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WFXT synergies with next generation radio surveys

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Abstract. I highlight the synergies of the Wide Field X-ray Telescope (WFXT) with the next generation radio surveys, including those to be obtained with the Australian Square Kilometre Array Pathfinder and the Square Kilometre Array, and discuss the overlap between the X-ray and radio source populations. WFXT will benefit greatly from the availability of deep radio catalogues with very high astrometric precision, while on the other hand WFXT data will be vital for the identification of faint radio sources down to $\approx 50\,\mu$Jy.

Key words. galaxies: active — galaxies: starburst — radio continuum: galaxies — X-rays: galaxies — surveys — telescopes

1. Introduction

The Wide Field X-Ray Telescope (WFXT)[1] is a medium-class mission designed to be about two orders of magnitude more sensitive than any previous or planned X-ray mission for large area surveys and to match in sensitivity the next generation of wide-area optical, infrared, and radio surveys (see Giacconi et al. 2009; Murray et al. 2009, and Rosati et al. this volume for details)

I explore here the possible WFXT synergies with future radio surveys. Sect. 2 describes the current status of radio surveys, while a selection of up-coming and future radio projects is described in Sect. 3. Sect. 4 deals with the source population in deep radio and X-ray surveys, while the X-ray/radio synergy is discussed in Sect. 5. My conclusions are summarised in Sect. 6 As this is *not* a review of future radio projects, only basic information on them will be provided. Readers wanting to know more should consult the relevant references and World Wide Web pages.

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[1] http://www.wfxt.eu

2. Current radio surveys

Currently available radio surveys can be divided, as it is the case for most observational bands, into two main categories: shallow/large area and deep/small area (see, e.g., Fig. 1 of Norris et al. 2009). The first group includes, above 0.5 GHz: the NRAO VLA Sky Survey (NVSS; Condon et al. 1998), which covers 82% of the sky ($\delta > -40°$) at 1.4 GHz down to 2.5 mJy, with a 45" resolution; the Faint Images of the Radio Sky at Twenty centimeters (FIRST; Becker et al. 1995), covering 22% of the sky (the North Galactic Cap) at 1.4 GHz down to 1 mJy, with a 5" resolution; the Sydney University Molonglo Sky Survey (SUMSS; Mauch et al. 2003), which maps

63% of the sky ($\delta < -30°$ and $|b_{II}| > 10°$) at 843 MHz down to $\sim$ 10 mJy, with a resolution similar to that of the NVSS. The second category includes a number of Very Large Array (VLA) small area surveys below 0.1 mJy at a few GHz, reaching a maximum area of ~ 2 deg^2 (VLA-COSMOS; Bondi et al. 2008) and a minimum flux density $\sim$ 15 μJy at 1.4 GHz (SWIRE; Owen & Morrison 2008) and $\sim$ 7.5 μJy at 8.4 GHz (SA 13; Fomalont et al. 2002).

3. Up-coming and future radio surveys

Radio astronomy is at the verge of a revolution, which will produce large area surveys reaching flux density limits way below current ones. I highlight here some of projects, which are being planned.

3.1. LOw Frequency ARray

The LOw Frequency ARray (LOFAR)[2] is a new radio telescope designed and built by ASTRON (the Netherlands Institute for Radio Astronomy) in collaboration with Dutch universities and other European partners. LOFAR operates in a largely unexplored region of the electro-magnetic spectrum (from below 20 up to $\sim$ 240 MHz), and consists of a distributed interferometric array of dipole antenna stations that permit large areas of the sky to be imaged simultaneously.

LOFAR will carry out large area surveys at 15, 30, 60, 120 and 200 MHz reaching different flux density limits (see Morganti et al. 2009, for details). For the largest area planned the 120 MHz survey will reach $\approx$ 0.5 mJy, which is equivalent to $\approx$ 0.1 mJy at 1.4 GHz for a power-law $\alpha_r = 0.7$ ($S \propto \nu^{-\alpha}$). The resolution is obviously dependent on the longest baseline and on the observing frequency, and will at best be $\sim$ 3" at 240 MHz. LOFAR has started operations in 2010.

LOFAR will open up a whole new region of parameter space at low radio frequencies. Based on our knowledge of the spectra of the various classes of radio sources and LOFAR's sensitivity, the large majority of detections should be radio- and star-forming galaxies, in contrast with X-ray surveys, which include mostly radio-quiet AGN (see Sect. 4). However, the deeper surveys will reach fainter radio sources and should have a larger overlap with the type of objects detected in the X-ray band by WFXT.

