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Synergy with new radio facilities: From LOFAR to SKA

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Radio astronomy is going through major changes and new radio telescopes are coming online, paving the way to the Square Kilometre Array (SKA). Their new capabilities—e.g., large field of view combined with good spatial resolution, broad instantaneous band, and fast response to transient objects—offer unique possibilities for the science. I will give a brief overview of these facilities, focusing mostly on LOFAR (LOw Frequency Array) and on the topics where a strong synergy with XMM (and X-ray in general) is present. I will describe the imaging surveys that are ongoing and the possibilities for the studies of active galactic nuclei (AGN) and galaxy clusters. New exciting capabilities are also becoming available for the study of the transient radio sky. Thanks to the rapid response of the new radio telescopes, radio frequencies will provide alerts on new transients and trigger other facilities. All these capabilities (and more) will be incorporated in the SKA. The entire project is evolving and progressing rapidly, and I will give a brief update of its present status.

KEYWORDS

instrumentation: interferometers, radio continuum: general, radio lines: general, telescopes, surveys

1 | INTRODUCTION

The synergy between the information provided by radio and X-ray observations has given interesting results in many fields of astronomy. Planning for the next decade of XMM offers a unique opportunity to strengthen such synergy by considering the exciting possibilities offered by the plethora of new radio facilities.

Radio astronomy is going through major changes with state-of-the-art technical developments implemented by the new facilities and a variety of data products that these facilities will be able to obtain and make available to the community. These exciting developments for megahertz and gigahertz radio astronomy (the topic of this short paper) are paving the way to the large project the radio community is heading to: the building and operating of the Square Kilometre Array (SKA). The new radio facilities that are coming online, also known as SKA pathfinders and precursors, are using new technologies and bring some major changes in the way we carry out radio observations, handle the data, and conduct science. New software for the calibration and data reduction is developed: we are moving toward a situation where most of the observations are reduced by pipelines,

something new for radio astronomy.

A number of new features are increasing the scientific possibilities of radio observations. Three of them are particularly exciting. Large field of view (FoV) combined with high spatial resolution has become widely available, making many of the radio telescopes “survey machines”. Large instantaneous observing bands with high spectral resolution (i.e., with a large number of channels) are becoming commonly available, allowing studies of the spectral properties of the radio continuum emission and of the rotation measure of the magnetic field, and, for the L-band receivers, providing a large look-back time where to search for H I (or other lines like OH). Last but not least, multiple beams and fast responses for the study of transient events will revolutionize this field. These possibilities are made available not only by the improved hardware but also by the increased computing capabilities and the possibly of handling large datasets. Interestingly, these new technical possibilities allow observations addressing different science to be done in a commensal way. For example, the observations will use a large band but with enough channels to maintain high velocity resolution, and, therefore, the data will be used for both continuum and line

(e.g., HI) studies. Thus, very different communities will use the same data for their science. A good coordination between the groups not only for setting up of the observations but also for the use of the data is required, which is something new for radio astronomy. The SKA pathfinders and precursors provide an ideal testbed in order to be prepared for SKA, which will involve an even larger community and a more complex operation. The unprecedented possibilities offered by the radio telescopes cannot be fully exploited without ancillary data. Thus, coordination with other facilities and telescopes is now more important than ever: the large number of new objects that can be observed and the fast response to transient events cannot be covered only by *ad hoc* multi-wavelengths observations but require to have in place large agreements between different telescopes, and XMM could be one of them.

It is impossible in such a short paper to give a complete summary of what is going on in the radio community and all the possibilities for synergy between radio and X-ray. Therefore, I will focus on the opportunities offered by the LOW Frequency ARray (LOFAR), one of the new-generation radio telescopes operating also as open-time facility and planning to provide new imaging surveys and new possibilities for the study of the transient sky. I will first (Section 2) give a brief overview of the new radio telescopes that are coming online. I will then describe LOFAR (Section 3) and briefly highlight some of the recent results on imaging and transients (Sections 4 and 5) relevant for the synergy with the X-ray. In Section 6, I will touch upon the new possibilities at gigahertz frequencies. Finally, in Section 7, I will briefly summarize the status of the SKA project.

