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LOFAR and the low frequency universe. Probing the formation and evolution of massive galaxies, AGN and clusters

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One of the most fundamental problems in modern astrophysics concerns the formation of galaxies and clusters of galaxies. The Dutch-European radio telescope LOFAR will open up the last unexplored window of the electromagnetic spectrum for astrophysical studies and make important contributions to our knowledge of the structure formation in the universe.

LOFAR's world-class observational capabilities will be used to survey the entire Northern low-frequency sky at a number of key frequencies. Studies of the most distant radio galaxies, clusters of galaxies and the cosmic star formation history and the exploration of new parameter space for serendipitous discovery were the four key topics that drove the areas, depths and frequency coverage of the proposed surveys. In addition to the key topics, the LOFAR surveys will provide a wealth of unique data for a huge number of additional important topics, including: detailed studies of AGN, and AGN physics, AGN evolution and black hole accretion history, nearby galaxies, strong gravitational lenses, cosmological parameters and large-scale structure formation, and Galactic radio sources.

In this contribution we will first briefly discuss the scientific topics that have driven the design of the surveys. Subsequently we will present the design of the surveys. We will then briefly report on commissioning work carried out to prepare the instrument and the software pipelines for carrying out these surveys. At the end we will elaborate on LOFAR studies on clusters and show some first LOFAR results related to the nearby rich cluster Abell 2256. With at the time of writing only 15 out of the planned 36 Dutch stations working and several aspects of the calibration pipleline not fully functional, the obtained 135 MHz image already is among the deepest ever produced at low frequencies. The central halo of A2256 is well detected, illustrating the potential of LOFAR to map diffuse steep spectrum radio emission.

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PoS(ISKAF2010)050

1. Introduction

An important goal that has driven the development of LOFAR since its inception is to explore the low-frequency radio sky through several surveys. The main science driving the design of these surveys will be to use the unique aspects of LOFAR to advance our understanding of the formation and evolution of galaxies, AGNs and galaxy clusters. Since LOFAR will open a new observational spectral window and is a radio "synoptic" telescope, the surveys will explore new parameter space and are well-suited for serendipitous discovery. Furthermore, carefully designed surveys with LOFAR that are easily accessible will ensure that a large astronomical community can benefit from its high-quality products. Because of its low operating frequencies, and the resultant large beam size on the sky, LOFAR is an ideal survey facility. For example, at 50 MHz each beam has a 7.5 deg field of view. With theoretical LOFAR sensitivities and feasible observing times, such a field will typically contain 1 $z > 6$ radio galaxy, 5 Abell clusters, 5 NGC galaxies, 5 lensed radio sources and several giant ($>$ 1 Mpc) radio galaxies (for an illustration see Figure 1). The aimed legacy value of our proposed LOFAR surveys will be comparable with previous high-impact surveys (e.g. Palomar,

