A Close Nuclear Black Hole Pair in the Spiral Galaxy NGC3393

Exploring the inner regions of active galaxies with the highest *Chandra* resolution

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The discovery of the M-sigma relation[1], the correlation between the masses of galaxy bulges and those of nuclear massive black holes (MBHs), has suggested that the evolution of galaxies and their MBHs are linked. Both are thought to grow and evolve by merging of smaller galaxy/MBH units pulled together by gravity (see review[2]). During this process, MBHs may also accrete stars and interstellar medium (ISM) from the surrounding merger galaxy, causing the MBH to grow and to "shine" as an active galactic nucleus (AGN). Radiation and winds from the active MBH—AGN feedback—may in turn provide a crucial regulatory mechanism for both galaxy and MBH/AGN growth[3].

The above scenario is consistent with the growing body of multi-wavelength observations, and has been validated by increasingly sophisticated theoretical simulations[4,5]. However, it includes also a big pinch of guesswork. Two open questions stand out: (1) What are the physical parameters of AGN feedback? (2) Can we set strong observational constraints on MBH merger evolution?

Since AGNs are easily detected in X-rays, *Chandra* can play an important role in pursuing these questions at the heart of galaxy evolution.

In this report I will discuss how our project to set observational constraints on AGN feedback with *Chandra* has also led to the discovery of a merging pair of active MBHs, providing a direct observation of later merger evolution.

Chandra observations have shown the entire gamut of nuclear activity from luminous quasars to "silent" or quasi-silent nuclear MBHs[6]. The effect of past AGN activity on the surrounding hot gaseous medium is evident in the large-scale (several to 100s kpc) loops and rings discovered in *Chandra* images of giant elliptical galaxies and clusters[7]. Merger-triggered MBH activity was first imaged with *Chandra* in NGC6240, where a ~2 kpc separation double AGN was discovered, both sources with prominent Fe-Kα lines[8] in their X-ray spectra.

Until recently, these studies were missing the inner (≤100 pc scale) regions of nearby galaxies hosting luminous AGNs, because of the instrumental constraints of ACIS, the most commonly used *Chandra* detector: the imaging resolution limits imposed by the ½ arcsec instrument pixel and the relatively slow ACIS readout resulting in 'pileup' of the strong point-like sources associated with luminous nearby AGNs. However, these inner regions are where we would have the best chance of setting direct observational constraints on the physical parameters of AGN feedback from currently active MBHs, as well as observing active MBHs in a later stage of merging.

In the attempt to investigate the inner circum-nuclear regions of AGNs, post-doc Junfeng Wang, Martin Elvis, Guido Risaliti and I have observed some of these nuclei with the HRC, which although less sensitive and without the energy resolution of ACIS, samples adequately the mirror PSF and is not affected by pileup. We have also acquired deep ACIS data and imaged it with sub-pixel binning (see insert).

Our pilot target was NGC4151 (at a distance of 13.3 Mpc). We obtained new deep HRC and ACIS data, which we analyzed in conjunction to the data already available in the *Chandra* archive. The HRC data allows a clean view of the innermost circum-nuclear region (1"~65 pc), which in ACIS is affected by pileup. The HRC instrumental pixel also oversamples the *Chandra* telescope (HRMA) PSF, and therefore the HRC images, although devoid of spectral information, are of a resolution comparable to the limits of the *Chandra* mirrors. The HRC+mirror PSF is well calibrated, allowing image deconvolution to minimize the effect of the PSF wings of the strong nuclear source on the extended circum-nuclear emission[9]. Fig. 1 shows how several features of the deconvolved HRC image of NGC4151 closely

Pushing *Chandra*'s Resolution to its Limit: NGC4151

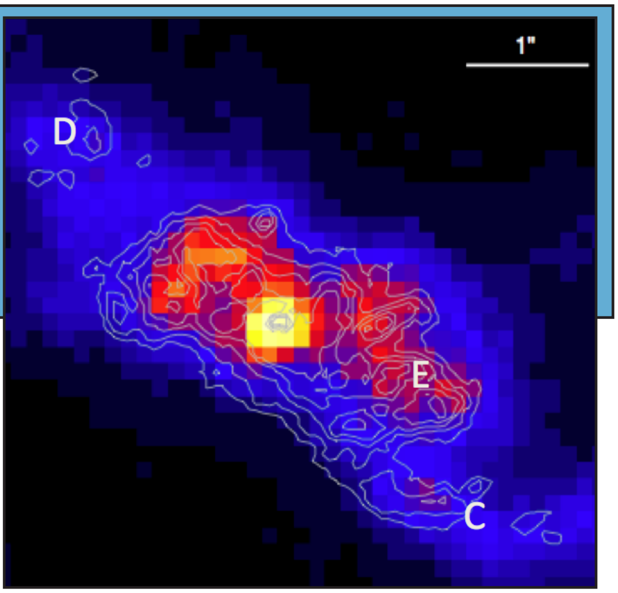


Fig. 1- Deconvolved HRC image[9], compared with [OIII] contours from the HST/FOC (white contours). The letters in the image refer to the regions labeled in the sub-pixel ACIS image shown in Fig. 2.

follow features observed in the *Hubble* [OIII] image.