2 | MANY NEW OPPORTUNITIES AND NEW SURVEYS

The new radio telescopes on the road to SKA can be separated in two groups: one covering the low (MHz) frequencies, and the other the GHz frequencies. A complete list of SKA pathfinders and precursors can be found on the SKA web site (<https://www.skatelescope.org>). Particularly important for SKA are the two precursors that, in addition of developing and testing the technology, are built on the future SKA sites, thus helping to put the complex infrastructure in place. Western Australia hosts the Murchinson Widefield Array (MWA, <http://mwatelescope.org>, Tingay et al. 2013), operating at low frequencies, between 80 and 300 MHz, and pathfinder of SKA1-low. In the same location is the Australian Square Kilometre Array Pathfinder (ASKAP) (<http://www.atnf.csiro.au/projects/askap>, Johnston et al. 2007), a phased-array-fed interferometer testing this technology for the GHz frequencies. In South Africa, the MeerKat radio telescope (<http://public.ska.ac.za/meerkat>, Booth & Jonas 2012) is the precursor of SKA-1 mid-frequencies (GHz frequencies). In Europe, in addition to the high resolution provided by the VLBI network (EVN) and the eMerlin, two interferometers are among

the SKA pathfinders: LOFAR and Apertif, the upgrade of the Westerbork Synthesis Radio Telescope (WSRT).

It is also worth mentioning, and likely interesting for the broader community, that new large radio surveys are starting to appear. Three of them (TIFR, GaLactic and Extragalactic All-sky MWA [GLEAM], and MSSS), all at 150 MHz, have been recently published, and they complement the other successful radio surveys already publicly available (i.e., NVSS, FIRST, WENSS, and VLSS). The TIFR GMRT Sky Survey (TGSS) reaches a resolution of $\sim 25''$ and median noise of $3.5 \text{ mJy beam}^{-1}$. The description of the survey and of the data available can be found in Intema et al. (2016). The GLEAM survey has been performed with the MWA radio telescope. Given the limited size of this array, the spatial resolution of the survey is only $2.5'$, and the description is given in Wayth et al. (2015). Finally, also LOFAR has a snapshot, low-spatial-resolution survey that, while providing useful data, has also helped in getting the full procedure of observing and quality control of this new radio telescope in place. The Multifrequency Snapshot Sky Survey (MSSS) of LOFAR (also done at 150 MHz) has a $\sim 1'$ spatial resolution and it is described in Heald et al. (2015).

3 | THE LOFAR

LOFAR is a new-generation radio interferometer that consists of dipole antenna stations distributed throughout the Netherlands and Europe. LOFAR uses a novel phased-array design and provides a number of unique observing capabilities. A detailed description of the telescope can be found in van Haarlem et al. (2013). It operates in the frequency range from 10 to 240 MHz (corresponding to wavelengths of 30 to 1.2 m) using two types of antenna: low-band antenna (LBA, operating around 60 MHz) and high-band antenna (HBA, operating around 150 MHz). Figure 1 shows one of the 38 stations including both HBAs and LBAs. The HBA has a total collecting area of almost $75,000 \text{ m}^2$ with 47,616 dipoles pairs. LOFAR can be defined as a “software telescope” because it has no movable parts, and the pointing (and beam-forming) is done in software. Unique to LOFAR is the unprecedented spatial resolution for a low-frequency telescope, combined with the huge field of view (FoV) (many sq. deg). Spreading out from a “core” of $\sim 300 \text{ m}$ located in the northeast of the Netherlands, it includes a total of 38 stations (like the one shown in Figure 1), reaching baselines of about 80 km and providing $\sim 5''$ resolution at 150 MHz. The presence of international stations distributed in different countries in Europe (i.e., Germany, UK, France, Sweden, Poland, and soon Ireland) ensures the sub-arcsec resolution.