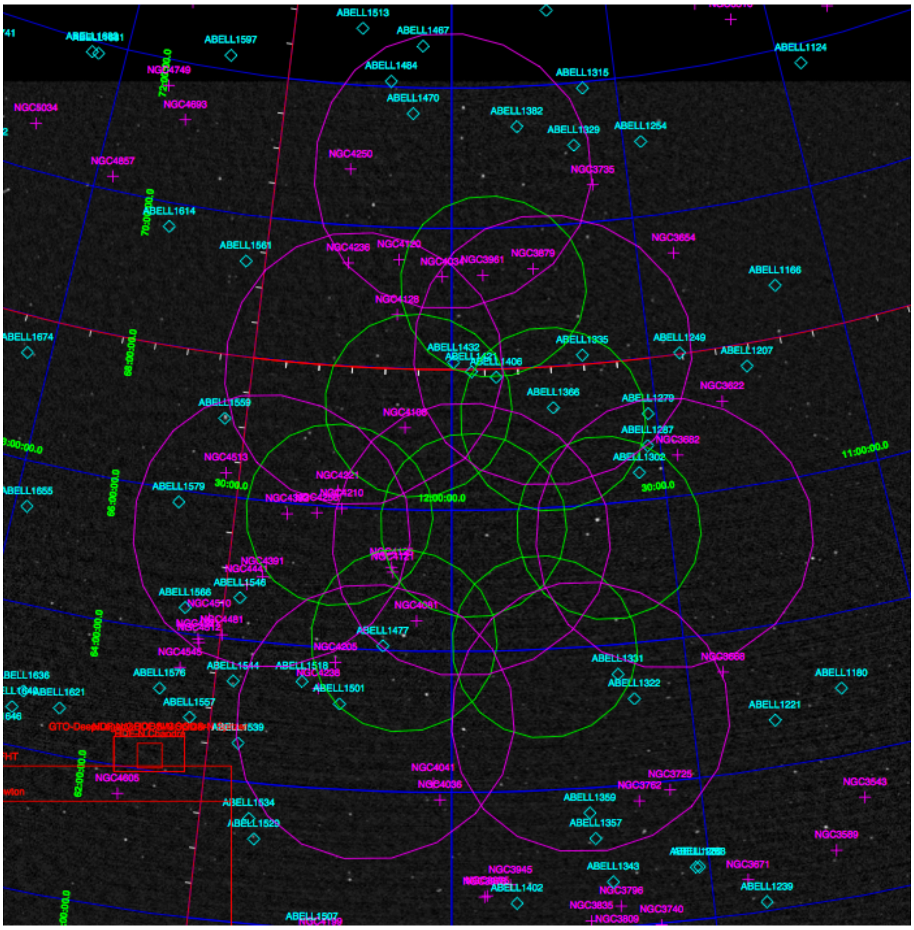

Figure 1: An example of the survey power of the LOFAR telescope. Shown are in green an 8 pointing mosaic at 130 MHz using the High-Band antennas and in magenta an 8 pointing mosaic at 50 MHz using the Low-Band antennas . Also are indicated the locations of the Abell clusters and NGC galaxies in this region.

IRAS, SDSS, GALEX, Spitzer, NVSS). Our LOFAR surveys will complement currently planned surveys in other wavebands (e.g. JEDAM, Euclid, Pan-STARRS, Herschel, Planck, VISTA, VST, E-VLA, ASKAP, MEERKAT, ATA). The surveys described here will provide meter-wave data on up to 10^8 galaxies and 10^4 clusters out to $z \sim 8$ and address a wide range of topics from current astrophysics.

In this contribution we shall first sketch the general science case for the surveys and show how this lead to the survey design. In the second part of this contribution we will show a few first observational results related to the general science case for the surveys. Particular emphasis will be given on the nearby cluster of galaxies A2256, for which LOFAR data were taken during the 2 months before the ISKAF 2010 meeting.

2. Science Case

The LOFAR Survey Key Project has from the outset been driven by four key topics. The first three are directly related to the formation of massive black holes, galaxies, and clusters. The fourth is the exploration of parameter space for serendipitous discovery. These four key topics drive the areas, depths and frequency coverage of the proposed surveys. In addition to the key topics, the LOFAR surveys will provide a wealth of unique data for a huge number of additional important topics. Furthermore, to maximise the usefulness of the survey data for the Magnetism Key-Project, our observations will be taken with sufficient bandwidth so that the technique of rotation measure synthesis can be applied to the data. We also plan to observe in several passes, spreading the observations for individual pointings logarithmically in time to facilitate searches for variable sources on various timescales, in collaboration with members of the Transient Key-Project. Here we shall describe briefly the goals of the key topics (2.1 - 2.4) and summarize the additional science topics (2.5 - 2.10).

2.1 Exploitation of Lofar surveys to investigate high-redshift galaxies - PI Miley

High-redshift radio galaxies (HzRGs, $z > 2$) are unique laboratories for studying the formation and evolution of massive galaxies, rich clusters and massive black holes. (see review by Miley and De Breuck, 2008). Focusing on rare ultra-steep spectra (USS) radio sources has resulted in the discovery of most known $z > 2$ HzRGs (Röttgering et al. 1997; de Breuck et al. 2002). Presently, the most distant HzRG has $z = 5.1$ (van Breugel et al. 1999). Because of its low operating frequency, LOFAR will detect large numbers of USS HzRGs. This should push studies of massive galaxies and protoclusters to $z \sim 8$. *Our goal is to detect 100 radio galaxies at* $z > 6$ to enable robust studies of the properties of $z > 6$ massive galaxies and protoclusters and provide sufficient number of radio sources within the Epoch of Reionization to facilitate HI absorption studies.

2.2 Exploitation of LOFAR surveys to study galaxy clusters - PIs Brüggen/Brunetti

Clusters often contain Mpc-sized diffuse radio sources not clearly associated with individual galaxies. Diffuse radio cluster sources are classified into either amorphous "halos" located close to the centres of clusters, or elongated "relics" located near the cluster peripheries. (e.g. Giovannini & Feretti 2004). Currently, such diffuse radio sources are known in about 30 nearby rich galaxy clusters and often have ultra-steep spectra. With its unprecedented low-frequency sensitivity, LOFAR should detect many thousands of diffuse cluster radio sources out to $z \sim 0.8$. Our survey goal is to detect *about 100 clusters at* $z \gtrsim 0.6$ *and to study 60 local clusters in unprecedented detail.* This sample will enable a robust study of magnetic fields, plasma shocks and particle acceleration mechanisms as a function of cluster properties and redshift. Also detailed studies of the radio galaxies, quasars and tailed sources in these clusters will provide important information on the overall thermal balance and star formation in clusters.

