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LOFAR and Radio Loud AGN

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Abstract. At very low frequencies, the new pan-European radio telescope, LOFAR, is opening the last unexplored window of the electromagnetic spectrum for astrophysical studies. LOFAR will deeply survey the northern sky from ~ 10 up to 240 MHz. In this contribution we briefly describe some of the capabilities of LOFAR and the surveys planned to study fundamental issues related to the formation and evolution of galaxies and clusters of galaxies. We describe some of the challenges of low frequency observations with LOFAR and our progress in overcoming them. Further, we present some recent results from the ongoing imaging commissioning efforts. In the second part we discuss our studies of Low Excitation and High Excitation Radio Galaxies in the Boötes field and how LOFAR Surveys will help in studying their evolution.

Keywords. Galaxies: active, surveys, telescopes, Instrumentation: interferometers

1. LOFAR

LOFAR, the Low Frequency Radio Array, is a new low freqency radio telescope in the Netherlands and surrounding European countries. Its revolutionary design makes use of phased arrays instead of the traditional and expensive dishes. The simple receivers are turned into a real telescope electronically. While LOFAR has been described in detail elsewhere (see van Haarlem *et al.* 2013), we provide here a brief overview of the telescope.

The array is composed of several 'stations' each containing a number of simple dipoles. There are two types of dipole antennas, one for the Low Band Array (LBA) operating at $10-80$ MHz range and one for the High Band Array (HBA) operating in the $110-240$ MHz range. As of Summer 2013, the Dutch part of the array consists of 37 stations; six stations reside in the 320 m diameter densely-packed 'Superterp', 24 are core stations located within a central 2 km radius, and the remaining 13 are remote stations going out to 80 km. The array is extended to baselines of up to 1200 km with a further eight stations in a number of other European countries: Germany (5), the UK (1), Sweden (1), and France (1). The array status is shown in Fig. 1†. It is very easy to add additional stations to the existing network as funds become available.

The signals from the antennas are digital, meaning that many beams or pointings can be formed simultaneously. This makes LOFAR an extremely efficient instrument for surveying large areas. The electronic nature of the beams makes LOFAR highly flexible. In terms of frequencies, up to 488 subbands of 195.312 kHz or 156.250 kHz are available, which can give a total bandwidth of up to 95 MHz. The Dutch array provides resolutions of $\sim 10'' \times 40''$ at 60 MHz and the inclusion of international baselines gives sub-arcsecond resolution in both the low and high bands ($\sim 0.7''$ at 60 MHz and $\sim 0.2''$ at 240 MHz).

† up-to-date information on the current status of LOFAR is available at http://www.astron.nl/~heald/lofarStatusMap.html, powered by Google Maps.

2. LOFAR Challenges and Progress

Many functional elements of the LOFAR imaging system are already in place. Here we briefly mention some of the challenges within the imaging process that have either been solved or are currently being worked on:

Data rates of up to Tbs/s Advances in computer storage and power, combined with the high speed connections between the stations and the correlator in Groningen, allow us to handle the high data rates from LOFAR, although correlating and processing the data still requires supercomputers. Already, there are several peta-bytes of data stored in the long term archive (LTA).

Radio frequencies interference (RFI) Flagging of RFI is a crucial step in the data analysis. Despite the high levels of RFI in Northern Europe, the high frequency and time resolution of LOFAR observations combined with clever algorithms such as that of Offringa *et al.* (2010) allow for the rejection of RFI with typically $< 10\%$ loss to the data at the worst freqencies.

Removal of A-team sources LOFAR's LBA system has an extremely large field of view; the individual dipoles essentially "see" the entire sky. Even within the formed station beam, the few extremely bright radio sources at low frequencies (Cygnus A and Cassiopeia A and the other so-called "A-team") dominate *any* LBA observation for which they are above the horizon. Simply subtracting their contributions is time-consuming and computationally intensive. Instead we have been using, very successfully, the "demixing" method of van der Tol *et al.* (2007).

Beam calibration LOFAR has several beams: the dipole beams, the tile beams (for the HBA), the station beams and the interferometric beam. With the exception of the dipole beam, all are formed digitally and are both complex-valued and complex and time-variable. The theoretical beams are included in the LOFAR calibration software, and have been verified to be reasonably accurate through commissioning projects.

Wide-field mapmaking The wide field of view of LOFAR makes it necessary to implement wide-field imaging techniques such as w-projection. Moreover, the time-varying beams and ionoshperic corrections, as well as the direction-dependent ionosphere corrections required, mean it is necessary to implement the A-projection (Bhatnagar *et al.* 2008) in imaging. Both these algorithms have been combined in the LOFAR AWimager (Tasse *et al.* 2013).

