LOFAR2.0 White Paper - v2023.1

A premier low-frequency radio telescope for the 2020s

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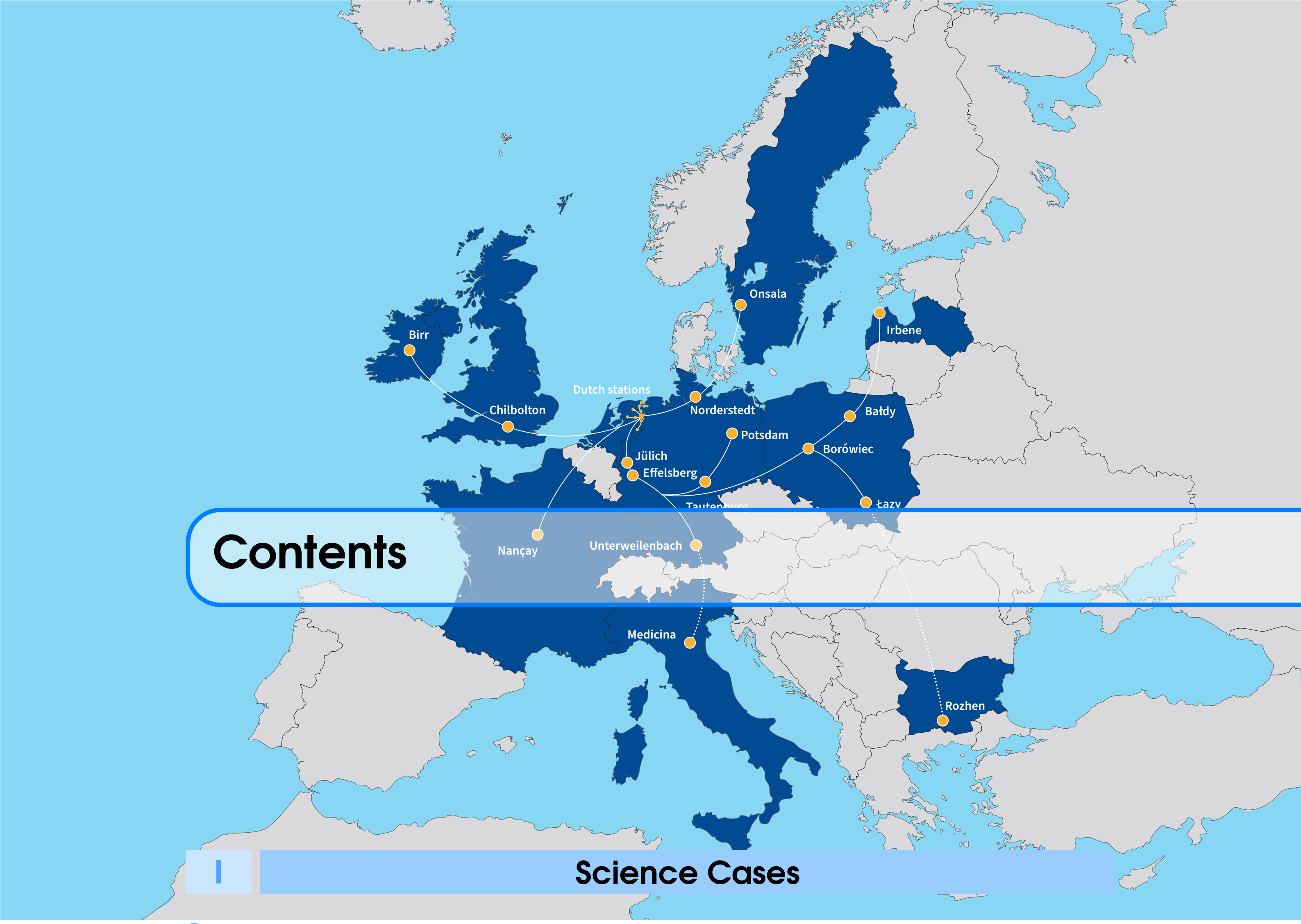