2.3 Cosmic starformation history- PIs Lehnert/Barthel

The deepest surveys will detect radio emission from millions of regular star-forming galaxies at the epoch when the bulk of galaxy formation occured. Galaxies with extreme star formation rates will be detectable out to the epoch of reionisation. The combination of LOFAR and infrared surveys will yield radio-IR photometric redshifts, enabling studies of the volume-averaged star formation rate as a function of epoch, galaxy type and environment. Such studies need surveys that cover a sky area large enough to sample diverse environments (from voids to rich proto-clusters) over a wide range of cosmic epochs. Our surveys are planned to contain *50 proto-clusters at* $z > 2$, sampling the most extreme (and rarest) peaks in the density field.

2.4 Exploration of new parameter space for serendipitous discovery.

One of the most exciting aspects of LOFAR is that its enormous instantaneous fields coupled with its unprecedented sensitivity at low frequencies equips LOFAR for the discovery of new classes of rare extreme-spectrum sources and low-frequency variables. The uncharted parameter space with the highest probability of serendipitous discovery is at frequencies < 30 MHz. These frequencies probe radiation mechanisms not observable at higher radio frequencies, such as coherent plasma emission. We note that the bright very-low frequency sky appears different from the sky observed at higher frequencies. The brightest celestial objects below 40 MHz are the Sun and Jupiter with ultra-steep spectra ($\nu^{-3.5}$).

2.5 Exploitation of LOFAR surveys for detailed studies of AGN, and AGN physics - PI Morganti

LOFAR will provide low frequency data for all northern nearby radio loud AGN, from the very young (few hundred years) GPS radio sources to the very old giant Mpc-sized radio galaxies with ages of $\sim 10^8$ years. The LOFAR survey data will yield several key physical parameters, will directly constrain models of the radio activity and its relation to the ISM and associated star formation rates.

2.6 Exploitation of LOFAR surveys for AGN evolution and black hole accretion history - PI Best

LOFAR Surveys combined with deep optical and IR datasets will determine the evolution of black hole accretion over most of cosmic time, and address several crucial questions about AGN evolution: the nature of the different accretion processes; the properties of the host galaxies; the role of AGN feedback for galaxy evolution; the radio source duty cycle; and the relation with the environment.

PoS(ISKAF2010)050

2.7 Exploitation of LOFAR surveys for observations of Nearby Galaxies - PIs Conway/Chyży

For nearby galaxies, the LOFAR survey data will provide new information about properties such as (i) the amount and distribution of T $\sim$ 1000 K gas through studies of free-free absorbed spectra and (ii) the magnetised medium and associated outflows.

2.8 Exploitation of the LOFAR surveys for strong gravitational lenses S - PI Jackson

The LOFAR surveys should contain $\sim 10,000$ strongly lensed radio sources. Ultimately, this will provide a powerful statistical probe of galaxy evolution and constrain the properties of dark matter at subgalactic scales

2.9 Cosmological Parameters and Large-scale structure - PIs Jarvis/Bacon

The all sky nature of LOFAR surveys combined with the large number of survey sources should facilitate studies of baryonic oscillations, the integrated Sachs-Wolfe effect, clustering of matter on > 10 Mpc scales and the dipole effect (- enhancement in the surface density of distant galaxies in the direction of motion of our Galaxy).

2.10 Galactic radio sources - PIs Haverkorn/White

LOFAR survey data will (i) increase the number of well studied supernova remnants and HII regions by an order of magnitude and (ii) provide new information about the strength and topology of the large scale galactic magnetic fields, plasma turbulence and ionised components.

3. Parameters of the proposed LOFAR surveys

3.1 Survey frequencies

We propose carrying out the LOFAR surveys with five frequency setups (see Table 1). For simplicity, hereafter these frequency set-ups will be referred to as the 15, 30, 60, 120, 150 and 200 MHz surveys. The proposed minimum total bandpass of 16 MHz improves UV coverage through multi-frequency-synthesis, as well as offering a significant benefit for polarisation studies.

