1. Overview

This proposal is concerned with the study of large samples of Active Galactic Nuclei (AGN), their evolution, properties, and relation to their host galaxies, over the bulk of cosmic time. In recent years it has become clear that AGN play a key role in galaxy evolution, with AGN outflows being responsible for controlling or terminating the star formation of their host galaxies (see review by Cattaneo et al. 2009). To properly understand the detailed process of galaxy formation and evolution – indeed even to explain the most basic parameters such as the galaxy luminosity function – there is an urgent need to identify and quantify the physical processes involved in ‘AGN feedback’, as well as to determine the influence of the AGN on their larger-scale environment.

Significant progress towards this end has been made in recent years, through studies in the local Universe, but to fully quantify the effect of AGN it is necessary to probe lower luminosity radio samples locally, and to extend such studies back to earlier cosmic epochs where the AGN and star-formation activity of the Universe peaked. This requires deep surveys and, equally importantly, large sky-area coverage in order to adequately sample the rarest environments. With LOFAR’s transformational increase in radio survey speed, it is ideally suited to satisfy these requirements. In addition, the low radio frequency of LOFAR is extremely valuable because, although there are many complications in the physics of radio sources, it remains crudely true that the observed (as opposed to intrinsic) duty cycle of radio activity increases with decreasing frequency: this is because of the longer synchrotron lifetimes of the lower-energy relativistic particles at lower frequencies.

The ‘AGN evolution and black hole accretion history’ working group forms part of the LOFAR Surveys Key Project (LSKP) and will primarily make use of the observations planned as part of that Survey; these are detailed in the umbrella proposal by Röttgering et al. The proposed surveys have the sensitivity to detect, over large sky areas, essentially all ‘high-excitation’ (quasar-like) radio-loud AGN to the highest redshifts, the bulk of the low radio luminosity (mostly ‘low-excitation’) AGN to \( z > 2 \), and a large fraction of the ‘radio-quiet’ AGN population. This represents a formidable dataset which, especially when combined with other deep multi-wavelength datasets, opens up a wide-range of scientific opportunities for AGN evolution studies. Our working group represents a large international team, whose interests in the study of distant AGN are extremely broad (too much so to do full justice to them in just 5 pages). Therefore in this proposal we restrict our attention to highlighting four of the most important science goals of the team: we will measure the evolution of black hole accretion over most of cosmic time; we determine the nature of the different accretion processes, study the properties of AGN host galaxies, and investigate the role of AGN feedback for galaxy evolution; we will investigate the influence of galaxy environment on AGN activity and AGN feedback; and, we will study the evolution of radio sources, and their interactions with the intergalactic medium, from their births to their deaths. We also briefly list a subset of other issues that the team will address.

Some of our science goals require the largest possible sky area coverage, but most require both very deep LOFAR observations and the availability of high-quality multi-wavelength datasets across a broad range of the electromagnetic spectrum. For this reason a significant focus of the effort of this working group will be on the Tier 2 and Tier 3 levels of the proposed LOFAR Surveys; we discuss the choice of ‘blank–field’ survey regions, and the ancillary data available in these fields that will enable us to achieve our goals.

Finally, we outline the management of the working group, and its relation with the LSKP.
2. Science goals: AGN evolution and black hole accretion history

2.1 The cosmic accretion history of black holes

AGN activity – i.e. black-hole growth – occurs in at least two different modes, each of which may have an associated feedback effect upon the AGN host galaxy (cf. Cattaneo et al. 2009):

(i) a fast accretion mode associated with quasars (e.g. Silk & Rees 1998); this radiatively–efficient accretion mode may be important in curtailing star formation at high redshifts and setting up the tight relationship between black hole and bulge masses observed in the nearby Universe (e.g. Magorrian et al. 1998).

