The swan song: the disappearance of the nucleus of NGC 4051 and the echo of its past glory

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ABSTRACT

On 9-11 May 1998, BeppoSAX observed the low-luminous Seyfert 1 Galaxy NGC4051 in a ultra–dim X–ray state. The 2-10 keV flux (1.26 × 10⁻¹² erg cm⁻² s⁻¹) was about 20 times fainter than its historical average value, and remained steady along the whole observation (~2.3 days). The observed flat spectrum (Γ ≃ 0.8) and intense iron line (EW≈600 eV) are best explained assuming that the active nucleus has switched off, leaving only a residual reflection component visible.

Key words: Galaxies: individual: NGC 4051 – X-rays: galaxies – Galaxies: Seyfert

1 INTRODUCTION

X–ray spectra of Seyfert galaxies above a few keV are dominated by two components: a power law (hereinafter “primary”) component emitted very close to the black hole, and a secondary (hereinafter “reflection”) component arising from the reprocessing of the primary radiation by neutral, optically thick matter (Pounds et al. 1990, Piro et al. 1990). The reflection component, produced by a Compton scattering, forms a broad hump peaking at about 30 keV, and an intense iron Kα fluorescent line at 6.4 keV (Lightman & White 1988; George & Fabian 1991; Matt, Perola & Piro 1991). While in many Seyfert 1s at least part of the reprocessing occurs in the inner accretion disc, as indicated by the observed relativistic effects in the iron line profile (Tanaka et al. 1995; Nandra et al. 1997), a further reprocessed component can arise if the nucleus is surrounded by any large amount of distant, optically thick and neutral matter (Ghisellini, Haardt & Matt 1994), such as the “torus” expected in the unification scenario (Antonucci & Miller 1985; Antonucci 1993) or the dust lanes visible in the high–resolution optical images of Seyfert galaxies (Malkan et al. 1998; Maiello et al. 1998). While the reflection component from the accretion disc should lag the primary emission by minutes or hours at most, the lag introduced by the distant reflector is probably of the order of at least weeks.

If the active nucleus suddenly switches off, the latter component would then continue echoing the primary component for some time, remaining for a while the only witness of the active nucleus past activity. We have observed what could be precisely this situation in the nearby (z = 0.0023), low–luminosity (< L₂–₁₀keV >≃ 5 × 10⁴¹ erg s⁻¹) Seyfert 1 galaxy NGC4051. BeppoSAX observed the source on 9-11 May 1998 and measured a constant flux along the whole observation (~2.3 days), which was a factor of five lower than the faintest state ever observed (which lasted only a few thousands of seconds, Uttley et al. 1998). A contemporaneous and longer EUVE observation suggests that such a faint state lasted for at least one week (Fruscione et al., in preparation). The spectrum above a few keV is completely dominated by a “bare” reflection component and implies a luminosity of the primary nuclear component Lₚₑₑₑ < 0.14 × 10⁴¹ erg s⁻¹. This is the first detection of a so dramatic and long-lasting fading in luminosity from NGC4051, and provides one of the first direct evidence for the presence of large amount of circumnuclear cold, thick matter in Seyfert 1s environment.

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NGC4051 was observed by the Italian-Dutch satellite BeppoSAX (Boella et al. 1997a) from 1998 May 9 09:56:44 UTC to May 11 18:05:06 UTC. In this paper, data of the imaging instruments (Low-Energy Concentrator Spectrometer, LECS, Parmar et al. 1997; Medium-Energy Concentrator Spectrometer, MECS, Boella et al. 1997), and of the collimated Phoswitch Detector System (PDS, Frontera et al. 1997) are presented. Cleaned and linearized event files have been obtained with the reduction software package SAXDAS (version 1.3.0), using standard screening criteria (see e.g. Matt et al. 1997). The PDS data have been further screened with a temperature–dependent rise–time threshold, which allows a ∼50% reduction in instrumental background. The total net exposure times are 55.9, 69.2 and 33.0 ks for the LECS, MECS and PDS, respectively.

In the following, uncertainties are quoted at 90% level of confidence for one interesting parameter (Δχ^2 = 2.71); energies are in the source rest frame; H_0 = 50 km s^{-1} Mpc^{-1} is assumed throughout.