Table 1: LOFAR survey frequency setups (in MHz)

Nominal survey freq.	Freq. range	Bandwidth pass	Band
15	15 - 23	4	10 - 90
30	30 - 50	16	30 - 90
60	60 - 80	16	30 - 90
120	120 - 150 (90 %)	14.5	110 - 190
	150 - 190 (10 %)	1.5	
150	126 - 174	48	110 - 190
200	180 - 210	16	170 - 230

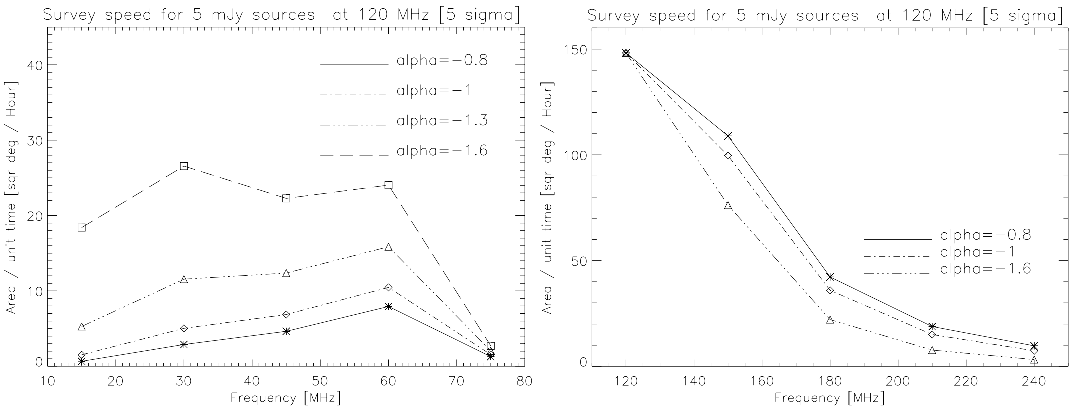

Figure 2: With one 4 MHz beam, the survey speed taken as the area on the sky covered per unit time deep enough to detect a 5 mJy source at 120 MHz at the 5 sigma level as a function of frequency and spectral index. Left: Low-band system. Right: High-band system.

To achieve our science goals, we need to take into account LOFAR's survey speed as function of frequency (see Figure 2). For the high-band system, 120 MHz is clearly the fastest survey system, irregardless of assumed spectral index. For the low band system the survey speed for an ultra-steep spectrum source ($\alpha < -1.4$) is approximately constant between 30 and 60 MHz. For the main work-horse frequency for the surveys, - 120 MHz - , the bulk of the bandwidth will be spread over the 120 to 150 MHz range, with some small fraction ($\lesssim 10\%$) being positioned between 150 and 190 MHz (the upper limit of the bandpass filter). Simulations by G. Heald (ASTRON) show that this setup is a good compromise between survey speed and sensitivity for a range of rotation measure studies.

For the deep pointed observations, the optimal frequency is around 150 MHz. To obtain the highest sensitivity we will use a 48 MHz band, yielding a frequency range of 126 - 174 MHz. In the low frequency band, observing simultaneously at 30 and 60 MHz would require the same antennae to be used, with a cost either in instantaneous sensitivity at 30 MHz or station beam area at 60 MHz. It is therefore proposed to use two separate frequency set-ups, one with a 16 MHz bandpass spread between approximately 30 and 50 MHz and the other roughly between 60 and 80 MHz. To reduce RFI from below 30 MHz, these observations will use the 30–90 MHz bandpass filter.

3.2 Proposed surveys

To achieve the goals of the four key science topics (2.1 - 2.4), a three-tier approach to the LOFAR Surveys has been adopted.

In Table 2 we give the details of the surveys, and also list the key and main science topics which the various planned surveys are designed to serve.

Tier 1: The "Large Area" 2π steradian surveys at 15, 30, 60, 120 and 200 MHz, together with 150 deeper pointing at 200 MHz yielding 1000 square degrees.

The depth and area of the planned 120 MHz survey are driven by the desire to detect ~ 100

Table 2: Proposed LOFAR surveys

f[1] MHz	Area deg^2	thermal rms mJy	BW MHz	Sources[2] /beam	Int. time[3] hrs	Number pointings	Days[4]	Total[2] sources	Key[6] Topic	Main[6] Topic
				Tier 1: The "Large Area" survey						
15	20626	10	4	17811	100	100	21	1.4e+06	4	10
30	20626	2	16	19106	22.3	218	42	3.5e+06	1,2	5,7,10
60	20626	0.75	16	30124	20.6	203	36	5.1e+06	1,2	5,7,10
120	20626	0.1	16	30016	3.8	1021	33	2.8e+07	1,2	5,7,8,9,10
200	20626	0.2	16	2472	1.0	3021	25	7.0e+06	1,2	5,7,10
200	1088	0.065	16	9373	9.3	150	12	1.4e+06	1,2	5,7,8,9,10
				Tier 2: The "Deep" survey						
30[5]	2806	0.7	16	53523	204	25	44	1.6e+06	2,3	5,6,7
60	3025	0.25	16	96763	207	25	44	2.9e+06,	2,3	5,6,7
120	555	0.025	16	204070	67	25	14	5.6e+06	2,3	5,6,7
200	362	0.016	16	66635	172	50	74	3.5e+06	2,3	5,6,7
				Tier 3: The "Ultra Deep" survey						
150	71	0.0062	48	543798	221	5	28	2.9e+06	3	5,6