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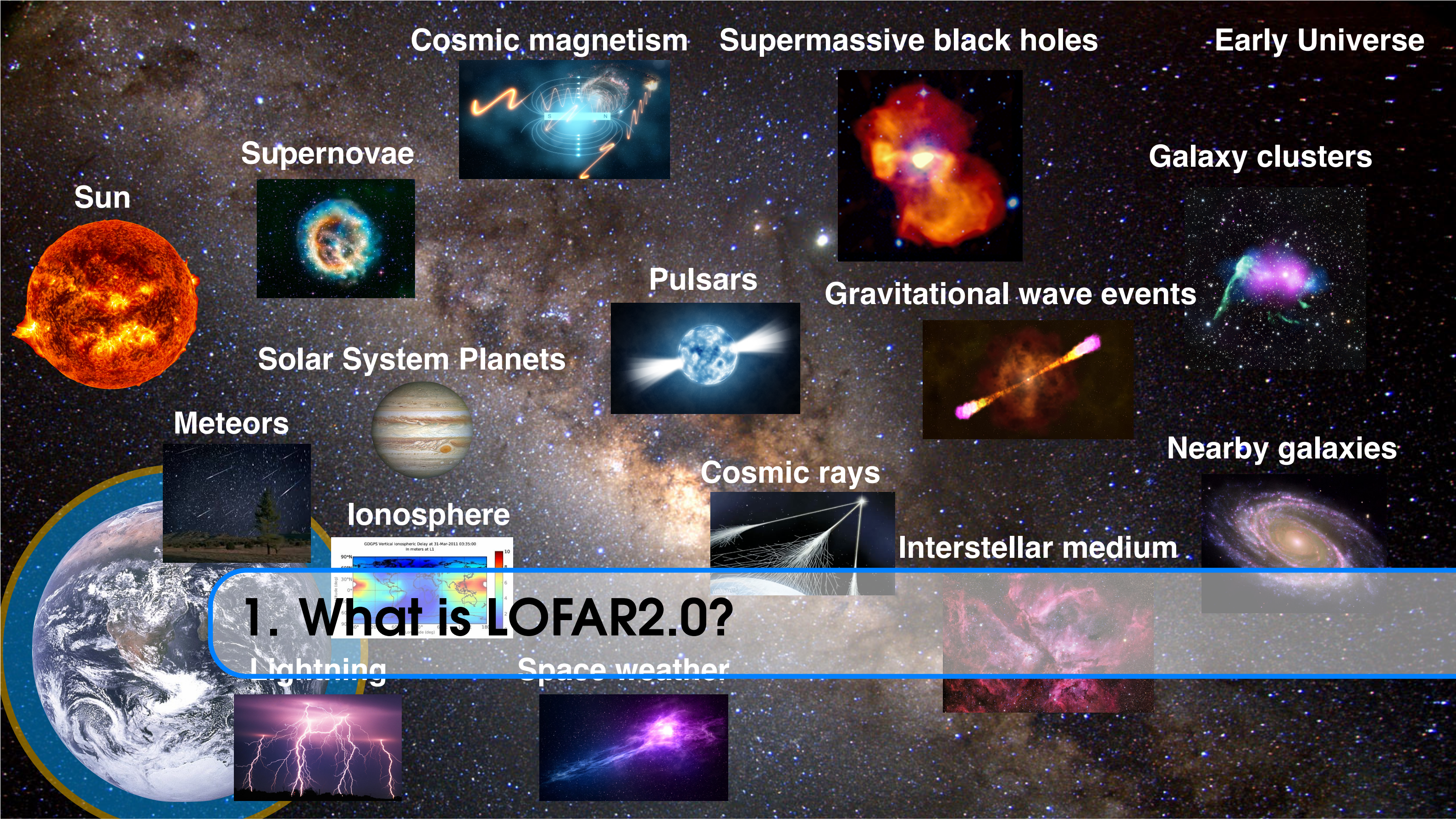


1. What is LOFAR2.0?

The International LOFAR Telescope

The LOw Frequency ARray (LOFAR) is the world's largest and most sensitive low-frequency radio telescope (Figure 1.1). It is a network of geographically distributed antenna stations, each containing hundreds of dipole antennas. LOFAR stretches across Europe, from Ireland to Latvia, with a dense 'Core' and 38 stations distributed throughout the Netherlands, as well as 13 **larger collecting area** stations located in the 8 partner countries that have joined the project since its inception. The pan-European array is called the International LOFAR Telescope (ILT).

Astronomy studies electromagnetic radiation produced by cosmic sources. Different wavelengths of the spectrum — from low-energy radio waves, like observed with LOFAR, up to high-energy gamma-rays — provide complementary information about the Universe and its constituents, including diagnostics of diverse physical processes. LOFAR is opening one of the last unexplored regions of the spectrum: very low radio frequencies.

LOFAR has given astronomers their best-ever tool to study the Universe using the lowest-frequency radio waves visible from Earth. While most classical radio telescopes collect radiation using large, steerable dishes, LOFAR is a 'digital phased array' that has no moving parts. Instead, radio waves are received by a network of fixed antennas that are grouped into stations, each the size of a football pitch, and which are 'steered' by applying delays before combining the signals. LOFAR employs two types of antennas: the low-band antennas (LBAs) are sensitive between 10 – 90 MHz, whereas the high-band antennas (HBAs) are sensitive from 110 – 240 MHz. These antennas are concentrated in the Netherlands, but the full International LOFAR Telescope also spreads $\sim$ 2000 km across Europe to provide imaging at resolutions comparable to that of the *Hubble Space Telescope*. The stations are linked to a central computing infrastructure in Groningen, the Netherlands, via a high-bandwidth fibre network. There, the signals are 'correlated' to make images of the sky. A central computing power of hundreds of Teraflops and a temporary storage facility of 2 Petabytes are needed to correlate in real-time with an incoming data stream of 230 Gbit/s. The LOFAR Long Term Archive hosts tens of Petabytes of data across multiple high-performance computing sites.