3.2. Expanded VLA

The Expanded VLA (EVLA)[3] Project will modernise and extend the existing VLA. When completed in 2012, the EVLA will provide the following capabilities: observing frequency between 1 and 50 GHz, reaching as low as 1 μJy r.m.s. in 6 hours (i.e., between 5 and 20 times better than the VLA), and resolution as good as $\sim$ 1" at 1.5 GHz and 0.03" at 45 GHz. To the best of my knowledge no large area surveys are being planned at present but some surveys will be obviously carried out by individual teams.

3.3. Evolutionary Map of the Universe

The Australian Square Kilometre Array [SKA] Pathfinder (ASKAP) will produce wide-deep radio surveys of the sky at 1.4 GHz. The highest ranked ASKAP continuum project is the Evolutionary Map of the Universe (EMU)[4].

The primary goal of EMU is to make a deep survey of the entire southern sky, extending as far north as $\delta = +30°$. By reaching a flux density limit $\approx$ 50 μJy EMU will have $\sim$ 50 times more sensitivity than NVSS, whilst covering a similar area (75% of the sky) with a five times better angular resolution (10"). EMU will then provide a similar gain with respect to previous surveys as WFXT in the X-ray band (see, e.g., Fig. 1 of Norris et al. 2009).

With a likely start of operations in 2013, the EMU catalogue, which will include around 70 million sources, should be available to the astronomical community by around 2015.

[2] http://www.astron.nl/radio-observatory/astronomers/lofar-astronomers

[3] http://science.nrao.edu/evla

[4] http://www.atnf.csiro.au/people/rnorris/emu

Besides ASKAP, other radio telescopes currently under construction in the lead-up to the SKA include the Allen Telescope Array[5] (ATA), Apertif[6], and Meerkat[7].

3.4. Square Kilometre Array

The Square Kilometre Array (SKA)[8] will represent a true revolution in radio astronomy by combining unprecedented versatility and sensitivity. It will provide an observing window between 70 MHz and 10 GHz reaching flux density limits well into the *nanoJy* regime. Resolution will likely need to be < 1" around GHz frequencies to avoid confusion, with a baseline extending to at least 3,000 km. The field of view will be large, up to ~ 200 deg^2 below 0.3 GHz and possibly reaching ~ 25 deg^2 at 1.4 GHz. Timeline for completion is 2020, with first science with 10% SKA around 2015 - 2016. Location will be in the southern hemisphere, either Australia or South Africa.

Many surveys are being planned with the SKA, possibly including an "all-sky" 1 μJy survey at 1.4 GHz and an HI survey out to redshift ~ 1.5, which should consist of ~ 10^9 galaxies.

4. The deep radio and X-ray skies

Before discussing the X-ray/radio synergy it is important to have a look first at the types of sources that are being detected in the two bands, as current deep radio and X-ray surveys are sampling somewhat different populations. For example, the X-ray selected sample of Polletta et al. (2007), with an X-ray flux limit $f(2-10\,\mathrm{keV}) > 10^{-14}$ erg cm^{-2} s^{-1} contains ~ 97% Active Galactic Nuclei (AGN), ≈ 10% of them radio-loud (as derived from the radio data provided in their paper). Similarly, the 1 Ms observations of the Chandra Deep Field South (CDFS) have shown that, amongst the optically brightest sources, 75% are AGN and only 22% are associated with galaxies [Szokoly et al. (2004); see also, e.g., Feruglio et al. (2008) and references therein]. On the other hand, deep ($S_{1.4\,\mathrm{GHz}} \geq 42\ \mu$Jy) radio observations of the VLA-CDFS have identified ≳ 40% AGN (about half of them radio-loud) and ≲ 60% star-forming galaxies (SFG) (Padovani et al. 2009). Therefore, while faint X-ray sources are mostly radio-quiet AGN, deep radio surveys are revealing SFG and AGN in almost equal numbers, with only about half of the latter, or ≈ 1/5 of the total, being radio-quiet.

This small population overlap is corroborated by the fractions of sources detected in one band with counterparts in the other one. Of the radio sources in the VLA-Extended CDFS (ECDFS) sample of Miller et al. (2008) ($S_{1.4\,\mathrm{GHz}} \geq 32\ \mu$Jy) only ~ 34% are found in the 2 Ms X-ray catalogue of Luo et al. (2008). And only ~ 20% of the X-ray sources in 2 Ms catalogue have a radio counterpart in the VLA-ECDFS survey (Vattakunnel & Tozzi, private communication).