The strength of LOFAR is in its computing capabilities: the data flow from all antennas combined is 1.7 TByte/s, which is reduced a factor more than 1,000 in real time by the beam former and correlation. A 10-h observation with the full array produced, after some averaging, datasets of 30 Tb: a pipelined

FIGURE 1 One of the 38 Dutch stations of LOFAR. The two type of antenna are marked: H represent the HBA, and L represents the LBA (with a zoom-in of the antenna in the inset). The small gray box marked B represents the station correlator where the beam-forming and first correlation of the dipoles in the field is happening.

process of the data and large computing clusters are absolutely necessary. Indeed, the observations are reduced by pipelines, a first one run by the LOFAR observatory at ASTRON (flagging, averaging, etc.) and the following ones developed with the help of the Key Science Projects (KSP) to obtain the data products needed for the science.

One of the main projects carried out by LOFAR is the statistical detection of the Epoch of Reionization H I signal (Patil et al. 2016). In addition to this, large projects are carried out by large teams grouped in KSP. The two most relevant for this paper are the Surveys KSP doing the continuum imaging surveys (PI: Huub Rottgering) and the Transients KSP (PIs: Rob Fender, Ben Stappers, Ralph Wijers). In addition to these, LOFAR operates also as an open-time telescope with two proposal deadlines every year.

4 | LOFAR IMAGING SURVEYS

The LOFAR surveys that are now ongoing will achieve higher spatial resolution and sensitivity than the MSSS survey described above. The LOFAR surveys are run by the Surveys KSP group, which is led by a core team representing the various countries and groups involved. The data are, therefore, proprietary in this initial phase, but images and catalogs will become available at a later stage. The goal of the LOFAR Surveys KSP is to conduct a survey with three tiers of observations: Tier-1 is the widest tier and includes LBA and HB observations across the whole 2π steradians of the Northern sky; deeper Tier-2 and Tier-3 observations are focusing on smaller areas with high-quality multi-wavelength datasets. The synergy with (slow) transients is ensured (in Tier-2 and Tier-3) by multiple passes (in different epochs) for each pointing.

A description of the LOFAR HBA 120–168 MHz Tier-1 survey (also known as LOFAR Two-meter Sky Survey, LoTSS) is presented in Shimwell et al. (2016a). This survey aims to image the entire Northern sky with observations of 8 h, and the goal is to obtain final images reaching $5''$ of spatial resolution and $100 \mu\text{Jy beam}^{-1}$ noise at most declinations. LoTSS is now preparing to enter production mode, and Shimwell et al. (2016a) describes the status. The imaging pipeline relatively easily can reach $20''$ of resolution for HBA data (at ~ 150 MHz). The techniques required for higher resolution imaging have been developed (e.g., van Weeren et al. 2016a), and a sophisticated pipeline to routinely image the datasets at high resolution is in the final stages of commissioning. Imaging Tier-1 LBA data (~ 60 MHz) is complicated by the effects of the ionosphere, and the calibration process is still being developed. The Tier-2 and Tier-3 strategies are also being finalized, and, while the desired depth has not yet been achieved, the first releases of shallow images (Tier-1 depth) of some of these fields are now beginning to be published (see below).

4.1 | The LOFAR view of famous fields

A number of famous fields have been observed as part of the Tier-2 and Tier-3 survey observations. These fields were observed with higher priority because of the wealth of multi-wavelength ancillary data and, therefore, the possibility of obtaining interesting scientific results. Figure 2 shows the image one of such fields, the Boötes field, presented in Williams et al. (2016). This field was observed at 150 MHz and imaged at $5''$ resolution with a measured astrometric accuracy of $\sim 0.4''$. The field (one pointing) covers an area of 19 deg^2 , and 6276 sources were detected. This very wide field image illustrates how the idea of targeted observations for LOFAR has become obsolete and a variety of different science can be done just with one pointing. For example, using the LOFAR Boötes field image, there are ongoing studies looking at AGN evolution, quasars' properties, starburst galaxies, the angular correlation of radio sources, protoclusters, and high- z Lyman break galaxies. The Boötes field is, so far, one of the few that has been studied with the LBA (~ 60 MHz), see van Weeren et al. (2014).