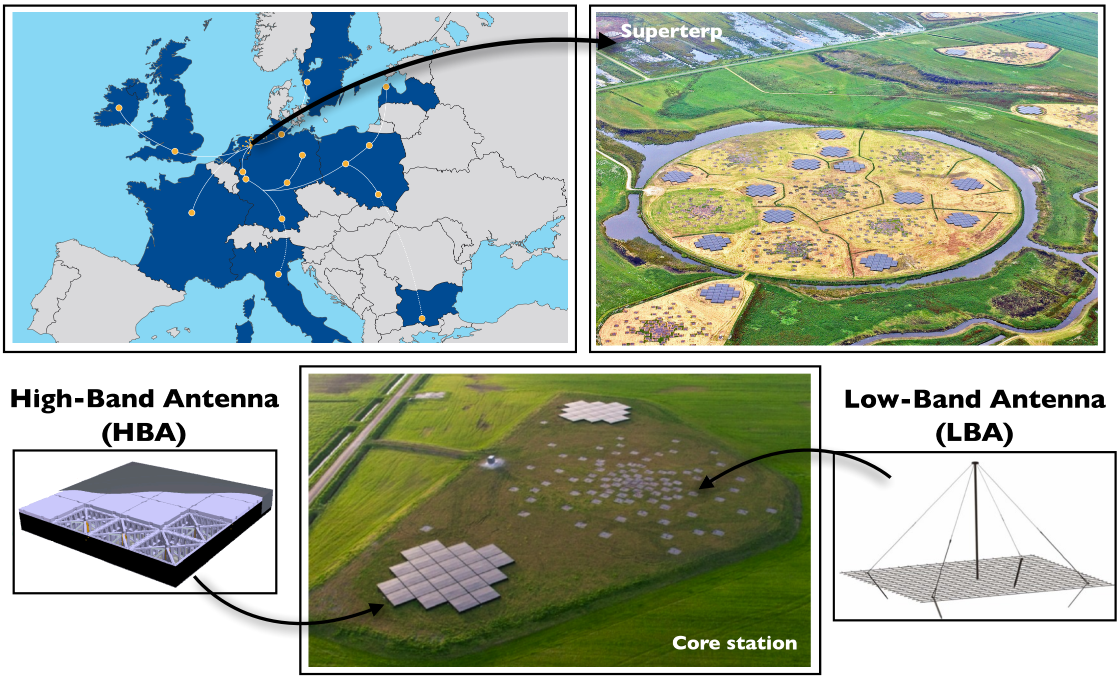


Figure 1.1: The International LOFAR Telescope.

LOFAR is a unparalleled low-frequency radio telescope. LOFAR is also the largest continuously operating radio astronomical infrastructure in Europe, and was highlighted as a scientific cornerstone of European radio astronomy in the recent report of the European Radio Telescope Review Committee (ERTRC[1]). This report was commissioned by the FP7-funded ASTRONET consortium in order to identify which major European radio telescopes are important for addressing the key questions of the Science Vision strategic roadmap for astronomy in Europe. LOFAR received top marks compared to all other European radio telescopes in terms of its ability to address the ASTRONET Science Vision questions. Efforts are now also underway to solidify the international LOFAR partnership under the umbrella of a European Research Infrastructure Consortium (ERIC).

The LOFAR 2.0 Programme

LOFAR2.0 is a coordinated set of staged upgrades that will keep LOFAR cutting-edge well into the 2020s. These enhancements are being implemented from 2021-2024, and together will provide a step function in LOFAR's overall scientific capabilities. LOFAR will continue to be unique and world-leading, with an angular resolution $> 10\times$ higher than that of the planned Square Kilometre Array low-frequency component (SKA-Low), and also accessing the largely unexplored spectral window below 50 MHz.

After ~ 10 years of algorithm and software development, the LOFAR community has successfully tackled the enormous challenge of automatically producing radio images that achieve the instrument's full theoretical sensitivity in the range of $110 - 190$ MHz (the LOFAR high-band). In many ways, this has required a reinvention of the way we analyze such data, because ionospheric disturbances and LOFAR's large field-of-view require innovative calibration techniques.

