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Radio/X-ray variability in Seyfert galaxy NGC 4051

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We present parallel X-ray and radio monitoring of the narrow line Seyfert 1 galaxy NGC 4051, over a 16 month period in 2000-2001. The X-ray observations were made approximately every 2 days with the Proportional Counter Array on the Rossi Timing X-ray Explorer (RXTE) and radio observations were made every 2 weeks at 8.4 and 4.8 GHz with the Very Large Array (VLA). We also present Very Long Baseline Interferometry (VLBI) observations. We combined European VLBI Network (EVN) data taken in 2003 with data from the Global VLBI network from 2004 where small jet-like structure was found.

What is interesting about NGC 4051 is that in the X-ray band it behaves very much like the analogue of a Galactic black hole binary (GBH) system in a 'soft-state'. In such systems, there has so far been no firm evidence for an active, radio-emitting, jet. Active jets are, however, found in 'hard state' GBHs. In NGC 4051 there is radio morphological evidence for a jet-like structure but it has not previously been clear whether the nucleus is currently active in the radio band and whether there is any link between the radio and X-ray emission processes.

Radio monitoring of the core of NGC 4051 is complicated by the presence of surrounding extended emission and by the changing array configurations of the VLA. Only in the A configuration is the core reasonably resolved. We have carefully removed the differing contaminations of the core by extended emission in the various arrays to offset all the flux to an equivalent A configuration lightcurve. This lightcurve shows no sign of large amplitude variability (ie factor 50%) over the 16 month period and is consistent with being constant.

Our radio and X-ray observations do lie close to the so-called radio fundamental plane for hard-state black holes whose emission is dominated by a jet. However, the lack of radio variability is not consistent with expectations for such systems.

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1. Introduction & Discussion

NGC 4051 is a relatively nearby (15.21 Mpc [Russell(2002)]) narrow line Seyfert 1 (NLS1) galaxy. It is one of the brightest and most variable Active Galactic Nuclei (AGN) in the X-ray sky and has been extensively observed by a number of X-ray observatories [McHardy et al.(2004), Ponti et al.(2006), Terashima et al.(2008), Breedt et al.(2010)]. One of the major results to emerge from these studies is that the X-ray variability characteristics of NGC 4051, as parameterised by the power spectral density (PSD), are very similar to those of the Galactic black hole X-ray binary (GBH) system Cyg X-1 when in the 'soft' state [McHardy et al.(2004)]. A classification of NGC 4051 as a soft state system is supported by the relatively high accretion rate ($\sim$ 15%) [Woo & Urry(2002)]. If it were identical to a soft state GBH then an active radio-emitting jet would not be expected.

NGC 4051 has, however, been known for some time to host a weak nuclear radio source [Ulvestad & Wilson(1984), Kukula et al.(1995), Christopoulou et al.(1997)]. It is also known that, at periods of low X-ray flux, the HeII 4686 line is absent from the rms optical spectrum, whereas it is present at higher fluxes [Peterson et al.(2000)]. The Balmer lines are present at all flux levels. Peterson et al therefore speculated that the inner part of the optically thick part of the accretion disc disappears at low flux levels, perhaps leaving an inner advective flow. Advective flows should produce more radio emission than radiatively efficient optically thick flows and so, over a period of 16 months in 2000 and 2001, we carried out a joint radio (with VLA) and X-ray (with RXTE) monitoring programme to search for an expected anti-correlation between the radio and X-ray fluxes.

Very little is know about radio variability in Seyfert nuclei. Only a small number of Seyferts have been systematically monitored in the radio [Neff & de Bruyn(1983), Wrobel(2000), Falcke et al.(2001), Mundell et al.(2009)] and finally [Bell et al.(2010)]. The most recent study by [Bell et al.(2010)] investigates the Seyfert galaxy NGC 7213, they find a weakly significant correlation between X-ray and radio emitting regions in this 'hard state' object. Secondly [Mundell et al.(2009)] investigates the variability of eleven Seyfert galaxies, where five show nucleur flux variaton over a seven year period, the largest variation was seen in NGC 2110 at 38%. The study by [Falcke et al.(2001)] at 8.4GHz of 30 radio-quiet and radio-intermediate quasars see a marginal variability in 80% of sources over a 2 year period. [Wrobel(2000)] investigated Seyfert galaxy NGC 5548 and found a photometric variability at 8.4GHz by 33% $\pm$ 5% and 52% $\pm$ 5% between VLA observations seperated by 41 days and 4.1 years respectively. They detect a milder variation in the 4.9GHz at 19% $\pm$ 5 % over the 41 day period.

