Black Holes from Stars to Galaxies – Across the Range of Masses
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An accretion disk laboratory in the Seyfert 1.9 galaxy NGC 2992

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Abstract. Over twenty five years of X-ray observations of the Seyfert 1.9 galaxy NGC 2992 show that it is a promising test-bed for severely constraining accretion disk models. The previous interpretation of the historical activity of NGC 2992 in terms of the accretion disk slowly becoming dormant over many years and then 're-building' itself is not supported by new data. A recent year-long monitoring campaign with *RXTE* showed that the X-ray continuum varied by more than an order of magnitude on a timescale of weeks. During the large-amplitude flares the centroid energy of the Fe K emission-line complex became significantly redshifted, indicating that the violent activity was occurring close to the putative central black hole where gravitational energy shifts can be sufficiently large. For the continuum, the Compton-y parameter remains roughly constant despite the large-amplitude luminosity variability, with $(kT)\tau \sim 20$–50.

Keywords. Accretion, accretion disks – galaxies: active – black hole physics

1. Introduction

In this paper we discuss some new results from X-ray observations of the nearby ($z = 0.00771$, Keel 1996) Seyfert 1.9 galaxy NGC 2992, which has been observed by every X-ray astronomy mission since the time it was discovered by HEAO-1 to be one of the brightest hard X-ray AGN in the sky, with a 2–10 keV flux of $\sim 7.2 - 8.6 \times 10^{-11}$ erg cm^{-2} s^{-1} (Piccinotti *et al.* 1982). In more than a quarter of a century of X-ray observations, the hard X-ray flux has varied by over a factor of 20 (see Figure 1), corresponding to a range in the intrinsic 2–10 keV luminosity of $\sim 0.55 - 11.8 \times 10^{42}$ erg s^{-1} (assuming $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Lambda = 0.73$, $\Omega = 1$). The mass of the central black hole in NGC 2992 has been estimated to be $5.2 \times 10^7\ M_\odot$ from stellar velocity dispersions (Woo & Urry 2002, and references therein). The large dynamic range in luminosity corresponds approximately to a range $\sim (8 - 180) \times 10^{-4}$ in $L/L_{\rm Edd}$. This wide coverage in $L/L_{\rm Edd}$ attained by variability that is slow enough to obtain high signal-to-noise X-ray spectra in a particular luminosity state is also a key factor that makes NGC 2992 a good test-bed for accretion disk models.

2. Historical behavior

During an *ASCA* observation in 1994, NGC 2992 was in its lowest continuum flux state thus far observed, with a 2–10 keV flux of $\sim 4 \times 10^{-12}$ erg cm^{-2} s^{-1} (Weaver *et al.* 1996). In that observation the Fe K line equivalent width (EW) was very high ($\sim 500 - 700$ eV), indicating that the line intensity had not responded to the declining continuum. In 1997 a *BeppoSAX* observation (see Gilli *et al.* 2000 for details) found NGC 2992 to be still

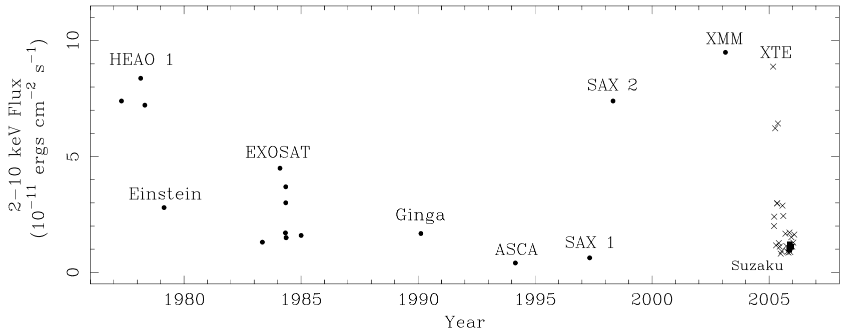

Figure 1. Historical 2–10 keV X-ray flux of NGC 2992.