It is important to note that X-ray data, including upper limits, play a very important role in the identification of faint (sub-mJy) radio sources, as shown by Padovani et al. (2009). In fact, the radio-to-optical flux density ratio is not a very good discriminant between SFG and AGN. Radio power fares somewhat better but is not helpful in separating SFG from radio-quiet AGN. On the other hand, high X-ray powers ($L_x > 10^{42}$ erg/s) can only be reached by AGN.

5. The X-ray/radio synergy

Figure 1 plots 0.5 – 2 keV X-ray flux vs. 1.4 GHz radio flux density and includes the limits of the WFXT, EMU, and SKA 1 μJy surveys (I am considering here only high-frequency radio surveys for the reasons discussed in Sect. 3.1.). Note that, confusion aside, SKA should be able to detect sources as faint as a few tens of nanoJy.

The loci of SFG, X-ray selected, and radio-quiet, radio-selected AGN are also shown. These give only order of magnitude estimates as the dispersion around the mean value can be quite large. For instance, AGN will span

[5] http://ral.berkeley.edu/ata

[6] http://www.astron.nl/general/apertif/apertif

[7] http://www.ska.ac.za/meerkat

[8] http://www.skatelescope.org

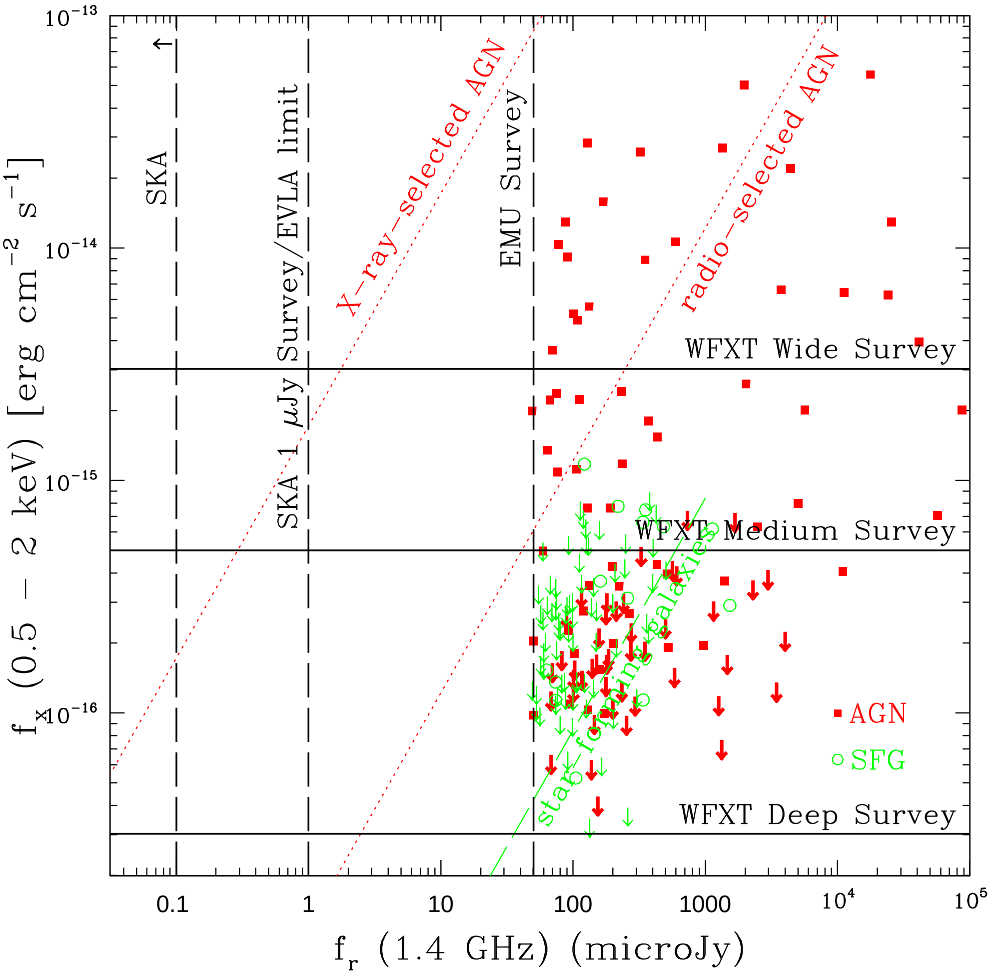

Fig. 1. The 0.5 – 2 keV X-ray flux vs. 1.4 GHz radio flux density for the AGN (filled squares) and star-forming galaxies (SFG; empty circles) in the VLA-CDFS sample (Padovani et al. 2009). Upper limits are also indicated (AGN: thick lines; SFG: thin lines). The loci of SFG (slanted dashed line; Ranalli et al. 2003), X-ray selected (mostly radio-quiet) (leftmost dotted line, from data in Polletta et al. 2007, converted to the 0.5 – 2 keV band) and radio-quiet, radio-selected AGN (rightmost dotted line from data in Padovani et al. 2009) are also shown. The position of these loci with respect to the survey limits determines the fraction of sources of a given class detected in one band with counterparts in the other. The horizontal solid lines indicate the limits of the WFXT Wide, Medium, and Deep surveys, while the two rightmost vertical dashed lines denote the limits of the Evolutionary Map of the Universe (EMU) and SKA 1 μJy surveys, both of which will cover a large fraction of the sky. The latter represents also the approximate EVLA r.m.s. level. The leftmost vertical dashed line at 0.1 μJy represents the upper limit for other smaller area SKA surveys, which will likely be conducted.

the full range between the two dotted lines in Fig. 1, with X-ray (radio) selection favouring sources with high (low) X-ray-to-radio flux density ratios. The position of these loci with respect to the survey limits determines the fraction of sources of a given class detected in one band with counterparts in the other. For example, very few AGN in the WFXT Wide survey will have a radio counterpart in the EMU survey because the locus of X-ray selected AGN (leftmost dotted line in Fig. 1) is to the left of the EMU limit for $f(0.5 - 2 \text{ keV}) \lesssim 10^{-13}$ erg cm^{-2} s^{-1}.

For illustration purposes the fluxes of the AGN and SFG VLA-CDFS sources are also shown (Padovani et al. 2009). The AGN below the radio-quiet AGN locus are identified with radio-galaxies.