3 SPECTRAL ANALYSIS

LECS (MECS) spectra have been extracted in circular regions of 4 (2) arcminutes and rebinned in order to have at least 3 (2) energy channels per resolution element. Background spectra from blank sky fields and response matrices publicly available at the Beppo SAX Science Data Center (SDC, September 1997 release) have been employed throughout. PDS spectra have been obtained by subtraction of the “off–” from the “on–source” intervals. The net count rates are (1.12 ± 0.05) × 10^{-2} s^{-1} in the LECS (0.1–4 keV), (1.09 ± 0.04) × 10^{-2} s^{-1} in the MECS (1.8–10.5 keV) and 0.123 ± 0.027 s^{-1} in the PDS (13–50 keV). No variability is observed both in the 0.1-3 and 3-10 keV energy bands, contrary to the factor up to 50 typically observed in various X–ray energy bands (McHardy et al. 1995; Guainazzi et al. 1996; Uttley et al. 1998; Fruscione et al., in preparation).

A fit of the 1.8–10.5 keV MECS spectrum alone with a simple power–law model, absorbed through a column of neutral Hydrogen with N_H = N_{H_{col}} = 1.3 × 10^{20} cm^{-2} (Elvis, Lockman & Wilkes, 1989), yields a very poor fit (χ^2 = 99.36) and residuals are due to a large emission feature at ∼6.4 keV. Adding an emission line improves the quality of the fit (∆χ^2 = 46). Best-fit parameters are: photon index Γ = 0.78±0.13, line centroid E_0 = 6.57±0.16 keV, line Gaussian dispersion σ = 0.3 ± 0.3 keV, line equivalent width EW = 1.9 ± 0.9 keV. The 2–10 keV flux is z = 1.4 × 10^{-12} erg cm^{-2} s^{-1} (2.84 ± 0.14) × 10^{36} erg s^{-1}.

These pieces of evidence suggest that the primary nuclear emission has switched off leaving the Compton reflection component (along with the iron fluorescent line) as an echo of the past activity. We therefore fitted the MECS (above 4 keV) and PDS spectra with a “bare” reflection component only plus a Gaussian. The model pezrav, assuming an inclination of 0◦, solar abundances, and no high–energy cut–off in the intrinsic power–law; such assumptions do not substantially affect the following results.

This model yields a significantly better fit (χ^2 = 1.17) than the ones where the continuum is fitted with a simple power–law (χ^2 = 1.38), or with a strongly absorbed (N_H ~ 3 × 10^{24}) Seyfert–like (Γ = 1.9) power–law + reflection from a plane–parallel infinite slab (χ^2 = 1.36), which both significantly underestimate the PDS counts below 30 keV. Table 1 summarizes the best-fit results. The spectral index of the illuminating (but now invisible) power–law (Γ ≃ 1.92, see Figure 1) turns out to be perfectly consistent with the typically observed value for NGC4051 (see Guainazzi et al. 1996 and references therein). The 2–10 keV flux (luminosity) as inferred from the best-fit is (1.26 ± 0.06) × 10^{-12} erg cm^{-2} s^{-1} (2.84 ± 0.14) × 10^{36} erg s^{-1}.

The 90% upper limit on the 1 keV relative normalization between the primary and reflected continua is ∼2%. This implies a nuclear flux decrease of at least a factor of 35 in 1.5 years, if compared with the average measured in the latest RXTE long–look pointing (Uttley et al. 1998). Alternatively, a column density of at least 1.4 × 10^{20} cm^{-2} is needed, if the fading is due to absorption rather than a switch off of the primary continuum.

The line centroid energy is consistent with fluorescence from neutral or mildly ionized iron (E_0 = 6.50±0.15 keV), with an EW ≃ 600 eV. The width of the line is unconstrained, the 90% upper limit on σ being an inconclusive 320 eV. However, some residuals in the blue wing of the line may suggest a line blending. Adding a further narrow emission line improves the quality of the fit only at a 93.7% confidence level. If we assume that an iron Kα/Kβ pair is produced in the same medium (and therefore with the same
Table 1. Best fit parameters for the May 1998 observation. Errors correspond to $\Delta \chi^2=2.7$. The iron line energy is given in the source rest frame.