Timing of the station clocks One of LOFAR's key advantages is that individual stations are cheap; however, they have cheap clocks which slowly drift. The station clocks can be calibrated by making use of the very wide frequency coverage and to simultaneously observe a calibrator source. This is however not trivial, and the details are still being worked on.

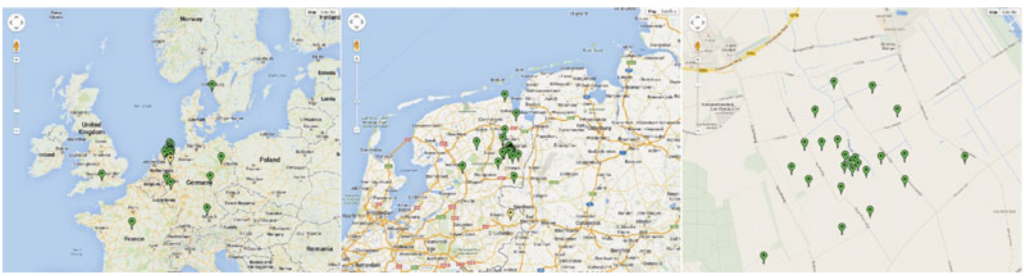

Figure 1. Current status of the LOFAR Array at three scales: *left* European scale showing the international stations; *centre* the Dutch scale showing the remote stations; and *right* the LOFAR core. The images are taken from George Heald's LOFAR Status map.

Ionosphere As the sun becomes more active, it is increasingly more important to correct for the effects of ionospheric phase distortions in LOFAR observations. Similar to optical "seeing" the ionosphere shifts the positions of radio sources and in bad cases distorts their shapes. The shifts and distortions depend on the ionosphere in the direction of each source and so can vary strongly accross a single LOFAR field. Experience with ionospheric corrections at low freqencies with the VLA and GMRT led to the development of the SPAM algorithm (Intema *et al.* 2009) which is being implemented and further developed for LOFAR.

3. LOFAR Science and Surveys

The primary scientific drivers for LOFAR are encapsulated in the Key Science Projects: (i) Epoch of Reionisation; (ii) Surveys; (iii) Transients; (iv) Cosmic Rays; (v) Cosmic Magnetism; and (vi) Solar Science and Space Weather. The Surveys project is most relevant to these proceedings, which together with projects like Cosmic Magnetism, will provide images of nearby galaxies, AGN, clusters and large deep extragalactic fields.

The three fundamental areas of astrophysics that have driven the design of the planned LOFAR surveys are: (i) forming massive galaxies at the epoch of reionisation, (ii) magnetic fields and shocked hot gas associated with the first bound clusters of galaxies, and (iii) star formation processes in distant galaxies. To achieve the goals of the LOFAR surveys, a tiered approach will be used (for details see Röttgering *et al.* 2010): Tier-1 is an all sky survey at 15, 30, 60 and 120 MHz; Tier-2 is a medium deep survey over 1000 square degrees at 30, 60, 120 and 200 MHz; and Tier-3 encompasses about 100 square degrees down to an extreme depth of 6 μJy rms at 150 MHz. The areas, depths and frequencies of the surveys have been chosen so that they would contain: (i) 100 powerful radio galaxies close to or at the epoch of reionisation, (ii) 100 radio halos at the epoch when the first massive bound galaxy clusters appeared, and (iii) 100 proto-clusters. The depth versus frequency of the proposed surveys is given in Fig. 2. Another important

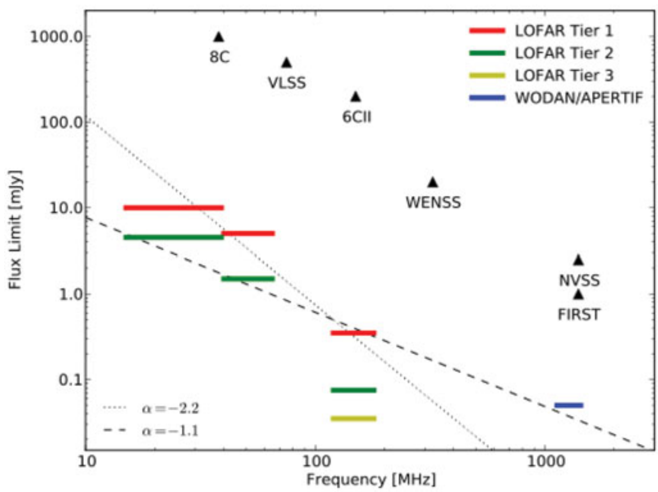

Figure 2. Flux limits (5σ) of the proposed LOFAR surveys compared to other existing radio surveys. The triangle represent existing surveys: NVSS, FIRST, WENSS, 6C, VLSS and 8C. The lines represent different power-laws ($S \sim \nu^{\alpha}$ with $\alpha = -1.1$ and -2.2) to illustrate how, depending on the spectral indices of the sources, the LOFAR surveys will compare to other current surveys. The proposed APERTIF/WODAN survey is also shown.