[1] Nominal names for frequency bands; see Section 5.2. [2] Number of sources in the beam and total number of sources with a signal to noise ratio larger than 5. Note that for the tier-3, the total noise is taken as the quadratic sum of the confusion noise and the thermal noise. [3] The integration time is quoted for 1 beam of 16 MHz, except for at 15 MHz where it is for a 4 MHz bandwidth. [4] The total number of days needed to complete the survey assuming (i) the availability of 12 beams of 16 MHz (or 16 beams of 4 MHz for 15 MHz observations) and (ii) the need for a factor of 2.5 more observing time over that as deduced from the theoretical LOFAR sensitivities. [5] If commissioning shows that it is possible to conduct useful deep surveys at frequencies below 30 MHz, we will change the 30 MHz observing frequency to the lowest frequency at which it is possible to make deep maps (this will require a change to the 10-90 MHz bandpass filter, and a reduction to a 4 MHz bandwidth beam), and may reduce the central frequency of the 60 MHz frequency band as well. [6] The numbers refer to the sub-sections in Section 3.

cluster halos at $z > 0.6$. This requires a 120 MHz large-sky ($\delta > 0^\circ$) survey[1] to a flux density level of 0.1 mJy rms (Enßlin and Röttgering 2002; Cassano et al. 2010)

For the 30 and 60 MHz large-sky surveys the depth and area are set by our goal of detecting ~ 100 $z > 6$ radio galaxies. At 30 MHz, this requires a large-sky survey with a flux density limit of 15 mJy (Wilman et al. 2008). To ensure sufficiently accurately measured spectral indices and to avoid contamination of spurious ultra-steep spectrum sources, we set a conservative level of 7.5 σ for the detection of 15 mJy sources. To measure the low frequency spectral shape of distant galaxy candidate sources, we require that we can detect at 60 MHz (at the $> 5\sigma$ level) sources in the 30 MHz survey with $\alpha = -2$.

[1]There are good reasons for extending the surveys down to $\delta = -10^\circ$ in order to maximise overlap with the optical, IR and millimeter telescopes of ESO and ALMA. However, the worse beam, reduced effective sensitivity and increased ionospheric effects will make this difficult. Based on the results of commissioning observations, we shall decide whether it is useful to extend the Tier 1 surveys to negative declinations.

Although the relatively fast 15MHz survey provides the exciting possibilities of detecting new types of sources, it is uncertain how deep LOFAR will reach at these frequencies. We aim to reach depths at 15 MHz that are comparable to those at the higher frequencies. With the severe condition imposed by the ionosphere, we have set an integration time per pointing to a maximum of 100 hours. In principle this will ensure that 15 MHz sources with spectral indices as steep as $\alpha = -2.3$ can be detected at 30 MHz.

Many of our science goals will benefit from the 200 MHz surveys. The increased angular resolution is important for delineating morphologies, and is crucial for optical and IR identifications. The additional flux measurement will allow spectral indices to be determined for the flatter spectrum sources that might remain undetected at the lower frequencies, as well as being valuable for identifying peaked sources. Since it would be prohibitively expensive to image the whole sky to a depth comparable to that at 120 MHz, the 200 MHz large-area surveys will be carried out using a two-pronged approach.

Firstly, a relatively shallow large-sky 200 MHz survey is planned. With an rms depth of 0.2 mJy it matches the depth of the 60 MHz survey for a typical spectral index of $\alpha = -1.1$. A 10 σ 120 MHz source with a spectral index $\alpha = -1$ will then be detected at 200 MHz to a 3 σ level. Spectral index information for all but the faintest 120 MHz sources should then be measurable from either the 30 or 200 MHz surveys.

Secondly, we plan to observe 150 pointings (1000 sq.deg.) at 200 MHz to a depth comparable with that of the 120 MHz survey for a typical spectral index of $\alpha = -0.75$. These pointings will be split between 3 different types of observations: (i) $\sim$ 200 sq. deg. coverage of some of the outer regions of the “deep" field observations (see Tier-2), (ii) $\sim$ 60 cluster or super-cluster fields and (iii) $\sim$ 60 nearby galaxies.