(ii) a radiatively–inefficient slow accretion mode (e.g. Croton et al. 2006, Bower et al. 2006), the observational manifestation of which is low-luminosity radio sources; this mode is thought to be responsible for maintaining elliptical galaxies at lower redshifts as ‘old, red and dead’ (e.g. Best et al. 2006) and for preventing strong cooling flows in galaxy clusters (e.g. Fabian et al. 2003).

One of the most fundamental issues in understanding the role of AGN in galaxy formation is the need to accurately measure the cosmic evolution of quasar activity and the accretion history of the Universe, and to compare this with the build-up of the stellar populations of galaxies: do black holes and their host galaxies grow co-evally, or does one preceed the other?; what is the primary mode of black hole growth? Much of the growth of black holes is believed to occur in an obscured phase, and these ‘Type-2’ AGN are difficult to identify: differently-selected samples give substantially different estimates of how the fraction of obscured AGN changes with both luminosity and cosmic epoch. At present, the preferred method for finding distant radio-quiet AGN is X-ray selection, but even the deepest current observations (e.g. the Chandra Deep Fields) cannot probe deeply enough to find the heavily absorbed sources which Cosmic X-ray Background synthesis models predict exist in abundance (e.g., Gilli et al. 2007); they also lack the areal coverage necessary to probe the bright end of the AGN luminosity function. This strongly suggests that most high-z quasar activity has yet to be detected directly.

The radio waveband offers an alternative route to identifying these distant AGN: ‘radio-quiet’ quasars are not radio-silent and their radio luminosity distribution peaks at about $L_{1.4\text{GHz}} \approx 10^{23}$ W Hz$^{-1}$ (e.g. Cirasuolo et al. 2003) – the effective limit reached by the Tier 2 LOFAR surveys at $z \sim 2$. LOFAR’s wide field of view, sensitivity, and the fact that radio wavelengths are not absorbed by dust and gas, mean that the proposed LOFAR surveys offer a method of identifying large numbers of these AGN, irrespective of whether or not they are obscured at other wavelengths.

The relative contribution of radio-quiet AGN to the faint radio source population remains a controversial issue – indeed, one of the primary goals of this working group will be to combine the LOFAR data with deep multi-wavelength data to accurately quantify the population mix at sub-mJy flux densities. Recent observational results (Simpson et al. 2006; Smolčić et al. 2008; Seymour et al. 2008) have indicated that a large fraction ($\sim 30\%$) of the radio source population with flux densities $50 \mu\text{Jy} \lesssim S_{1.4\text{GHz}} \lesssim 300 \mu\text{Jy}$ (corresponding to $S_{120\text{MHz}} \approx 1 \text{mJy}$) are ‘radio-quiet’ AGN with quasar-like luminosities. Above this range, radio-loud AGN dominate the source counts, while below it, the population is increasingly dominated by distant star-forming galaxies. These results are consistent with the model predictions of Jarvis & Rawlings (2004) and Wilman et al. (2008) for the faint radio source sky. Figure 1 shows the model predictions for the numbers of radio sources of different types that will be detected in the LOFAR Tier 2 survey; more than $10^5$ radio-quiet AGN will be found, over half of which will be at $z > 1$. These will be used to determine the cosmic evolution of quasars, the history of radiatively-efficient accretion in the Universe, the link with star formation, and the dependence on environment, many years before next generation hard X-ray missions.