Preliminary analysis of the data did not, however, reveal a strong radio/X-ray anticorrelation. Instead the datasets appeared to be positively correlated [McHardy et al.(2005)], suggesting instead a jet-like origin for the radio emission. We therefore undertook radio Very Long Baseline Interferometry (VLBI) observations both with the European VLBI Network (EVN) in 2003 and the Global VLBI network in 2004 and a small jet-like structure was found (see Fig 1 for the combined map at 1653 MHz and for further information see [McHardy et al.(2005)]). Similar EVN observations were later performed by [Giroletti & Panessa(2009)], revealing a broadly similar structure.

We investigated the flux density and spectral index of the core of NGC 4051 at both 4.8GHz and 8.4GHz in both A and B configuration seperately and we find no evidence of large scale variability see Fig. 2. Given the difficulty of measuring core fluxes we do not over-interpret these results, however we do note that all the maps from which the fluxes were derived were constructed in an identical way. With that proviso we note that these observations reveal an average $\alpha = -0.2$, similar to that found by [Christopoulou et al.(1997)], with a slight hardening at the beginning of the observations followed by a gradual softening such as might be explained by an injection of electrons with a relatively flat energy distribution, e.g. perhaps as a result of a shock, followed by radiative energy losses. When offsetting all configurations (A,B,C,D combined configurations) to an A configuration using the offset method there does appear to be a slight correlation by eye with the 2-10KeV X-ray flux. However, this variation also correlates with the change in the VLA

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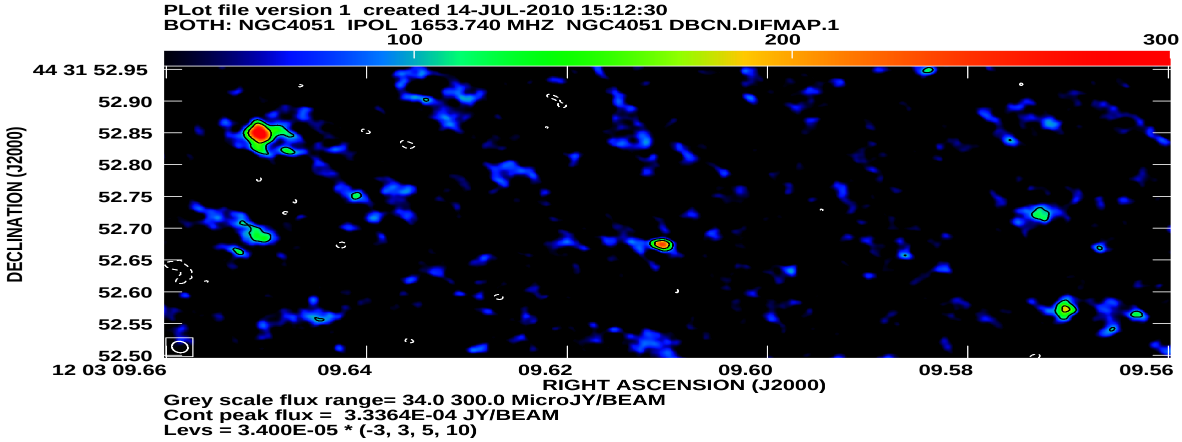

Figure 1: Map of NGC 4051 at 1653MHz from combined European VLBI Network (EVN) and Global VLBI data. We see the core (which was the main focus in our VLA investigation) seperated from the eastern and western component, which we believe are jets. The rms noise level is 3.336×10^{-4} and the beam size is $18.6 \times 16.6 mas^2$ at position angle 34.3 degrees. The contours are at $rms \times -3, 3, 5, 10$.

