NCG 4388 is extended, according to HRI data, its count rate was evaluated within a circle of 75" in radius and background was taken in a ring between 135" and 750" from the source. The total net counts are 495±23, corresponding to a count rate of 0.0425±0.0019 cts/s. The spectrum has binned imposing a signal-to-noise ratio of 3 per bin; the resulting number of bins is 27. The spectral analysis was performed with the XSPEC software package.

We firstly fitted the spectrum with a simple, absorbed power law. The power low index is quite steep (Γ=2.9±0.6). The fit is good (χ^2_r=0.74 for 24 d.o.f.), but the column density is significantly greater than the Galactic value ($N_H=8.5^{+9.5}_{-3.1}\times10^{20}$ cm^{-2}, while $N_{HGal}=2.63\times10^{20}$ cm^{-2}). If the column density is fixed to the Galactic value, we obtain Γ=1.7±0.2 but a significantly worse fit (χ^2_r=1.30 for 25 d.o.f.). The latter result is in agreement with that of Rush & Malkan (1994). The 0.1–2.4 keV flux is $\sim6\times10^{-13}$ erg cm^{-2} s^{-1}, fully consistent with that obtained by M94 with the ROSAT HRI. A summary of the fits can be found in Table 1.

The power law is, however, not a good description of the two most likely explanations for the extended emission observed by M94, i.e. thermal emission from an optically thin plasma and collection of compact sources. Of course the two models are not necessarily orthogonal. If the emission would be due to e.g. a starburst region, a mixture of thermal plasma radiation and compact sources is indeed to be expected. Unfortunately, there are no detailed theoretical calculations for such an emission (the actual spectrum depending critically on many unknown quantities, mainly the relative importance of different classes of sources). It is therefore very difficult to directly test this model.

On the contrary, simple thermal emission from a hot plasma can be easily tested. We have done this by fitting the spectrum with a Raymond–Smith (Raymond & Smith 1977) model. Firstly we fixed the abundances of the elements to the cosmic values (Feldman 1992), i.e. $Z = Z_\odot$. As can be seen in Table 1, the fits are poor, both with the column density left free (χ^2_r=1.46, 24 d.o.f.) and fixed to the Galactic value (χ^2_r=1.44, 25 d.o.f.). The fit is instead good if the abundance of the metals is left free, but the best fit value is very low (90% upper limit of 0.07). The fits and corresponding residuals are shown for the $Z = Z_\odot$ and Z free cases (models 4 and 6 in Table 1) in Fig. 1 and 2, respectively. This finding is in agreement with those obtained by Iw96 using good energy resolution ASCA data.

Iw96 found that a good fit to the ASCA data requires, besides a very obscured hard power law (to be identified with the nuclear component) and a thermal soft X–ray component (describing the extended emission), another flat component to account for excess counts in the 1–3 keV band. They model this component with a power law with the same spectral index of the nuclear radiation, but with an intermediate absorption. This component could be due to scattering by ionized matter of the nuclear radiation. We included this component in our fit, fixing all parameters at the Iw96 values as the PSPC band does not permit to directly evaluate them. The result is rather different if

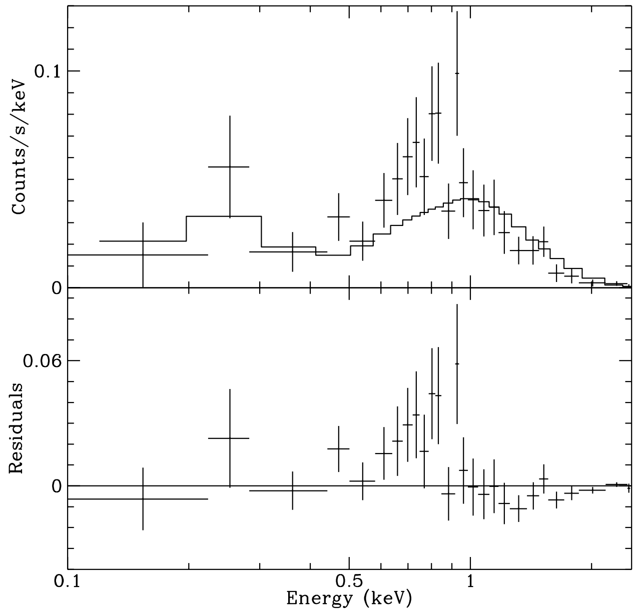

Fig. 1. *Upper panel:* The PSPC spectrum of NGC 4388. The solid curve is the best fit spectrum with model 4 of Table 1, i.e. with a Raymond–Smith model with the metal abundance fixed to solar. *Lower panel:* Corresponding residuals

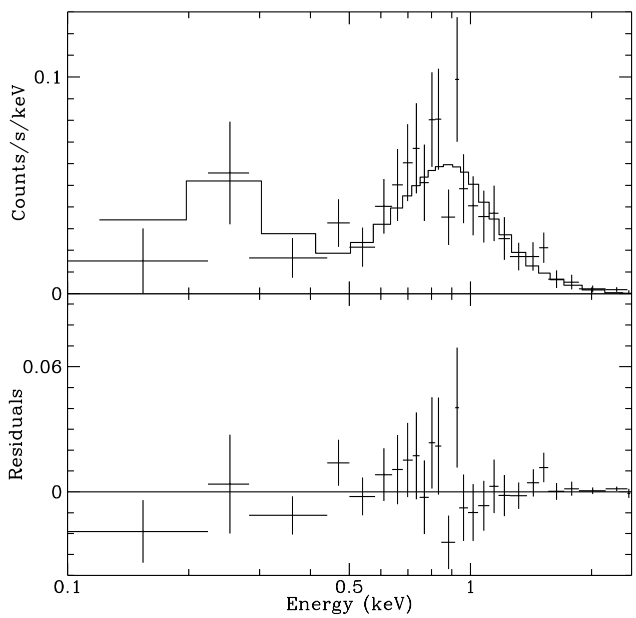

Fig. 2. *Upper panel:* As for Fig. 1, but with the metal abundance left free (model 6). *Lower panel:* Corresponding residuals