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motivation of LOFAR is to provide the entire international astronomical community with unique surveys of the radio sky that have a long-lasting legacy value for a broad range of astrophysical research. The fundamental astrophysical research topics for which LOFAR surveys will have a significant impact include (i) the formation and evolution of large scale structure of the Universe, (ii) the physics of the origin, evolution and end-stages of radio sources, (iii) the magnetic field and interstellar medium in nearby galaxies, and (iv) Galactic sources such as supernova remnants, HII regions, exoplanets and pulsars.

The LOFAR surveys will have excellent synergies with other proposed surveys, including the WODAN, EMU and optical surveys such as Euclid. WODAN (Westerbork Observations of the Deep APERTIF Northern-Sky) will be a deep (10 μJy) all-(Northern)-sky survey at 1400 MHz using the phased array feeds to be installed on the Westerbork Radio Telescope (WSRT). EMU (Evolutionary Map of the Universe, see the contribution by Ray Norris in these proceedings), using the Australian SKA Pathfinder (ASKAP), will do the same for the Southern sky. Euclid is an ESA mission to be launched in ~2020 and will survey 15,000 square degrees (also a deep survey of 40 square degrees) providing visual images down to AB= 24.5 mag; NIR images in Y, J and H bands down to AB= 24 mag; and NIR slitless spectroscopy. Primarily a Dark Energy mission, Euclid will provide shapes and photometric redshifts for ~ 1.5 billion galaxies.

4. Recent LOFAR Results

It should be noted that at present the measured noise in LOFAR images is dominated by calibration and imaging errors and a significant amount of both continued commissioning and technical research will be needed to obtain maps with the theoretical noise levels. However, the maps that are already being produced are the deepest ever at these low frequencies and high resolutions. The ongoing commissioning and early-science observations are producing some excellent imaging results. We highlight here a few recent results. For nearby galaxies, de Gasperin *et al.* (2012) have studied Virgo A (M87) in detail. This bright source is difficult to image because it is very bright and it lies at low declination for LOFAR. Nevertheless, they obtain very good images with noise levels of ~ 6 mJy/beam at 140 MHz with $19'' \times 14''$ resolution and 0.6 Jy/beam at 25 MHz with $85'' \times 44''$ resolution. The Epoch of Reionisation group makes images with dynamic ranges of the order of $800,000:1$, resolutions down to $15''$, noise levels of 100 μJy/beam across a wide band of $120-180$ MHz (see Yatawatta *et al.* (2013) for some recent results).

Extragalactic fields that have been imaged with LOFAR include the Groth Strip (part of the calibrator, 3C295, field) and Boötes (see van Weeren *et al.* in prep) with images at $55-70$ MHz (noise $4-5$ mJy, resolution $20''$), $40-50$ MHz ($6-7$ mJy, $30''$), and $30-40$ MHz (11 mJy, $40''$), revealing sources deeper than are visible in VLSS (at 74 MHz). Moreover, source counts have been determined for these fields. See also the contribution in these proceedings by Prandoni *et al.* where they present LOFAR observations of the Lockman Hole. Exploiting the very large field of view and looking at sources detected in the cluster field A2256 (see van Weeren *et al.* 2012), Rafferty *et al.* (in prep), have studied the low frequency SEDs of WISE-selected starbursts. They find that most ($\sim 75\%$) of the starbursts have SEDs that continue to rise below ~ 60 MHz.