Tier 2: “Deep” surveys at 30, 60, 120 and 200 MHz over fields centred around 25 selected regions.

Major science drivers for the “Deep” survey include studies of the evolution of star-forming galaxies, studies of radio-loud and radio-quiet AGNs, etc. and detailed studies of the targeted nearby galaxies and clusters. The 25 LOFAR selected regions will consist of the following targets:

- 13 well-studied blank-fields that already have superb degree-scale multi-wavelength data;
- 6 fields centered on clusters or super-clusters;
- 6 fields centered nearby galaxies.

The depth of the 120 MHz deep survey is set by the requirement that galaxies with a star formation rate SFR > 10 M$_\odot$/yr will be detectable at the 5σ level to $z = 0.5$ and those with a SFR > 100 M$_\odot$/yr to $z = 2.5$. Following Carilli and Yun (1999) this translates into an rms at 120 MHz of 25 μJy. The depth of the 200 MHz deep survey should match the depth of the 120 MHz deep field data for $\alpha = -0.75$.

The depths of the 30 and 60 MHz deep regions are chosen to match the depth of the 120 MHz large-sky data for $\alpha = -1.4$. If during commissioning it appears possible to make high dynamic range observations below 30 MHz, then we will change the 30 MHz observations to the lowest frequency at which it is possible to make maps at a depth comparable to the currently proposed 30 MHz observations.

For the blank field regions, single pointings at 30, 60 and 120 MHz will be sufficient. About half the fields have such extended deep multi-wavelength data sets that 2-4 200 MHz pointings are needed to tile the fields and an extra 25 200MHz pointings will be required. The areas of the 120 MHz beam not tiled by deep 200 MHz observations will be targeted as dedicated pointings in the shallower Tier-1 survey at 200 MHz.

Tier 3: "Ultra-deep" integrations on five pointing centres at 150 MHz.

It is proposed to carry out "ultra-deep" pointings for 5 fields with excellent multi-wavelengths data. This will yield an area large enough to probe a range of environments, from low density ones to rich proto-clusters for which we aim to detect 50 at $z > 2$. Extremely deep observations are most efficiently being done at frequencies centered at 150 MHz. We aim to reach confusion levels. Galaxies with a star formation rate larger than 10 $M_{\odot}yr^{-1}$ at $z \sim 1.5$ and larger than 100 $M_{\odot}yr^{-1}$ at $z \sim 5$ have flux densities comparable with the confusion level of 5 μ Jy at 150 MHz. We note that this sensitivity is similar to that needed for the EOR Key Project.

3.3 Summary

The proposed surveys will not only be unique due to their low frequencies, but are also very important due to their depth as compared to other surveys. To illustrate this we have plotted the limits of a number of radio surveys in Figure 3 as a function of frequency together with the proposed surveys. It is clear that the proposed LOFAR surveys go 2-3 orders of magnitude deeper than any other existing large sky radio survey.

4. Status commissioning LOFAR for imaging observations

Each new large facility undergoes a commissioning process in which the facility is optimised for the intended scientific goals. This requires close interaction between scientists and engineers over a prolonged period. Due to the innovative design of LOFAR, commissioning will be particularly important and time-consuming because of (i) the need to minimise the effect of the ionosphere and RF interference on the observations at low frequencies, (ii) the effect of sidelobes from the large number of sources located within the extremely wide instantaneous field, (iii) the planned novel calibration procedures and (iv) the high dynamic range needed to attain some of the scientific goals, and (v) the large range of required exposure times, ranging from nanoseconds for cosmic rays to many weeks for the deepest observations. Commissioning is also particularly demanding, since it has to be done for each of the frequencies of interest as well as for various distributions of baseline combinations. There are a number of critical issues that must be addressed during astronomical commissioning activities. These include determining (i) the best interference excision, (ii) the complexity of an ionospheric model needed for calibration, (iii) the stability and number of degrees of freedom of the beamshapes, and (iv) the number of calibration and deconvolution computational cycles required.