we use the SIS or the GIS values (the SIS have a better energy resolution, the GIS a higher sensitivity). Using the SIS parameters (i.e. Γ=1.6, F(1 keV)=4.6×10^{-13} erg cm^{-2} s^{-1} keV^{-1}, N_H(p.l.)=1.1×10^{22} cm^{-2}), we obtain that the fit with the metal abundance fixed to solar is significantly worse than that with Z left free on the basis of the F–test (the improvement is statistically significant at more than 99.9% confidence level), but the fit is nevertheless acceptable. On the contrary, if the GIS best–

Table 1. Best–fit parameters

#	N_H (10^{20} cm^{-2})	kT (keV)	$Z/Z_\odot$	Γ	N_H(p.l.) (10^{20} cm^{-2})	χ^2/d.o.f.
1	$8.5^{+9.4}_{-3}$	–	–	2.9±0.6	–	17.7/24
2	2.63 (fixed)	–	–	1.7±0.2	–	32.4/25
3	$1.2^{+1.3}_{-0.8}$	$1.0^{+8.6}_{-0.1}$	1 (fixed)	–	–	35.1/24
4	2.63 (fixed)	$3.7^{+5.8}_{-2.1}$	1 (fixed)	–	–	35.9/25
5	$5.2^{+4.0}_{-2.0}$	$0.70^{+0.34}_{-0.21}$	<0.07	–	–	16.3/23
6	2.63 (fixed)	$0.83^{+0.29}_{-0.17}$	$0.09^{+0.09}_{-0.05}$	–	–	21.3/24
7	2.63 (fixed)	$0.34^{+0.12}_{-0.06}$	1 (fixed)	1.6 (fixed)	110 (fixed)	20.8/25
8	2.63 (fixed)	$0.46^{+0.18}_{-0.14}$	$0.12^{+0.46}_{-0.07}$	1.6 (fixed)	110 (fixed)	17.1/24
9	2.63 (fixed)	$0.64^{+0.29}_{-0.32}$	1 (fixed)	1.5 (fixed)	310 (fixed)	33.2/25
10	2.63 (fixed)	$0.74^{+0.15}_{-0.20}$	$0.08^{+0.11}_{-0.04}$	1.5 (fixed)	310 (fixed)	18.7/24

fit parameters (i.e. Γ=1.5, F(1 keV)=6.3×10^{-13} erg cm^{-2} s^{-1} keV^{-1}, N_H(p.l.)=3.1×10^{22} cm^{-2}) are used, the fit with $Z = Z_\odot$ is unacceptable. The difference is mainly due to the greater column density found by the GIS for the intermediate component, which implies a lower contribution in the ROSAT band.

3. Discussion

We have analyzed the ROSAT PSPC data of NGC 4388 in order to put some constraints on the nature of the extended X–ray emission discovered by M94 in the ROSAT HRI image. We fitted the spectrum with the optically thin plasma model (Raymond & Smith 1977), obtaining a temperature of 0.6–0.8 keV (note that the lower limit of 0.3–0.4 keV on the temperature given in M94 is overestimated due to a numerical error in computing the plasma emissivity in Eq. 2 of that paper; the actual lower limit is below the PSPC energy band). The quality of the fit is quite good. However, we find that the metal abundance, Z, is significantly lower than solar, its 90% upper limit being ∼0.2. If the abundance is set to 1, the fit is unacceptable. Evidence for subsolar abundances remains, even if not so strong, even if a further, harder component (suggested by Iw96 to account for excess emission in the 1–3 keV ASCA data) is included. A low metal abundance would appear rather unusual for a spiral and in particular an active galactic nucleus, where the metallicity is thought be at least solar on both theoretical (e.g. Matteucci & Padovani 1994) and observational (e.g. Netzer 1990) ground. It is therefore likely that the extended emission observed by M94 is not due (at least not completely) to a pure optically thin thermal plasma, so implicitly favoring the alternative scenario, i.e. collection of compact sources. In reality, the best hypothesis is probably a mixture of the two, i.e. a combination of compact sources and hot plasma, possibly a supernovae driven wind, maybe in an active star forming region. A similar scenario has been suggested e.g. by Watson et al. (1983) for M82. As evidence for extended emission is now present in many nearby galaxies, a quantitative model for the X–ray emission from starburst region would be welcomed.

Finally, it is worth noticing that the M94 photoionization argument against a scattering origin of the extended emission holds only if *the presently observed X–ray luminosity is assumed*. To overcome the problems connected with the thermal emission, pointed out in their and present papers, Iw96 suggested that the soft X–ray emission would be due to scattering of a nucleus which was about two orders of magnitude brighter over a thousand years ago. While this solution is able to solve many puzzling problems about the soft X–ray emission of NGC 4388, it does not seem able to overcome the second of the M94 arguments against scattering, i.e. the lack of strong spatial correlation between the soft X–ray emission and the optical ionization cones.

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