| # | Model         | $\Gamma$         | $E_1^i$ (keV) | $\sigma^i$ (eV) | EW$^i$ (eV) | $E_2^i$ (keV) | $\sigma^2$ (eV) | EW$^i$ (eV) | $\chi^2$/dof |
|---|---------------|------------------|---------------|-----------------|------------|---------------|----------------|------------|-------------|
| 1 | PO            | 0.76$^{+0.17}_{-0.12}$ | 6.52$^{+0.17}_{-0.09}$ | 160$^{+270}_{-150}$ | 1400$^{+500}_{-500}$ | 6.50$^{+1.46}_{-1.09}$ | 1400$^{+500}_{-500}$ | 6.50$^{+1.46}_{-1.09}$ | 1400$^{+500}_{-500}$ | 85.0/35 |
| 2 | PO+BL         | 0.75$^{+0.15}_{-0.12}$ | 6.49$^{+0.10}_{-0.09}$ | 0$^i$ | 600$^{+300}_{-300}$ | 6.50$^{+1.46}_{-1.09}$ | 1400$^{+500}_{-500}$ | 6.50$^{+1.46}_{-1.09}$ | 1400$^{+500}_{-500}$ | 44.1/32 |
| 3 | PO+CR+BL     | 1.9$^i$ | 6.50$^{+1.46}_{-1.09}$ | 160$^{+270}_{-150}$ | 1400$^{+500}_{-500}$ | 6.50$^{+1.46}_{-1.09}$ | 1400$^{+500}_{-500}$ | 6.50$^{+1.46}_{-1.09}$ | 1400$^{+500}_{-500}$ | 43.6/32 |
| 4 | CR            | 1.94$^{+0.18}_{-0.14}$ | 6.49$^{+0.10}_{-0.09}$ | 0$^i$ | 600$^{+300}_{-300}$ | 6.50$^{+1.46}_{-1.09}$ | 1400$^{+500}_{-500}$ | 6.50$^{+1.46}_{-1.09}$ | 1400$^{+500}_{-500}$ | 37.4/32 |
| 5 | CR+NL         | 1.92$^{+0.15}_{-0.14}$ | 6.49$^{+0.10}_{-0.09}$ | 0$^i$ | 600$^{+300}_{-300}$ | 6.50$^{+1.46}_{-1.09}$ | 1400$^{+500}_{-500}$ | 6.50$^{+1.46}_{-1.09}$ | 1400$^{+500}_{-500}$ | 38.4/33 |
| 6 | CR+BL         | 1.92$^{+0.15}_{-0.14}$ | 6.49$^{+0.10}_{-0.09}$ | 0$^i$ | 600$^{+300}_{-300}$ | 6.50$^{+1.46}_{-1.09}$ | 1400$^{+500}_{-500}$ | 6.50$^{+1.46}_{-1.09}$ | 1400$^{+500}_{-500}$ | 56.8/35 |
| 7 | CR+BL+BL     | 1.92$^{+0.15}_{-0.14}$ | 6.49$^{+0.10}_{-0.09}$ | 0$^i$ | 600$^{+300}_{-300}$ | 6.50$^{+1.46}_{-1.09}$ | 1400$^{+500}_{-500}$ | 6.50$^{+1.46}_{-1.09}$ | 1400$^{+500}_{-500}$ | 33.6/32 |

Notes: PO is a power-law, CR is the “bare” Compton reflection continuum, NL is a narrow Gaussian emission line, BL a Gaussian emission line where the intrinsic width is left as a free parameter. Photoelectric absorption with $N_H = N_{H_{Gal}} \equiv 1.3 \times 10^{20}$ cm$^{-2}$ has been added to all the models above, except for the model # 3, for which $N_H = (2.9 \pm 0.9) \times 10^{24}$ cm$^{-2}$. In model # 3 the relative normalization between the primary and Compton reflected component has been held fixed to 1.

intrinsic width), the best fit ratio of the $K_{\beta}/K_{\alpha}$ intensities is $0.5^{+0.3}_{-0.2}$, higher than, albeit not formally inconsistent with, the theoretically expected value (≈ 11%). Interestingly enough, the line flux ($I \approx 1.0 \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$) is only a factor of 3 lower than observed by ASCA (Guainazzi et al. 1996) and RXTE (Uttley et al. 1998) in NGC 4051 “normal” states. This shows that a substantial contribution to the iron line is likely not to be produced in the immediate vicinity of the black hole, as previously suggested by Guainazzi et al. (1996) and Uttley et al. (1998).

A prominent excess above the extrapolation of the hard X-ray best-fit is evident below 4 keV A detailed spectral description of the soft X-ray spectrum is beyond the scope of this letter, and is deferred to a forthcoming paper. We only note that if a simple power-law model is added to the model CR+BL in Table 1, the soft X-ray spectral index turns out to be $\Gamma_{soft} = 3.0^{+0.3}_{-0.2}$ totally inconsistent with the intrinsic spectral index of the primary nuclear emission ($\Gamma_{primary} = 1.75^{+0.20}_{-0.18}$, $\chi^2 = 116.9/93$ dof). There is no evidence of absorption edges and/or emission lines, the 90% upper limit on the optical depths of the O vii or O viii photoabsorption edges being 0.34 and 0.13, respectively. The 0.5–2 keV (0.1–2 keV) observed flux is $\approx 7.4 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, corresponding to an unabsorbed rest frame luminosity of 1.7 (7.0) $\times 10^{40}$ erg s$^{-1}$.