2.2 The role of low-luminosity radio sources in galaxy evolution

It is now becoming widely accepted that there exists a population of low luminosity radio sources which show little evidence for radiative emission from an accretion disk, and in which the bulk of the accretion power is channelled into the expanding radio jets (e.g. Merloni & Heinz 2007; Hardcastle et al. 2007). These are distinct from the high-excitation (quasar-like) radio sources in their luminosity function, Eddington accretion ratios, host galaxy properties, and possibly cosmic evolution (at given radio luminosity; e.g. Best & Heckman 2012). Their radio jets pump energy into their environments, inflating cavities and bubbles in the surrounding inter-galactic and intra-cluster medium (cf. Figure 2). The high angular resolution offered by Chandra has
enabled such cavities to be detected in a large number of systems, from galaxy to cluster scale, and for the energy associated with the radio jets to be estimated from the mechanical energy required to inflate the cavities (e.g. Cavagnolo et al. 2010). In a small number of nearby systems which can be studied in detail, the energies estimated for the radio source agree well with the Bondi accretion rates expected from the hot hydrostatic gas haloes surrounding the galaxies (e.g. Allen et al. 2006); this suggests that this hot gas forms both the fuel for the radio source, and the repository of its energy, offering the potential for a feedback cycle.

Studies of low-excitation radio-AGN in the nearby Universe have shown that the fraction of galaxies that host radio–loud AGN (with $L_{1.4\,\text{GHz}} > 10^{23}\,\text{W Hz}^{-1}$) is a strong function of stellar mass, rising from nearly zero below a stellar mass of $10^{10}M_\odot$ to more than 30% at stellar masses of $5 \times 10^{11}M_\odot$ (e.g. Best et al. 2005; Janssen et al. 2012; see Figure 3a). Combining this relation with estimates of the mechanical energy output associated with radio–loud AGN activity, the time–averaged energy output associated with recurrent radio source activity can be calculated in a galaxy of given mass: as shown in Figure 3b, for massive elliptical galaxies the radio–source heating roughly balances the radiative energy losses from the hot gas surrounding the galaxy. This offers observational evidence that radio-AGN activity may indeed be able to control the rate of growth of galaxies.

How does this relation between galaxy mass and radio-AGN fraction (the radio source duty cycle) evolve with redshift? Out to what redshift does AGN-heating continue to balance cooling? How does the total energetic output of low-luminosity AGN evolve? The answers to these fundamental questions remain uncertain, due to the lack of sensitive radio surveys over sufficient sky volume to properly probe the low radio luminosity population beyond $z \sim 0.5$. The LOFAR Tier 2 surveys have the sensitivity to detect sources with $L_{1.4\,\text{GHz}} \approx 10^{23}\,\text{W Hz}^{-1}$ right out to $z \approx 2$, the peak epoch of galaxy formation. At these redshifts, the sky area for which the Tier 2 survey data overlaps with the high-quality ancillary multi-wavelength datasets (several tens of square degrees) probes a cosmic volume equivalent to that of the local Universe studies.

**2.3 The importance of galaxy environment**

The environment in which a galaxy resides is one of the most important factors influencing its evolution. In the nearby Universe, star formation is strongly suppressed in dense environments (e.g. Lewis et al. 2002), an effect which remains true out to at least redshift one (e.g. Sobral et al. 2011), although it diminishes with redshift with hints that it disappears altogether at $z \sim 2$ (Kodama et al. 2007). Do AGN play any role in this environmental dependence? – it has been argued, for example, that a single powerful radio outburst in one galaxy of a forming cluster may lead to a synchronized shutdown of both star formation and black hole activity throughout the cluster (Rawlings & Jarvis 2004). If AGN do play a role, where precisely in terms of epoch and environment does AGN feedback begin to become important?

Studies using clusters selected from the SDSS data suggest that, locally, the radio–AGN feedback is stronger in richer environments: brightest cluster galaxies have a much higher duty cycle of low-luminosity radio-AGN activity than other galaxies of the same mass (e.g. Figure 3a). Towards moderate redshifts ($z \sim 0.5$–1) there are indications that low-luminosity radio-AGN lie in denser environments than their more luminous quasar counterparts (both from direct environment estimators, e.g. Tasse et al. 2008, and as determined through their cross-correlation properties, e.g. Donoso et al. 2009), although such surveys do not have the sensitivity to detect the majority of the low luminosity radio population.