Other famous fields have been studied with LOFAR, for example, the Herschel-ATLAS (Hardcastle et al. 2016), the Lockman Hole (Mahony et al. 2016), the HETDEX area (Shimwell et al. 2016a), and the Elais-N1 (Best et al. in preparation). The combination of the LOFAR and the ancillary data has allowed the study of the spectral properties of the radio sources down to the low frequencies. This is important for understanding the life-cycle of radio sources and for identifying relics and restarted sources (Brienza et al. 2016). Source counts and luminosity functions for active and star-forming galaxies have also been studied (see e.g., Hardcastle et al. 2016). The importance of combining radio and X-ray

FIGURE 2 LOFAR image of the Boötes from Williams et al. (2016) (see that paper for details). The image covers $\sim 19 \text{ deg}^2$ and has detected 6276 sources. The noise in the central part of the image is $\sim 110 \mu\text{Jy beam}^{-1}$.

observations for separating and studying star-forming galaxies and AGN has been shown by, e.g., Padovani et al. 2011. X-ray observations (but only covering limited areas) of some of the LOFAR famous fields are presented in, e.g., Murray et al. (2005) and Brunner et al. (2008) for the Boötes and Lockman Hole, respectively.

4.2 | AGN and galaxy clusters

The studies of radio AGN and galaxy clusters are among the topics that benefit from a strong synergy between radio and X-ray observations. An example of this is the study of the energetics of radio galaxies, which is the key to understanding the impact of the radio plasma in galaxy evolution. The common assumption made is of equipartition between the energy density of the particles in their lobes. However, a more robust calculation of the total energy content for powerful radio galaxies can be obtained by combining X-ray and radio data (e.g., Croston et al. 2005). Initial results following this approach have been obtained using LOFAR. Interestingly, the first objects studied by Harwood et al. (2016) have shown that the lobe energy density is greater than previous estimates at least in powerful radio galaxies (Figure 3).

The study of clusters and the intra-cluster medium (ICM) has been traditionally done with a combination of radio and X-ray observations. One of the main goals of the LOFAR surveys is to search for new clusters and radio halos and relics, which are thought to trace turbulence and shocks in the ICM, respectively, in order to understand and distinguish between the different particle acceleration mechanisms (see, e.g., Feretti et al. 2012 for a review). The initial results from van Weeren et al. (2016b) and Shimwell et al. (2016b) have shown the wealth of details that can be reached by deep, low-frequency observations. This is essential for a proper comparison with the X-ray images. Initial observations of well-known clusters are already offering new insights and posing new questions in this area. For instance, in the

FIGURE 3 LOFAR image at 138 MHz of the radio galaxy 3C 452. The inset shows the synchrotron/inverse-Compton model fitting for the lobes of 3C 452. The solid black line represents a synchrotron spectrum; the blue dotted and green dash-dot lines indicate constraints placed by X-ray measurements on the fitted inverse-Compton model and synchrotron self-Compton. From Harwood et al. (2016), see that paper for details.

FIGURE 4 Chandra ACIS-I 0.5-2.0 keV image of the Toothbrush cluster with superposed radio contours from the LOFAR image. From van Weeren et al. (2016b), see that paper for details.

van Weeren et al. (2016b) study of the Toothbrush cluster (Figure 4), a precise characterization of the spectral properties of a radio halo revealed, for the first time, an apparent homogeneity of the turbulence in the ICM. Furthermore, in the Shimwell et al. (2016b) study of Abell 2034, LOFAR revealed an unexpectedly rich variety of diffuse structures, including a radio relic that is exceptionally far from the cluster center, a bright unexplained filamentary structure in the central region, and an apparent hole in the radio halo which hints at a link between the X-ray-detected shock and the generation of cluster-wide turbulence.