During the 6 weeks before the conference the LOFAR system could be operated with a maximum of 20 station yielding sufficient number of baselines that selfcalibration and even the "peeling

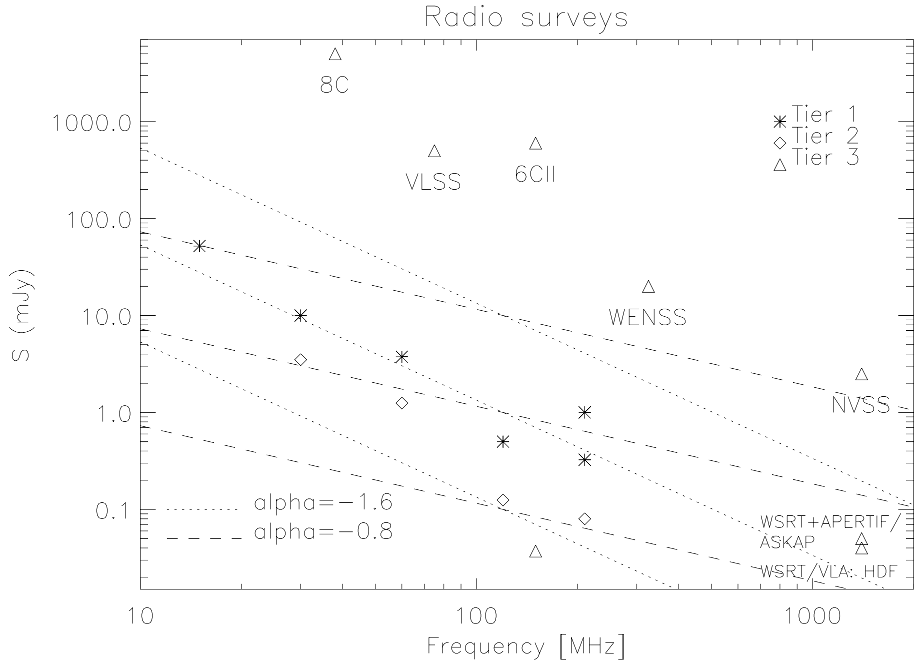

Figure 3: *Flux limits (5 sigma) of the proposed LOFAR surveys compared to other existing radio surveys. The triangle represent existing surveys: HDF (VLA Richards et al. 2000; WSRT Garrett et al. 2000), Wenss, NVSS, 6C, VLSS and 8C. The lines represent different power-law ($S \sim \nu^{\alpha}$, with $\alpha = -1.6$ and -0.8) to illustrate how, depending on the spectral indices of the sources, the LOFAR surveys will compare to other surveys.*

technique" could be applied. Data sets were taken on a range of objects including M51, Cygnus A, 3C61.1, NGC 6251, and a few clusters including A2256. The work on M51, Cygnus A and 3C61.1 was very well presented in this conference by respectively George Heald, Olaf Wucknitz and Ger de Bruyn. Here I will concentrate on the observations of A2256, since it turned out that the results on A2256 give an excellent glimpse of what a powerful science machine LOFAR is about to become.

4.1 LOFAR observations on clusters

Clusters of galaxies are large ensembles of hundreds of galaxies embedded in hot gas and held together by gravity (e.g. Rosati et al. 2002). They are the most massive bound structures in the Universe with typical masses of 10^{15} solar masses. Besides the hot thermal gas observed in X-ray, the intra-cluster-medium (ICM) contains relativistic electrons and magnetic fields ($1 - 10\mu$Gauss), which have been detected via synchrotron emission in the radio band. Synchrotron emission provides unique diagnostic of the large-scale magnetic fields, relativistic particles mixed with the thermal ICM and of cluster wide shock systems due to cluster mergers. LOFAR is uniquely suited to probe the complex physical processes in the ICM through simultaneous observations of three classes of diffuse radio emitting objects: relics, halos and phoenixes (e.g. e.g. Ferrari et al. 2008, Cassano 2009 for recent reviews).

Cluster relics are large elongated diffuse structures at the periphery of clusters. The most tenable explanations seems that a binary cluster merger creates two giant outward shock waves travelling in the direction of the merger axis. In the shock front particles are accelerated to relativistic speeds and in the presence of the cluster magnetic fields emit the observed synchrotron radiation.

A second class of diffuse radio sources are *cluster radio halos*. They are located at the centres of clusters, often have enormous sizes of ~ 1 Mpc and have morphologies following that of the X-ray emission. The combined radio and Chandra X-ray observations of the merging cluster MACS J0717.5+3745 ($z = 0.5$) showed the most powerful radio halo known (van Weeren et al. 2009, Bonafede et al. 2009). The co-location of the steep spectrum radio emission with a region of high temperature X-ray gas presented further evidence that the presence of radio halos is tightly connected to the dynamical status of the hosting clusters (see also Cassano et al. 2010a). The scenario is that cluster-cluster mergers can induce turbulence in the hot X-ray gas that (re)accelerate relativistic radio emitting particles. Interestingly, within such a scenario, a large number radio halos with ultra steep spectra (spectral indices < -1.6), the so called Ultra Steep Spectrum Radio Halos (USSRH) should exist. Recent low-frequency radio observations revealed the first USSRHs sources (e.g. A521, Brunetti et al. 2008, Dallacasa et al. 2009 and A697, Macario et al. 2010). The LOFAR surveys are expected to discover many of such sources (e.g. Cassano et al 2010b).