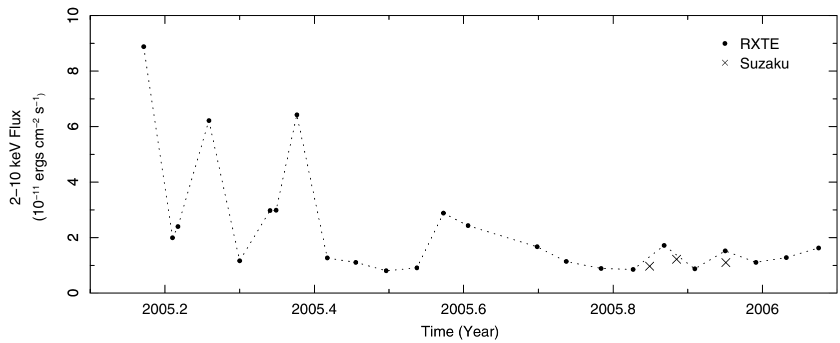

Figure 2. Flux versus time from the *RXTE* monitoring campaign.

in a low continuum state, and the Fe K line EW was even higher, with an additional component due to highly ionized Fe making an appearance (although the interpretation of the Fe K complex was ambiguous because of the limited spectral resolution). Then a second *BeppoSAX* observation in 1998 revealed that the source continuum had fully recovered to its bright HEAO-1 state (see Gilli *et al.* 2000). In this state, the EW of the Fe K line was very low ($<$ 100 eV) since the line intensity again did not respond to the change in continuum level. These measurements were mostly sensitive to the Fe K line core, which from the lack of variability, likely arises in a distant, parsec-scale reprocessor, as suggested by Weaver *et al.* (1996). Gilli *et al.* (2000) interpreted the *apparently* slow decline in the continuum luminosity of NGC 2992 over many years, and the rise back to a high state over a period of $\sim$ 1 year (see Figure 1) in terms of diminishing accretion activity followed by a 're-building' of the accretion disk during 1997–1998. This interpretation found support in the fact that in the high state NGC 2992 behaved more like a type 1 Seyfert galaxy, showing broad optical lines and rapid X-ray variability in the high state (see Gilli *et al.* 2000).

NGC 2992 was observed by *Suzaku* in 2005 and the data showed that the intensities of broad and narrow components to the Fe K line could be decoupled for the first time in this source. A lower limit of $\sim 30°$ on the inclination angle of the putative accretion disk was obtained from fitting disk-line profiles to the broad Fe K line, but this lower limit was not sensitive to other parameters in the disk-line model, including the black-hole angular momentum.

NGC 2992 was the subject of an *RXTE* monitoring campaign consisting of 24 observations in the period 2005 March to 2006 January. Full details will be presented by K. D. Murphy *et al.* (2007, in preparation) but here we summarize some key results.

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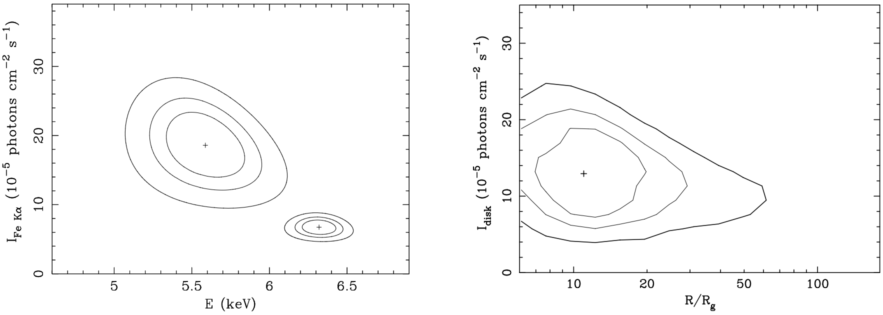

Figure 3. Joint 68%, 90%, and 99% *RXTE* confidence contours from (a) *(left)* the low-state and high-state spectra for the Fe Kα line intensity versus the line centroid energy, and (b) *(right)* the high-state Fe Kα disk-line intensity versus the outer disk radius when the the line is modeled with a dual, Gaussian and relativistic disk line.

3. Was Accretion Activity Quenched for Years?

We extracted spectra from the 24 *RXTE* observations and Figure 2 shows the 2–10 keV flux measured from spectral fitting to each of the spectra (details in Murphy *et al.* 2007, in press). Prior to this campaign, NGC 2992 had never been observed by *RXTE*. The *RXTE* fluxes are also shown in Figure 1. It can be seen that the flux varied by nearly an order of magnitude, showing large amplitude excursions on the sampling timescale (i.e. days–weeks). In particular, three large flares occurred in the first part of the campaign. The fact that in one year alone the *RXTE* flux and luminosity covered such a large range suggests that this is typical behavior and that sparse sampling in the historical lightcurve (Figure 1) gave the illusion that NGC 2992 slowly switched off over many years followed by a 'recovery'. Continuous large-amplitude variability is common in Seyfert 1 galaxies, yet 'switching off' only occasionally invoked in those AGN. There is little evidence to suggest that the accretion process is quenched in the low X-ray flux states of NGC 2992 and therefore it is unlikely that the two *BeppoSAX* observations (Figure 1) were revealing a re-building of the accretion disk.