5 | THE TRANSIENT RADIO SKY

Transients sources represent a relatively heterogeneous group including objects—e.g., pulsars, gamma ray bursts, fast radio bursts, X-ray binaries, radio supernovae, flare stars, and exoplanets—all with different requirements both for the discovery and for the follow-up. The LOFAR Transients KSP (<http://www.transientsksp.org/>, PIs Rob Fender, Ben Stappers, Ralph Wijers) is focusing on all time-variable astronomical radio sources, and it also includes a Multi-Messenger Follow-Up Working Group. At radio frequencies, searches for transients have so far been limited to archiving data, a few dedicated observing programs, and, of course, serendipitous discoveries. A large contribution from the radio frequencies is in follow-up studies of discovered transients (e.g., Fender & Bell 2011). This group of objects has expanded thanks to new discoveries mostly from the high-energy observatories both in the X-ray and γ -ray regime. The studies of transients are, therefore, biased toward these high energies. However, a new class of radio transients, known as fast radio bursts (FRBs), has emerged in recent years, making the need for large areas and rapid response search at radio frequencies particularly urgent. FRBs are single, bright bursts discovered using high time resolution, which typically last for a few milliseconds (see Keane et al. 2016; Lorimer et al. 2007; Spitler et al. 2016). These bursts also exhibit high dispersion, indicating that the population could be extragalactic in origin (see e.g., Keane et al. 2016; Lorimer et al. 2007).

Radio transient surveys will be revolutionized by the development of the new generation of radio facilities with rapid response, large FoV, high spatial resolution, and sensitivity. The goal with these new capabilities is that radio frequencies will provide alert on new transients instead of only respond to alert! However, the difficult journey to reach this goal has only just started. The finding of transients in radio can be split in two approaches: imaging for slow transients, and imaging and time-domain for fast transients. Two main problems, especially in the case of fast transients, need to be overcome: the reliability of the transient signal (i.e., how to distinguish it from radio interferences), and the capability of analyzing/imaging large datasets in real time. Radio telescopes like LOFAR and MWA have already the advantage of no movable parts and, therefore, no slew time limitations. The first results in this area have been obtained for low-spatial-resolution images, making the calibration easier and the handling of the data possible on the fly. MWA already has a fast response, and it has been able to put limits on prompt radio emission from the short GRB 150424A. The observations started 26 s after the occurrence of GRB (10 s after the alert was received), see Kaplan et al. (2015). However, the spatial resolution of these observations is too low for a good identification of the objects. Also, LOFAR provides a comparable low-spatial-resolution capability, the Amsterdam—ASTRON Radio Transients Facility and Analysis Centre (AARTFAC, PI: Ralph Wijers). When completed,

it will be able to send real-time alert, see Prasad et al. (2014) for details. Reaching higher spatial resolution combined with fast response will be the task of the LOFAR Transients KSP. The goal is to have the “transient pipeline” robust enough to be able to trigger from radio transients and accurately locate their positions. The first radio transient in one of the LOFAR fields (the NCP) and imaged at relatively large spatial resolution has been recently confirmed, see Figure 5 and Stewart et al. (2016).

Last but not least, a few words about pulsars, a class of transients discovered and studied in depth at radio frequencies but where the synergy with high energies has become in the last year even stronger with the results of the Fermi satellite, see Abdo et al. (2013). The large FoV and multibeam capabilities of LOFAR have made possible blind searches for pulsars that are already going on, see Coenen et al. (2014). Furthermore, follow-up studies combining the low frequencies of LOFAR and the X-ray to study their mechanism have already given important results. A nice example of synergy between radio and X-ray is presented in Hermsen et al. (2013). This study has discovered a pulsar magnetospheric mode switching, which has been achieved by the correlated radio (LOFAR) and X-ray (XMM) observations. This result shows that global changes occur to the conditions in the magnetosphere of pulsars.