5. LOFAR and AGN Studies

AGN activity occurs in at least two different modes, each of which may be important, in different ways, for feedback on their host galaxies. The most commonly considered mode of AGN accretion is the 'standard' mode associated with quasars. This

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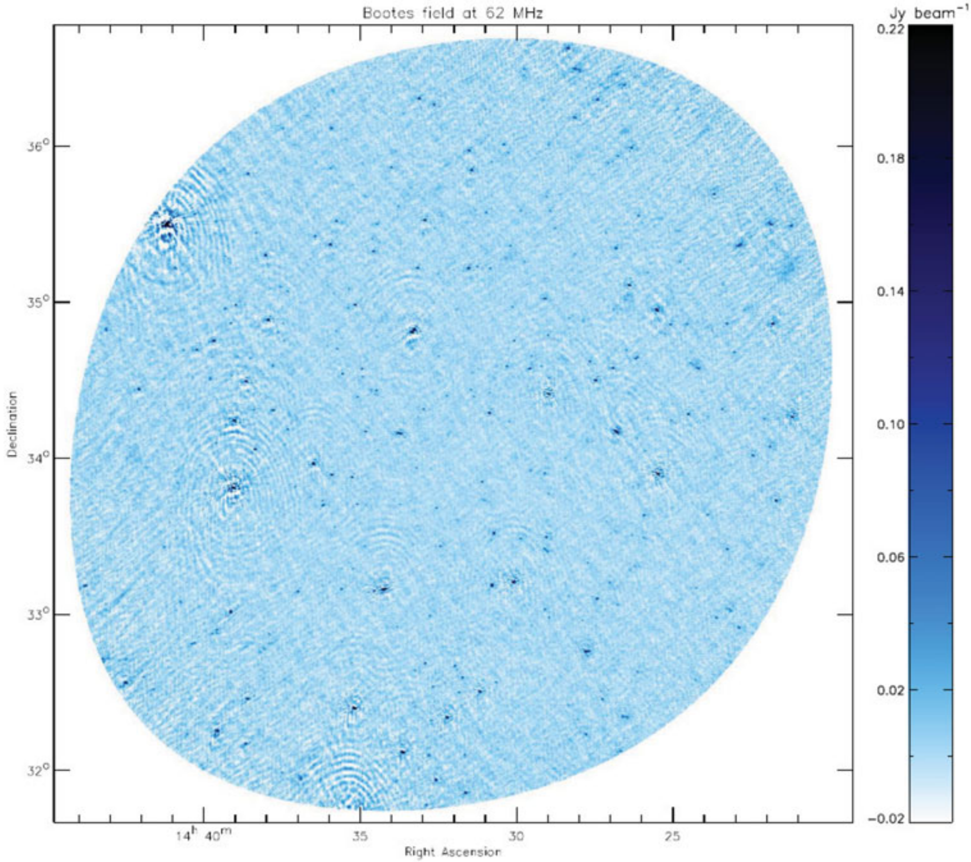

Figure 3. The Boötes field observed with LOFAR at 62 MHz mosaic. The image covers 19 square degrees. The average noise is 4.8 mJy beam^{-1} and the resolution is $31'' \times 19''$ (van Weeren *et al.* in prep).

mode, often and variously referred to as 'quasar-mode', 'cold-mode', 'radiative-mode', or 'high-excitation', is characterised by strong optical emission lines, MIR emission and/or absorption associated with a dusty torus (or other absorbing structure), along with possible X-ray emission. Here material is accreted on to the black hole through a radiatively efficient accretion disc. The second mode of AGN activity occurs with little radiated energy, but can lead to the production of highly energetic radio jets. Here, the strong emission lines are absent (Hine & Longair (1979)) and they lack other evidence for accretion disks. These 'radiatively inefficient', 'radio-mode', 'hot-mode', or 'low-excitation' AGN are thought to be fueled by radiatively inefficient advection-dominated accretion flows (ADAFs) (e.g. Narayan & Yi 1995).

Using the SDSS value-added spectroscopic sample of radio loud galaxies (Best & Heckman 2012) which has been classified into Star-Forming and Low Excitation and High Excitation radio AGN, Janssen *et al.* (2013) looked at the fraction of galaxies that are hot-mode radio emitters as a function of their SDSS colours. LOFAR will be invaluable in extending samples such as these out to higher redshifts, and will shed light on the different evolution of the two accretion modes.

In anticipation of the LOFAR surveys we have surveyed the Boötes field with the GMRT at 153 MHz. The Boötes field is part of the NOAO Deep Wide Field Survey