4 THE GLORIOUS PAST OF NGC4051 (AND ITS HUMBLE PRESENT)

NGC 4051 is well-known to exhibit large X-ray flux variability on relatively short ($\sim 10^9$ s) timescales (Lawrence et al. 1987; Matsuoka et al. 1990; Guainazzi et al. 1996; Uttley et al. 1998). BeppoSAX instead observed NGC 4051 in an ultra–dim and steady state for the whole ~ 2.3 days of the observation. The measured average 2–10 keV flux is more than one order of magnitude lower than any historical published flux (with the exception of a poorly constrained EXOSAT 1985 measure, see Figure 2). The only comparable example of such a fading is the Narrow Line Emission Galaxy NGC 2992, which showed a flux decrease by a factor of ~ 20 in 16 years (Weaver et al. 1996). This dramatic flux decrease is associated with an equally dramatic spectral change. In

Figure 2 we show the 4–50 keV best-fit models as observed by ASCA (1994, Guainazzi et al. 1996) and Beppo-SAX. In its “normal” state, the NGC4051 2–10 keV spectrum is dominated by a continuum with typical intrinsic spectral index of $\Gamma \approx 1.9$, to which a Compton reflection component is superimposed, flattening the spectrum above $\approx 7 – 8$ keV. This BeppoSAX observation is readily explained if the nucleus has switched off leaving the reflection component as the only witness of the past brightness. This interpretation is further supported by a contemporaneous and even longer (8–15 May) EUVE (0.02–0.21 keV) monitoring, which caught NGC 4051 in a much fainter and constant state than usual (Fruscione et al., in preparation). The implied decrease of the nuclear luminosity ($L_{nuc} < 0.14 \times 10^{43}$ erg s$^{-1}$) may be explained, if the accretion occurs through a disc, either by a proportional (to the luminosity) change in the accretion rate or by a smaller change but sufficient to trigger a transition of the disc from a radiatively efficient Shakura–Sunayev disc

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of the observed soft X–rays. Alternatively, the observed soft tic components (supernovae winds, hot halos) as the bulk possible that the dimming of the nucleus has left the galac-
but not uncommon for a “normal” galaxy. It is therefore
in NGC 4151 (Morse et al. 1995) and coinciding with the

intrinsic 0.1–2 keV luminosity inferre d
by the present data is
\( \sim \times 10^{40} \) erg s\(^{-1}\), a luminosity high

argues against a nuclear origin of the soft X–rays. However, the steepness of the spectrum and the 6.4 keV fluorescent line from the SgrB2 molecular cloud have been interpreted as the signature of

The soft X-rays may provide support to the idea that thermal–viscous hydrogen ionization disc instabilities play a major role in the onset of the AGN phenomenon, which could represent the “outburst” phase of accretion from unstable discs (Burderi et al. 1998).

The present, reflection dominated X-ray spectrum of NGC4051 closely resembles those observed in Compton–thick Seyfert 2 galaxies (Iwasawa & Comastri 1998; Iwasawa, Matt & Fabian 1997; Matt et al. 1996, 1997). In those cases, the nucleus is likely to be completely obscured rather than switched off, a possibility which cannot be formally ex-

The soft X-rays have undergone a decrease similar to

occurs with our own Galactic Center, where the reflection spectrum and the 6.4 keV fluorescent line from the SgrB2 molecular cloud have been interpreted as the signature of past activity in the now quiescent Galactic Center (Sunayev et al. 1993; Koyama et al. 1996; Sunayev & Churazov 1998).

The soft X-rays have undergone a decrease similar to

\( N_H > 1.4 \times 10^{26} \) cm\(^{-2}\) has obscured the nuclear region in coincidence with the BeppoSAX pointing. It is not easy to imagine that such an amount of absorbing matter could be dynamically active and remain stable under the combined action of the gravitational and radiative pressures in the active nucleus environment. Therefore, the closest similarity

\( n_e < 1 \text{ cm}^{-3} \) gas, in pressure equilibrium with the Narrow Line Region clouds. High energy and spatial resolution ob-

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