6 | POSSIBILITIES AT GIGAHERTZ FREQUENCIES

Relevant for the synergy with X-ray observations are also the new (or upgraded) instruments observing at GHz frequencies. One of the main goals of these radio telescopes is the detection and imaging of H I in galaxies, over large areas and to higher redshift than currently possible. However, other key topics for these telescopes are the study of the continuum (to complement what is obtained at low frequencies), magnetism, and the detection and study of transients at frequencies where dispersion is less severe compared to the low frequencies.

Among these new instruments, the largest ones are the Aperture Tile in Focus (Aptertif) upgrade of the WSRT (Oosterloo et al. 2009), ASKAP (see Johnston et al. 2007), and MeerKat in South Africa (see Booth & Jonas 2012). The first two use phased-array feed technology. It is worth mentioning the particular relevance of Aptertif as an important complement to LOFAR for the study of the spectral properties of the radio continuum and for transients. The FoV of Aptertif of ~ 8 deg² will allow the survey of large areas of the sky. The potential that the broad spectral band has for the search of H I over a wide range of redshifts is illustrated by the serendipitous detection of H I absorption in a young radio galaxy at $z = 0.44$ obtained with ASKAP by Allison et al. (2015). This capability will be key, for example, for deriving the occurrence and characterizing fast H I outflows (e.g., Morganti et al. 2005). These outflows are now recognized to include different phases of the

FIGURE 5 Sequence of images in time (before and after the event) of the transient detection from Stewart et al. (2016) from the LOFAR observations. See the paper for details.

gas. Understanding the connection between the cold (H I) and the hot component detected in X-ray (e.g., Tombesi et al. 2012 and Cappi in these proceedings) will allow understanding the role of these two components of the gas (see e.g., Tombesi et al. 2015) in AGN-driven outflows and AGN feedback.

7 | THE SQUARE KILOMETRE ARRAY

The SKA will combine all the capabilities (and more) of the pathfinders and add extra sensitivity. Figure 6 shows the latest design of the antenna for the low frequencies (50–350 MHz) SKA1-low to be located in Western Australia. SKA1-low will be about 8 times more sensitive than LOFAR. The mid-frequencies (350 MHz–14 GHz) SKA1-mid will be located in the Karoo in South Africa.

The extensive science case of SKA1 is summarized in the book *Advancing Astrophysics with the Square Kilometre Array* (Bourke et al. 2014). Like with other pathfinders and precursors, the science for SKA will also be organized in KSPs, and the discussion about topics and membership has just started. The participation to the project will be based on the contribution of the countries but some open time is also foreseen. However, the complex structure of the project is being put in place right now with the ongoing negotiations for an intergovernmental organization. This process and the entire project are evolving rapidly; therefore, the web site of the project (<https://www.skatelescope.org>) and other social media are the best places to find the most updated news. The

FIGURE 6 Artistic impression of the SKA1-low from the SKA web site: <https://www.skatelescope.org>.

project welcomes the contribution from the broad community to make sure that the best science can be achieved. Furthermore, the synergy with telescopes at other wavelengths and other facilities will be extremely important for SKA. It is never too early to improve the coordination between radio and other wavelengths and, in particular, X-ray. This will allow the study of larger and less biased samples of interesting

objects and provide an important synergy valuable to both communities.

In summary, radio astronomy is changing rapidly. The increasing importance of pipelines for the reduction of radio data should ensure the availability of final products to the broad astronomical community of non-radio experts. For the study of the transient sky, we should soon enter the era of a “two-ways” synergy where the radio telescopes will not only do the follow-up but also the triggering. Radio astronomers are working hard to make the next step in the study of the radio sky. It is not an easy path, but new results are already appearing and more are expected soon, providing interesting data for everybody.

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