A third class of diffuse emitters are the *radio phoenixes*. The scenario that Enßlin and Kopal-Krishna (2001) suggested is that shocks in the cluster gas adiabatically compress old radio plasma ejected by former active galaxies. This compression would result in diffuse objects with an extremely steep radio spectrum: radio phoenixes.

4.2 The rich cluster of galaxies Abell 2256

Abell 2256 is a rich X-ray cluster at $z = 0.058$ that has undergone a merging event estimated to have happened 0.3 Gyr ago (e.g. Miller et al 2003). Apart from 9 tailed sources, it rather exceptionally contains three classes of diffuse cluster radio sources: relics, halos and phoenixes. The northern relics have been discovered a long time ago (Bridle and Formalon 1979) and was studied in detail by Clarke and Enßlin (2006). They also clearly showed that A2256 possesses a central halo with a luminosity following the X-ray - radio halo luminosity relation. In very deep 325 MHz GMRT radio maps van Weeren et al. (2009) recently discovered three diffuse elongated radio sources with extremely steep spectral indices located about 1 Mpc from the cluster center. These properties indicate that these objects can be classified as phoenixes.

As A2256 is one of the most luminous radio emitting clusters showing so many intriguing characteristics, it was one of the prime candidates to be observed during commissioning of LOFAR. It was observed in the HBA band in May 2010 for about 8 hours. The data were taken with 10 core stations and 5 remote stations and the observed frequencies ranged from 115 to 165 MHz. An image from 18 subbands covering a total of 4 MHz of bandwidth around 135 MHz was made (see Figure 4). The resolution of the image is 31×19 arcsec and the noise is ~ 5 mJy/beam. So far, the deepest image at low frequencies have been obtained with the GMRT at 150 MHz (Intema 2009, Intema et al. submitted, Kale and Dwarakanath 2010). The GMRT image clearly shows the relic and several of the head tail galaxies that are also visible on the LOFAR image. The GMRT image recovers the central part of the halo emission. With LOFAR's very sensitive central core, the full extent of the halo is visible, showing LOFAR's power to study diffuse steep spectrum emission from clusters. Next steps in improving this image are reducing the data from all the 256 subbands,

PoS(ISKAF2010)050

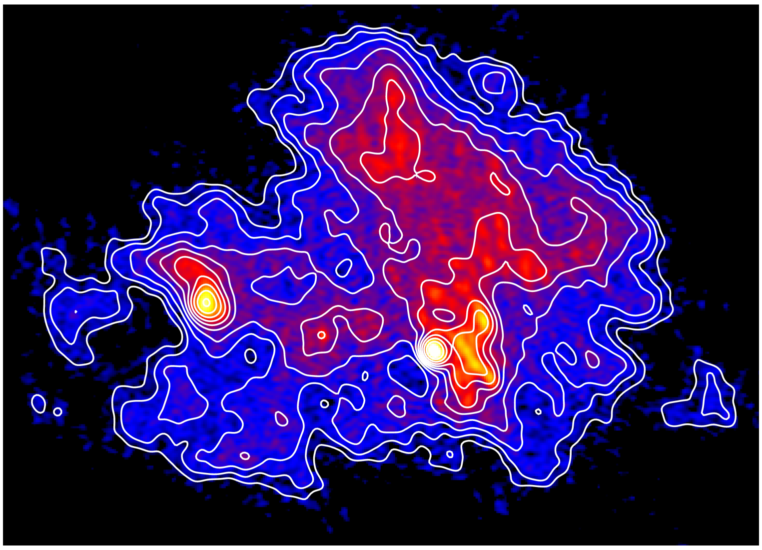

Figure 4: A 135 MHz LOFAR image of the rich X-ray cluster of galaxies A2256 at $z = 0.058$. The image has been made from data were taken with 10 core stations and 5 remote stations. Only 4 MHz bandwidth out of a total 48 MHz was used during the reduction. The resolution of the image is about 31×19 arcsec and the noise is ~ 5 mJy/beam. Beside several tailed galaxies and the relic structures, the image shows for the first time a spatially resolved central halo of A2256 at low frequencies.

and the application of more sophisticated data reduction algorithms. These include proper wide-field imaging taking the varying station beams into account, iteration of self-calibration/peeling loops, and removal of ionospheric corrections following the "SPAM" method (Intema et al. 2009). Furthermore, at the end of 2010 the station calibration coming operational and all the 36 station Dutch stations available, new observations should be able to reach two orders of magnitude deeper. This will be truly spectacular.

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