In order to probe how the relationship between environment and AGN activity evolves to earlier cosmic epoch, it is necessary to study sufficient sky area to include the full range of galaxy environments. As indicated in Figure 4, this requires areas of several tens of square degrees, as will be provided by the overlap regions between the LOFAR Tier 2 surveys and the complementary multi-wavelength datasets.

**2.4 The growth of radio sources, their duty cycle, and interactions with the intergalactic medium**

Radio sources undergo considerable evolution throughout their lifetimes, as the jets blast their passage through the intergalactic medium. They begin life as compact, synchrotron self-absorbed, sources, known as GPS (Gigahertz Peaked Spectrum) or CSS (Compact Steep Spectrum) sources; they may then grow and evolve into classical double radio sources of either Fanaroff-Riley Class I (FR I, in which the radio jets are disrupted and flare) or Class II (FR II, where the jets remain collimated) morphology; finally, they may reach the opposite end of the radio source lifecycle as giant radio sources, with linear sizes $> 1$ Mpc. Open questions remain
as to whether all GPS and CSS radio sources eventually evolve into FR I / FR II sources or whether some remain short-lived (e.g. Kunert-Bajraszewska et al. 2006; de Vries 2009), what exactly leads to the FR I / FR II morphological divide, and what represent the last stages of evolution of radio sources.

A fuller description of these issues can be found in the ‘Physics of Nearby AGN’ proposal by Morganti et al. In our working group, the focus will be on investigating how the radio source populations evolve across cosmic time: how do the radio luminosity functions of different radio morphology classes (compact, FRI, FRII, hybrid) evolve with redshift, and what light does this shed on the inter-relationships between the populations?; how do the numbers, luminosities and characteristics of distant CSS and GPS sources compare with radio source evolution models?; can giant radio sources be identified at moderate to high redshifts? – if so, then they can be used to probe the cosmic evolution of the Mpc-scale intergalactic medium; can we detect previous radio outbursts around detected AGN (especially ‘radio-quiet’ quasars, which may indicate a radio-loud / radio-quiet duty cycle like that seen in X-ray binary systems, e.g. Fender et al. 2004), identify dying radio sources where the radio jet has switched off but the lobe electron population continues to radiate with a very steep radio spectrum, and quantify the prevalence of re-started (double-double) sources? For all of these goals, LOFAR’s sensitivity and low-frequency of operation will be critical issues.

2.5 Other science goals

- We will accurately determine the luminosity dependent evolution of the radio luminosity function down to radio luminosities an order of magnitude below previous studies (e.g. Rigby et al. 2011, Simpson et al. 2012), and with a sample ~100 times larger.
- We will study how the Type-1 / Type-2 AGN fraction evolves as a function of both luminosity and redshift.
- We will study the low-frequency spectral index properties of large samples of AGN, to find synchrotron self-absorbed sources and search for any low-frequency cut-off in the electron energy distribution.
- We will compare the LOFAR data with sub-mm and far-IR surveys (e.g. SCUBA-2, Herschel) to identify and study large samples of dust-enshrouded AGN.
- We will combine LOFAR and X-ray data to investigate the fundamental plane of black hole activity.

3. The LOFAR surveys and multi-wavelength datasets

3.1 The LOFAR surveys

The area, depth and frequency coverage of the LOFAR Surveys are described in the umbrella project by Röttgering et al. The Tier 1 (2π) survey will be exploited for some science goals, particularly the identification of peaked-spectrum sources, dying radio sources and giants. However, the primary focus for much of the work of this working group will be the Tier 2 surveys, which include 25 ‘blank-field’ pointings down to an rms noise level of $S_{150\text{MHz}} = 20 \mu\text{Jy}$, over the 120-180 MHz frequency range. The blank-fields have been chosen to be the regions where the best degree-scale ancillary datasets are available, as these are essential to identify the radio sources, facilitate the separation of AGN from star-forming galaxies, obtain photometric redshifts, measure bolometric AGN luminosities, and allow a wide range of the science goals to be addressed.