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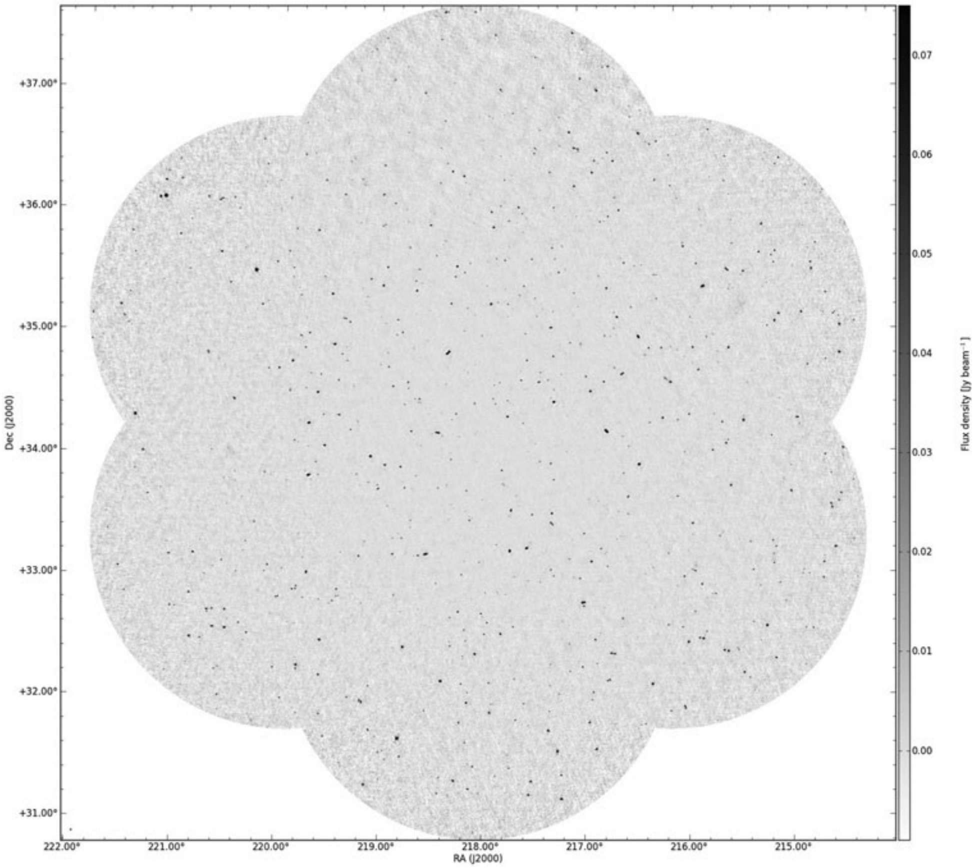

Figure 4. The GMRT Boötes 153 MHz mosaic covering 30 square degrees. The greyscale shows the flux density from -3σ to 25σ where $\sigma = 3.0$ mJy beam^{-1} is the average *rms* across the entire mosaic.

(NDWFS; Jannuzi et. el. 1999) and covers $\sim$9 deg^2 in the optical and near infra-red B_W, R, I and K bands. There is a wealth of additional complementary data available for this field, including X-ray (Murray *et al.* 2005, Kenter *et al.* 2005), UV (GALEX; Martin *et al.* 2003), and mid infrared (Eisenhardt *et al.* 2004, Martin *et al.* 2003). The region has also been surveyed at radio wavelengths with the WSRT at both 1.4 GHz (de Vries *et al.* 2002) and 325 MHz (Croft *et al.* 2008), and the VLA at 1.4 GHz (Higdon *et al.* 2005). Recently, the AGN and Galaxy Evolution Survey (AGES) has provided redshifts for 23 745 galaxies and AGN across 7.7 deg^2 of the Boötes field (Kochanek *et al.* 2012).

Our GMRT observations cover 30 square degrees at a resolution of $25''$ (Williams *et al.* 2013). The resulting mosaic is shown in Fig. 4; the *rms* noise is 2 mJy beam^{-1} in the centre of the image, rising to $4-5$ mJy beam^{-1} on the edges, with an average of 3 mJy beam^{-1}. Seventy-five per cent of the area has an $rms < 4$ mJy beam^{-1}. The extracted source catalogue contains 1289 sources detected at 5σ, of which 453 are resolved. We have matched these sources to the NDWFS I catalogue using the Likelihood Ratio and are using the multi-wavelength data available to construct SEDs and determine photometric redshifts and host galaxy properties such as stellar mass for the whole GMRT Boötes field sample. Such work will be readily extendible to the larger LOFAR sample soon to be available.

6. Prospects

LOFAR has been producing excellent quality interferometric data for a number of years now. The commissioning period is over and Cycle 1 observations started in November 2013. During the commissioning period, a number of crucial challenges were overcome relating to the calibration and imaging of low frequency aperture array interferometric data, including handling RFI, beam calibration, bright source removal and wide-field imaging.

LOFAR Surveys have already started imaging a handful of deep fields towards the surveys Tier-1 depth. The combination of the LOFAR surveys data and other ancillary multi-wavelength data available in many of the extra-galactic deep fields will make LOFAR a great tool for studies of AGN, distant clusters and galaxies.

Acknowledgements

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