The HRMA's PSF (half-power diameter HPD = 0.6" at E ~ 1.5 keV; see the *Chandra* POG) is under-sampled by the ACIS CCD pixels (0.492" × 0.492"); the ACIS native pixel image of the central region of NGC4151 in the soft energy interval relatively less affected by nuclear pileup, is shown in Fig. 2a. However, the real sampling of the PSF is better than that provided by the ACIS detector pixel, because of the dithering pattern of the *Chandra* telescope. We took advantage of this telescope dithering by using a finer pixel size (0.0625", ~1/8 of the native ACIS pixel size) when extracting the images (see full explanation[10]). This sub-pixel binning approach has been adopted previously in imaging studies of X-ray jets pushing for the highest spatial resolution[11]. The ACIS images with sub-pixel binning (see Fig. 2b) reveal curvy extensions 2" away from the nucleus (labeled as "C" and "D"), which are not discernible in the native pixel soft ACIS image, but are present in both [OIII] and the HRC image.

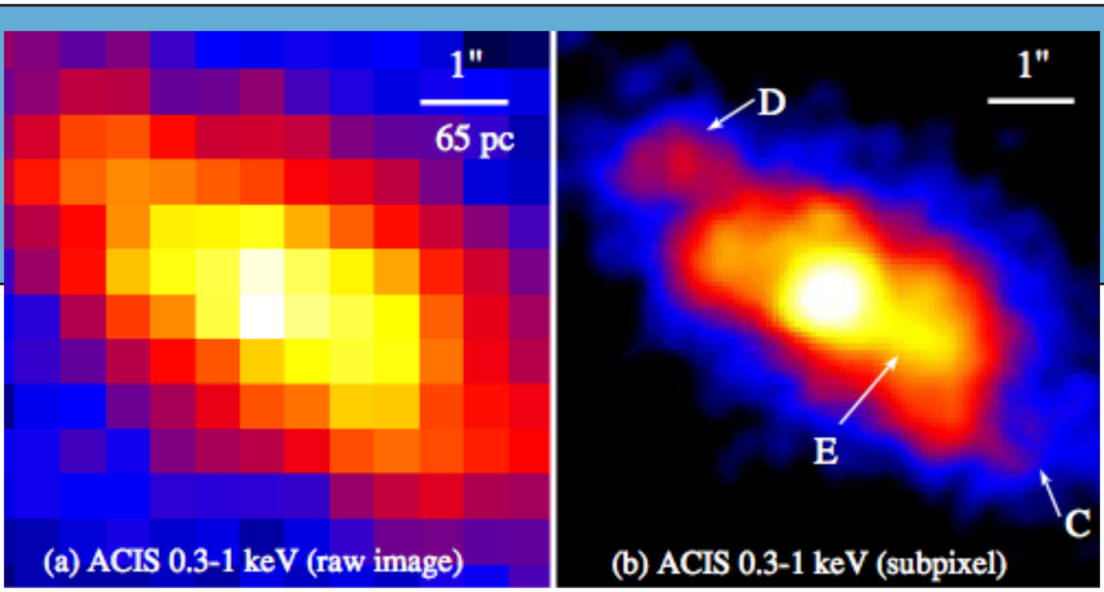


Fig. 2 - a) ACIS image using the native ACIS pixel; b) Same data, sub-pixel binned (1/8 of ACIS pixel), and smoothed with an FWHM = 0".25 Gaussian kernel for better visualization of faint extended features.

By comparing the HRC data with the ACIS sub-pixel image, we demonstrated that we could recover the full resolution of the *Chandra* mirror even in the spatially under-sampled ACIS data. Sub-pixel imaging allows us to expand ultimate high-resolution studies to other active galaxies.