In Table 1 we present the proposed choice for these Tier 2 blank fields. Some of these fields are at low declination: should on-going commissioning work indicate that the performance of LOFAR (ionospheric calibration, dynamic range limitations) is not sufficiently high at these declinations, they will be replaced by alternative northern fields. We note that we can also make valuable use of the outer regions of the Tier 2 pointings centred on nearby galaxies and clusters (described in the proposals led by Conway/Chyzy and by Brüggen/Brunetti respectively), as well as the deeper Tier 3 data (see the proposal of Lehnert/Barthel).

The addition of international baselines to these deep LOFAR pointings will be extremely beneficial. The sub-arcsec angular resolution that these offer would not only provide morphologies for the detected sources (valuable for distinguishing different source populations), but also be well-matched to the optical/near-IR images, greatly facilitating the issue of cross-matching and identifying the radio sources (NL-only LOFAR observations would be close to the confusion limit at these depths, complicating the process).

3.2 Existing and forthcoming multiwavelength data

To address many of our science goals requires an overlap between the Tier-2 LOFAR Surveys and ancillary multi-wavelength datasets of ideally around 100 square degrees. The choice of Tier 2 fields has been designed
to maximise the scientific potential by drawing together survey areas with different combinations of available multi-wavelength data. This means that different fields will be best-suited for different science goals. The fields broadly fall into three categories.

First, 9 individual fields have been chosen which have the highest-quality multi-wavelength data over degree–scale regions. Wide and deep multi-band optical data is available in each field, from either the deep fields of the PanSTARRS survey (of which the PI is a member; 7deg$^2$ each), the CFHT wide-area survey (>10 deg$^2$), the NOAO deep and wide field survey (9deg$^2$ field), or mosaicked pointings with Subaru SuprimeCam. In many fields multi-band near-IR data is available over ∼5deg$^2$ degree regions from either the UKIDSS DXS or the VISTA VIDEO survey, and the Spitzer SERVS survey provides 3.6 and 4.5µm IRAC data over 2–4 deg$^2$. At other wavelengths the fields have different available datasets (see Table 1 for details): mid-IR from Spitzer SWIRE, deep Akari, or Herschel HerMES; UV from Galex; X-rays from XMM or Chandra; sub-mm from the SCUBA-2 Cosmology Legacy Survey. Many of the fields also have existing deep radio data, especially with the GMRT at 610 MHz and/or the VLA at 1.4 GHz, which will be a valuable addition to the radio frequency coverage. Although the extent of the multi-wavelength datasets in these fields is such that they generally do not fill the entire LOFAR primary beam, they do fill a significant fraction of it, and in combination these fields offer ∼30deg$^2$ of overlap between the deep LOFAR surveys and the highest quality ancillary data.

Second, we propose a contiguous 8-field region (∼50deg$^2$) within the Herschel-ATLAS northern area. H-ATLAS is the largest-area Herschel survey, offering a uniquely powerful ancillary dataset. It is fast becoming one of the most important extra-galactic fields for future large-scale surveys, with ongoing follow up at optical, near-IR and radio wavelengths, amongst others. As an additional benefit, it contains the Coma cluster.

Third, we propose to observe a series of 8 fields (∼50deg$^2$) along the strip of the Hobby Eberly Telescope Dark Energy Experiment (HETDEX) spectroscopic survey. HETDEX will measure redshifts for over 200,000 Lyα-emitting galaxies between 1.9 < z < 3.5 in this sky area over the period of the LOFAR Surveys, as well as a comparable number of lower redshift galaxies. This will be an unparalleled resource for many of our science goals.

### 3.3 LOFAR's first six month observing period.

Although the ultimate science issues raised in this proposal require the wide-area deep surveys that the LSKP will eventually provide, many can begin to be addressed using shallower surveys in conjunction with the multi-wavelength datasets in the Tier 2 sky regions. Therefore, in the first 6-month call for LOFAR proposals, it is anticipated that a request will be made to observe a subset of the Tier-2 fields down to the depth of the Tier 1 shallow survey.