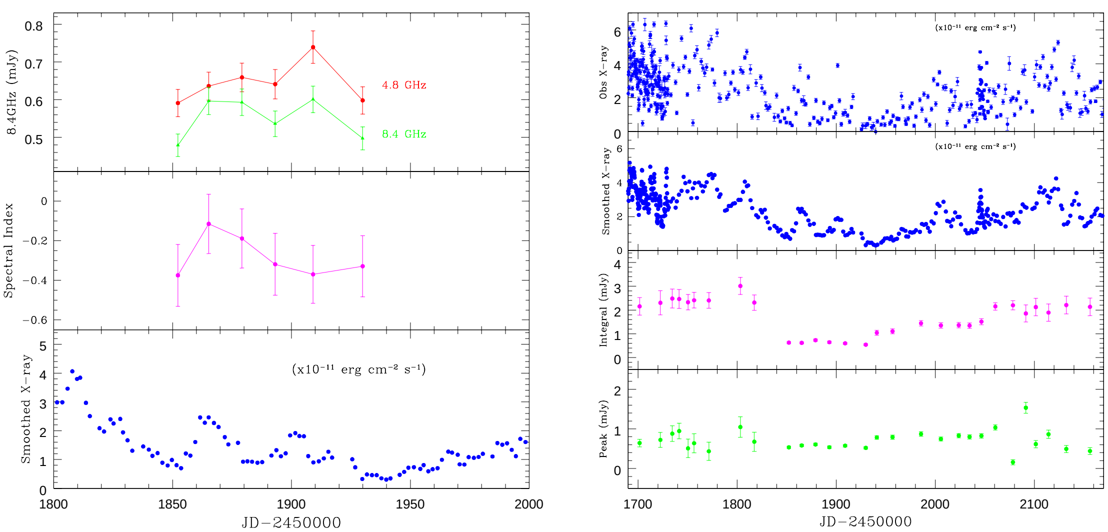

Figure 2: Left Graph: Upper panel: The core peak flux density (mJy) at 4.8 GHz and 8.4 GHz during the A configuration derived from maps made with identical restoring beams at each frequency. Any variation of the core 8.4GHz flux, if real, is very small, and certainly of much lower amplitude than that seen in the X-ray observations . See Jones et al (2010) for more details. Middle panel: The 2-point 8.4 to 4.8 GHz spectral index, α where $S(\nu) \propto \nu^{\alpha}$. Bottom panel: Smoothed X-ray flux for the time period of the observations in A configuration. Observations occur approximately once every 2 days with typical duration 1ksec. It is well known that NGC 4051 varies very rapidly in the X-ray, and that rapid variability can easily be seen here.
Right Graph: Top panels: Observed and Smoothed X-ray flux for the full epoch of our VLA observations. Third Panel: Integral flux density at 8.4GHz offset to A configuration. Bottom Panel: Peak flux densities offset to the A configuration. Fluxes are consistent with being constant.

configuration every ≈100 days. This suggests the offset method may not have removed all the flux from the extended emission when offsetting to A configuration.

2. Conclusions

Despite factors of 10 X-ray variability, we see no evidence for variability of the core of the soft state narrow line Seyfert 1 galaxy NGC 4051 at 8.4GHz over a 16 month period of monitoring at 2-weekly intervals, with the possible exception of very low amplitude (~ 0.12mJy) variations during the A configuration observations where the core is best resolved from surrounding structures. The latter tentative variations correlate weakly with the much larger amplitude X-ray variations. Our resultant radio and mean X-ray luminosity place NGC 4051 close to the radio fundamental plane for hard state accreting black holes but the lack of large amplitude radio variability is not what would be expected from such jet-dominated systems. Hard state (jet dominated systems) are typically described by $L_R \propto L_X^{\beta}$ where $\beta \sim 0.7$ for variations in individual objects [Corbel et al.(2003), Gallo et al.(2003), Gallo et al.(2006)]. For NGC 4051 $\beta = 0$, or possibly $\beta = 0.1$ during the A configuration observations.

Further, more sensitive, radio observations, with high angular resolution and a fixed beamshape, are required to confirm whether the radio emission from NGC 4051 does indeed vary.

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