To study the spectral variability of NGC 2992 during the *RXTE* monitoring campaign, we constructed averaged spectra and response matrices from 15 of the lowest-flux spectra (low-state spectrum), and the 3 highest-flux spectra (high-state spectrum). The spectra were fitted in the 3–15 keV band with a simple model consisting of a power-law continuum (with a photon index Γ), Galactic absorption, and a single Gaussian emission-line component. The latter, which represents Fe K line emission, had three free parameters, namely the centroid energy, E_c, the intrinsic width, σ, and the line intensity, I. We note that the 3–15 keV *RXTE* spectra are not sensitive to absorption at the level measured by *Suzaku* and previous missions.

4. Gravitationally redshifted Fe K line emission

In the low-state spectrum the Fe K emission line was consistent with a centroid energy of ~ 6.4 keV ($E_c = 6.3 \pm 0.2$ keV), had an EW of 550 ± 120 eV, and was unresolved ($\sigma = 0.3 \pm 0.3$). All errors quoted here are 90% confidence for one parameter. In the high state the Fe K line centroid energy became significantly redshifted ($E_c = 5.6 \pm 0.4$ keV), and the line became broader ($\sigma = 0.8^{+0.4}_{-0.3}$ keV). The EW of the line in the high state was 190^{+70}_{-60} eV. Joint 99% confidence contours of the line intensity versus the centroid energy for the low and high states are shown in Figure 3(a). We interpret this behavior as an indication that the violent activity during the continuum flaring illuminates the inner-most regions of the accretion disk, where strong gravity effects significantly redshift

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the Fe K line photons. In the low continuum state a significant fraction of the Fe K line emission may be from distant matter, but in the high state the Fe K line emission is dominated by the disk component, and a distant-matter component being simultaneously present with an intensity equal to that measured by *Suzaku* (Yaqoob *et al.* 2007) is not ruled out. Thus we fitted a dual, disk line (`diskline` in XSPEC) plus Gaussian line model to the high state spectrum, including a Compton-reflection continuum. Detailed fitting results are discussed in Murphy *et al.* (2007, in press) and here we just show the disk-line intensity versus outer disk radius constraints in the form of joint confidence contours in Figure 3(b). It can be seen that the redshifted Fe K line in the high state is required to originate within a region of $\sim 60R_g$ on the inner accretion disk. Similar behavior was reported in the Seyfert 1 galaxy MCG −6-30-15 by Iwasawa *et al.* (1999).

5. Comptonization models of the X-ray continuum

We also fitted the low-state and high-state spectra using a simple thermal Comptonization model (the `comptt` model in XSPEC – see Titarchuk 1994), plus a Gaussian component to model the Fe K emission line). The model has only two free parameters, namely the temperature of the Comptonizing plasma, kT, and its Thomson depth, τ. Detailed fitting results are discussed in Murphy *et al.* (2007, in press) but here we simply note that the 99% confidence contour of kT versus τ for the high state lies inside that of the low state contour, and both contours are roughly diagonal (and open), satisfying $(kT)\tau \sim 20$–50. Essentially, this means that the Compton-y parameter remains approximately constant (around a few tenths) as the continuum luminosity varies by an order of magnitude. This is consistent with our finding that the hard X-ray slope ($\Gamma \sim 1.6$–1.8) from the power-law fits did not show significant variability. In order to achieve an approximately constant product of kT and τ in the face of such large changes in the energy of the Comptonizing plasma there must be a mechanism that decreases the Thomson depth of the plasma as its temperature is raised. Alternatively, if kT and τ individually remain approximately constant then the only way to increase the energy in the plasma is to increase the number of Comptonizing electrons. More sensitive spectral measurements (than currently available) in the hard X-ray band will be able to distinguish between different scenarios because the kT can then be directly measured from the high-energy spectral turnover.

In conclusion, nearly three decades of X-ray observations of NGC 2992 have shown that it has desirable properties for testing accretion disk models and future multi-wavelength observations should take advantage of this.

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