### 4. Management of the working group, and the LSKP

The LSKP has been set up to plan, conduct and exploit the LOFAR Surveys. As described in the umbrella proposal by Röttgering et al., the overall Surveys team has been split into a number of science working groups, of which our team is one. Our working group will collaborate closely with other working groups of the LSKP, in particular: (i) the ‘Physics of nearby AGN’ team led by Morganti, who will provide a fundamental understanding of the on-going physical processes in nearby AGN, which can then be applied to our larger distant samples; (ii) the ‘Distant radio galaxies’ team led by Miley, who aim to study the very high redshift AGN within the LOFAR samples, providing a natural extrapolation of our work to earlier cosmic times; (iii) the ‘Cosmic Star Formation history’ team led by Lehnert and Barthel, who will study LOFAR-selected star forming galaxies at the same redshifts as our AGN. The PI is a member of all three of those other teams, and many CoIs also offer cross-links, ensuring good co-ordination between the different science working groups.

Members of our working group will play very active roles in the overall execution of the LSKP at all stages of the process (preparation, development of data reduction tools, data processing, catalogue production, cross-matching with multi-wavelength datasets, scientific analysis, follow-up observations). Many members are already active in the analysis of LOFAR commissioning data. Other members of the team have access to the various multi-wavelength surveys which are essential to our science goals. The working group will be organised into sub-teams with responsibilities for different aspects of the exploitation; the PI will take overall responsibility for establishing these teams and co-ordinating the different tasks, in collaboration with the core team of the LSKP and the leaders of the other science working groups.
Fig. 1: The number of sources predicted to be detected in the Tier 2 LOFAR survey from the models of Jarvis & Rawlings (2004), split into the various radio source sub-populations. The solid line represents the star-forming galaxies, the dot-dashed line represents the radio-quiet quasars, the dashed line shows the FR I radio galaxies and the dotted line denotes the FR II radio galaxies.

Fig. 2: Bubbles and cavities inflated by the low luminosity radio source Perseus A in the intra-cluster medium of the Perseus cluster. Note also the ‘relic’ outer bubble in the north-west corner of the image, in which no radio emission is currently detected. LOFAR’s low frequency of operation may enable a radio detection of this previous outburst, offering constraints on the radio source duty cycle.

Fig. 3: Left – the fraction of galaxies in the local Universe which host radio–loud AGN, as a function of their stellar mass; this is a remarkably strong function of mass, and is boosted for brightest cluster galaxies (from Best et al. 2005, 2007). Right – the radio-AGN heating versus radiative cooling balance in elliptical galaxies (from Best et al. 2006). The data points show bolometric X-ray luminosity ($L_X$; the rate at which elliptical galaxies radiate energy from their hot gas haloes), vs optical luminosity ($L_B$) for elliptical galaxies from the sample of O’Sullivan et al. (2001). The large filled circles show the mean values of $L_X$ for galaxies in 5 bins of $L_B$. The solid line shows the prediction for the amount of heating produced by recurrent radio-loud AGN activity: this balances radiative cooling losses remarkably well, across the full range of optical luminosities (masses).
Fig. 4: A slice of the Universe at $z = 2$, from the GALFORM semi-analytic models (Benson et al. 2000). Galaxies are shown distributed on the underlying density field and are size-coded on the basis of the luminosities of their stellar populations. These simulations illustrate the early formation of galaxies in the highest density regions which go on to form the passive cores of rich clusters at the present-day. The boxes indicate regions of one square degree, illustrating the cosmic variance on this scale, and the need to cover tens of square degrees in order to sample a fair volume of Universe and include the full range of galaxy environments.

Table 1: Details of the 25 proposed blank-fields for the Tier 2 of the LOFAR Surveys, and a description of associated multi-wavelength data in these fields over degree–scale areas.

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<th>Dec</th>
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References