Starting with our pilot study of NGC4151 (PI: Fabbiano), we are now pursuing a program of deep sub-arc-second resolution spatial/spectral studies of the circum-nuclear regions of a sample of nearby AGNs with extended optical emission line regions (CHEERS, PI: J. Wang). We can study details of the circum-nuclear regions down to ~100 pc, spatial scales commensurable with those reached by high-resolution optical and radio telescopes. One of these galaxies is NGC3393, a prominent bulge spiral at a distance of ~50 Mpc, with a highly absorbed (Compton thick[12]) AGN and an extended, spiral like circum-nuclear narrow emission line region (Fig. 3).

NGC3393 had been previously observed with *Chandra* for 30 ks with ACIS[13] to study the Compton thick AGN. This work had reported a nuclear source X-ray spectrum with a featureless continuum and a prominent 6.4 keV Fe-K line. We observed NGC3393 for an additional 70 ks as part of CHEERS. The extended X-ray emission, associated with the optical line emission, is clearly seen in the image (see blue insert in Fig. 3, showing the total screened combined exposure of ~90 ks.) We detected a total of 279±16 counts (3–8 keV) from the nuclear source in the combined exposure, with an ACIS spectrum—also shown in Fig. 3—consistent with that previously reported[13].

Junfeng and I were looking at the combined deep X-ray image using DS9, zooming in to look at the central AGN, when we had a surprise: the hard-band emission (3–8 keV), which should not be affected by softer photo- or shock-ionized circum-nuclear components, did not look point-like. Its spectrum, however, was typical of a Compton-thick AGN (see Fig. 3). The X-ray image, with ¼ pixel binning, is shown in Fig. 4. The X-ray centroid agrees with the emission line central source position (diamond), but the radio position is displaced to the SW, towards the elongation of the X-ray source.

This spatial extension of the hard nuclear emission was puzzling enough to warrant further experimen-

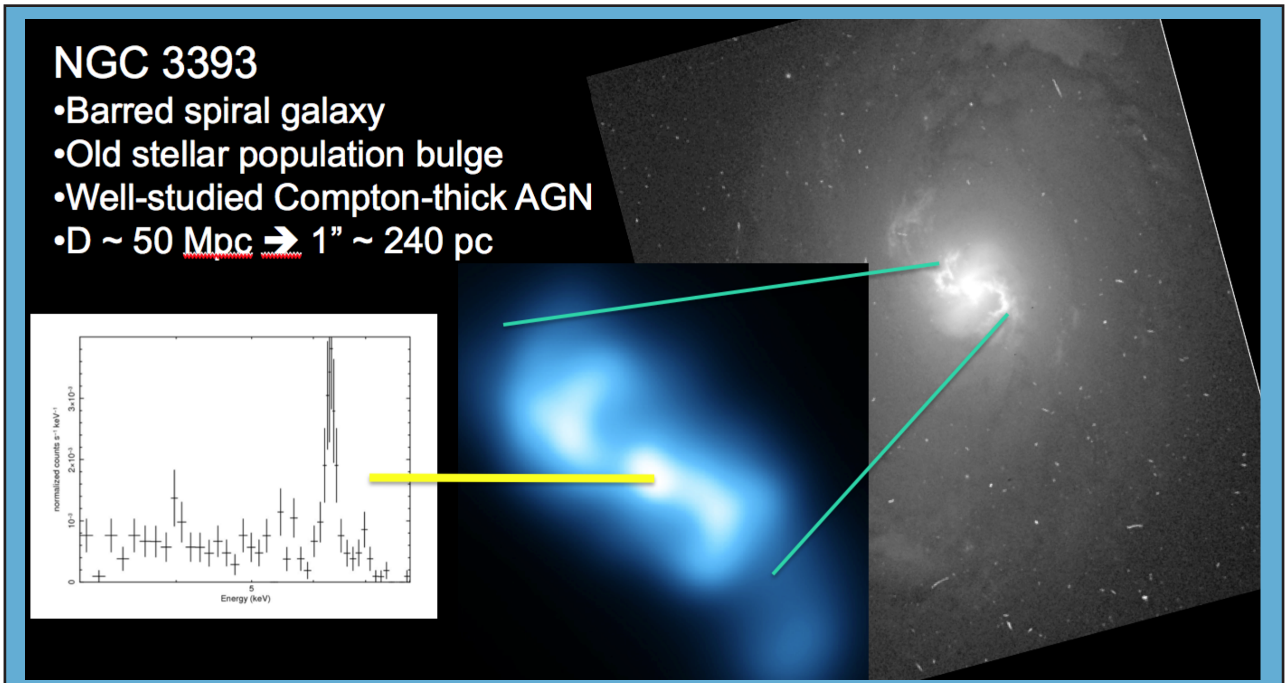


Fig. 3 - HST/WFPC2 F606W image of NGC3393 (gray, background)14 showing the inner ~40” spiral arms, which are also prominent in the [OIII] line, compared with a similar scale ACIS image of the soft X-ray emission (0.3–2 keV), including a total of 90 ks exposure time. The ACIS image is sub-pixel binned (1/4 of the native ACIS pixel, ~0.125”) and adaptively smoothed (Wang, J. et al. 2012 in preparation). The nucleus is seen at the center of the X-ray image; the spectrum of the nuclear source shows featureless continuum emission and a prominent Fe-Kα 6.4 keV emission line.