5.1. The X-ray survey perspective

Figure 1 shows that the bulk of the X-ray sources in the WFXT Wide survey will have a radio counterpart in a possible SKA 1 μJy survey. This should help in the identification work of the 10 million or so expected objects by also providing very accurate positions. Similarly, most objects belonging to the Medium survey will be detected in SKA surveys at, or below, the ≈ 0.3 μJy level.

Finally, most SFG in the Deep survey will have a radio counterpart already at the EMU levels, while they will all be detected in an SKA 1 μJy survey. Radio detection of the bulk of the AGN will need much fainter (< 0.1 μJy) radio flux limits. This might be accomplished by the SKA given also the small area of the WFXT Deep survey (~ 100 deg^2). All of this, and what follows below (Sect. 5.2), obviously requires that WFXT surveys are carried out in the southern sky.

5.2. The radio survey perspective

Figure 1 shows that the bulk of the radio-quiet AGN in the EMU survey will have an X-ray counterpart in the WFXT Medium Survey, which should greatly facilitate their optical identification. Overall, one expects $< 34\%$ X-ray detections, based on the CDFS, which goes deeper in the X-rays. However, most EMU sources, including SFG, should be detected by the WFXT Deep survey. The EMU/WFXT combination will provide in this case a better sample than the VLA-CDFS one on an area ~ 500 times larger, for a total of $> 100,000$ sources.

The bulk of radio-quiet AGN in an SKA 1 μJy survey will have an X-ray counterpart in the WFXT Deep survey. However, at these flux density levels most objects are expected to be of the SFG type (see, e.g., Padovani et al. 2009), which means that the majority of these radio sources will not be detected in the X-rays even at the deepest WFXT limit.

Finally, a fraction of the radio-quiet AGN in SKA surveys reaching below 0.1 μJy should have an X-ray counterpart in the WFXT Deep survey. Since at these levels the expected optical magnitudes are very faint even for unabsorbed sources ($\gtrsim 26$), X-ray information is going to be vital for source identification.

6. Conclusions

Radio astronomy is at the verge of revolutionary advances, which over the next ten years or so will allow the detection of radio sources as much as $\gtrsim 100$ times fainter than currently available.

Although at present X-ray and radio surveys detect somewhat different sources, with AGN making up most of the deep X-ray sky while sharing this role with star-forming galaxies in the radio band, synergy between the two bands is already required since, for example, X-ray information is vital to establish the nature of faint radio sources.

The availability of deep radio catalogues with very accurate source positions will be a huge asset to WFXT. Similarly, WFXT data will provide vital help with the identification of faint radio sources down to ≈ 50 μJy. At lower flux densities the X-ray counterparts of most radio sources are expected to be fainter than the WFXT deepest limit.

In summary, the combination of future deep radio surveys with WFXT will shed light on the nature of very faint X-ray and radio sources.

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