tation. Mindful of the double AGN of NGC6240[8], both with prominent Fe-Kα lines, we decided to derive separate images in the hard continuum (3–6 keV) and in the Fe-K line regions of the spectrum. As can be seen in Fig. 5, a single source, coincident with the optical emission line nucleus, dominates the continuum, while two sources appear in the Fe-K band: one coincident with the optical nucleus, the other closer to the radio position. The two sources are separated by 0.6” in the plane of the sky, corresponding to 150 pc at the distance of NGC3393.

The ACIS spectra of the two sources are shown in Fig. 5; both spectra sport the prominent Fe-Kα lines of Compton-thick AGNs, and each source has X-ray luminosity of a few 10^{42} erg s^{-1}. It appears that NGC3393 contains not one, but two Compton thick obscured active MBHs.

This result is reported in detail in a letter to Nature[15] (*Chandra* press release *http://chandra/photo/2011/n3393/*) and, as discussed there, has clear implications for the galaxy/MBH merger evolution scenario.

The idea of merger evolution was first modeled for the Antennae galaxies and other nearby ‘disturbed’ galaxies[16]; François Schweizer originally (and controversially) advocated merging of spiral galaxies as a general major formation path for elliptical galaxies[17].

In more recent times, increasingly sophisticated simulations have explored the evolution of galaxies (stars and gaseous components) and their MBH for a range of merging parameters, including major collisions and mergers of similar mass galaxies, minor mergers of different

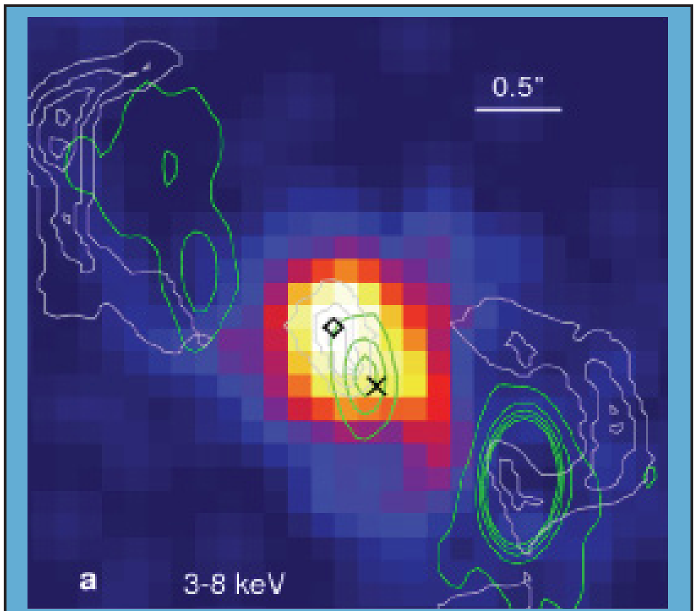
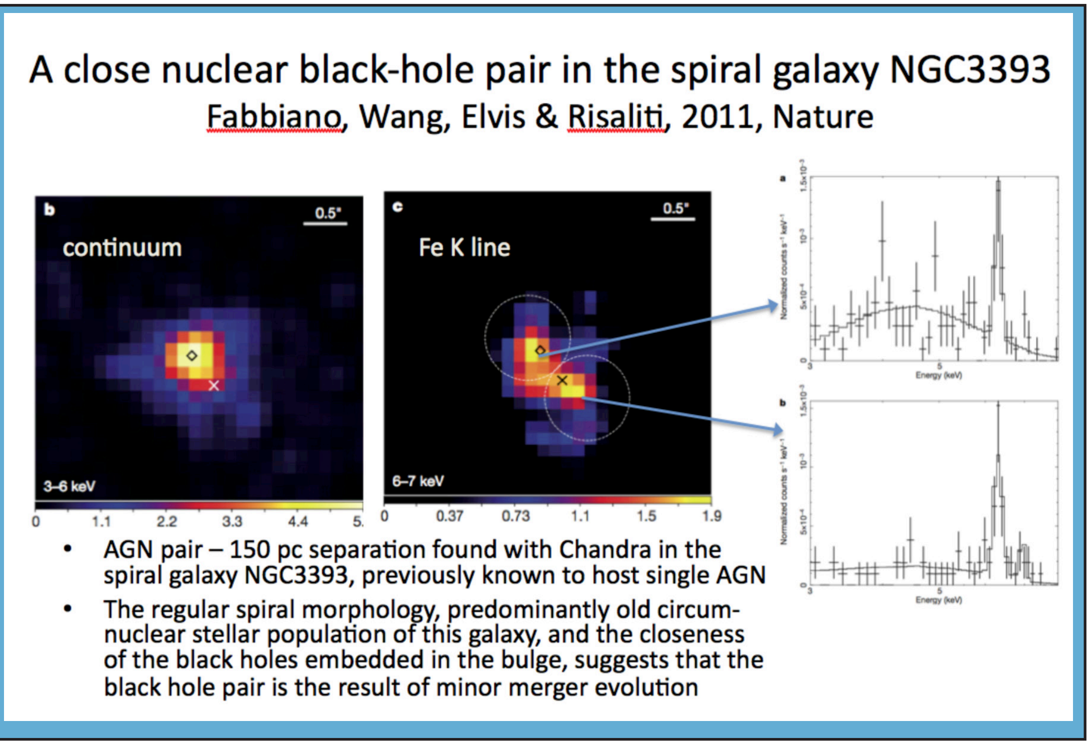


Fig. 4 - 3–8 keV image of the NGC 3393 nuclear region with ¼ subpixel binning, smoothed with a Gaussian of FWHM=0.25”. Contours of HST F664N Hα and VLA 8.4 GHz emission are shown in gray and green, respectively (see Fabbiano et al 2011[15] for details and references.)

Fig. 5 - b) Continuum image (3–6 keV), with the same processing as in Fig. 4; c) 6–7 keV image, dominated by Fe Kα line emission. The ACIS spectra of the two sources are shown as indicated.



A close nuclear black-hole pair in the spiral galaxy NGC3393

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- AGN pair – 150 pc separation found with Chandra in the spiral galaxy NGC3393, previously known to host single AGN
- The regular spiral morphology, predominantly old circum-nuclear stellar population of this galaxy, and the closeness of the black holes embedded in the bulge, suggests that the black hole pair is the result of minor merger evolution

mass galaxies, and looser tidal interactions. While the galaxies interact and merge, the nuclear MBHs are carried along until they are directly interacting with each other. Gravitation drag from stars and even more from gas causes the MBHs to form a close binary, which eventually collapses with emission of gravitational waves[4].

The observational evidence of MBH merging evolution is still rather sparse. Most reported double MBHs are quasar pairs with separation 10 to 100 kpc[18], therefore in the initial stage of their merging interaction. The last stage, with sub-parsec separation leading to MBH collapse and emission of gravitational waves, has been inferred from the spectra and variability of two more quasars[19, 20]. Direct imaging of active MBH pairs in spiral galaxies undergoing a major merger is exemplified by the double AGN of NGC6240[8] with a separation of ~2 kpc, while the double radio nucleus with 7.3 pc separation of the elliptical galaxy 0402+37921 suggests the late evolution of a major merger.

With a separation of 150 pc between the two active MHBs, NGC3393 provides an important and so far unique observational point. The galaxy is a barred spiral, with prominent bulge and grand design arms. Although images show tidal features in the outer region, consistent with gravitational interactions, the morphology is basically regular, suggesting either the later stages of a major merger or a minor merger. The stellar population of the inner bulge does not show any sign of the rejuvenation expected in the case of a major merger for the observed MBH separation, thus arguing for a minor merger. Moreover, in a major merger of similar mass MBHs, the time scale to final collapse at the observed separation of 150 pc would be rather short ~1 Myr, while in the merger of unequal mass galaxies (and MBHs), longer timescales up to 1 Gyr are expected, making the detection of such a system more likely[5].

NGC3393 is the first reported double AGN with ~100 pc scale separation in a spiral galaxy. Simulations suggest that the detection of such a close AGN pair should be a relatively rare event[22, 23], so we may have just been lucky. However, I believe it's healthy as an observer to keep an open mind, and not to be unduly influenced by theory. The observational constraints are still rather loose: NGC3393 is only one observational point. Even another detection in a well-defined sample would provide important information. One thing we have learnt from NGC3393 is that normal looking large bulge galaxies, not just clearly disturbed mergers, may be a good hunting ground for closely interacting merging active MBHs. We intend to continue pursuing this hunt with *Chandra* in the future.

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