These cutting-edge imaging techniques are enabling LoTSS, the LOFAR Two-meter Sky Survey[134], by far the deepest (0.1 mJy/beam sensitivity) and highest-resolution ($5''$) wide-area

[1] https://www.astronet-eu.org/sites/default/files/d5.10_1.pdf

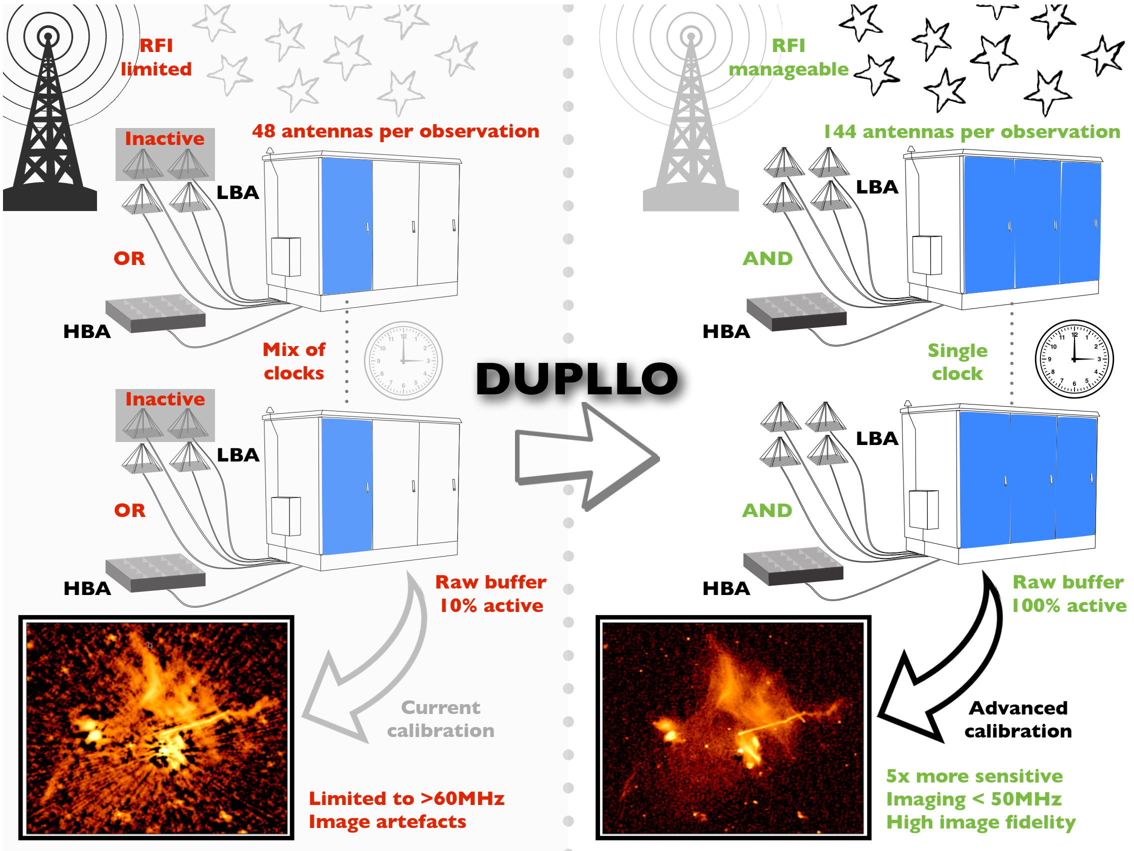


Figure 1.2: Schematic of the DUPLLO upgrade project.

survey ever conducted at radio frequencies. In parallel, there have recently been demonstrations of automatic pipeline imaging of the full LOFAR including international baselines of both selected multiple objects within the field of view and of the whole field of view. The next major challenges for LOFAR are to enable full-sensitivity imaging at $10-90$ MHz (across the LOFAR low-band), to fully exploit the $0.2-1$ arcsecond imaging afforded by the international baselines, and to use the full complement of available antennas simultaneously and for commensal observations.

We now briefly describe the expected technical capabilities enhanced by the different sub-components of the LOFAR 2.0 upgrade programme.

DUPLLO (Digital Upgrade for Premier LOFAR Low-band Observing): DUPLLO will maximally utilize the existing LOFAR infrastructure and technical accomplishments to date to transform the science of very-low-frequency radio astronomy. To do this, we need to replace the computational 'brains' in the LOFAR stations. Each Dutch LOFAR station contains 96 LBAs and 48 HBAs; the international LOFAR stations contain 96 LBAs and 96 HBAs. Due to limitations in the electronics capacity at each station, it is currently only possible to use 48 (Dutch stations) or 96 (international stations) antennas in any single LOFAR observation. With DUPLLO, we will triple the computational capacity of the Dutch LOFAR stations and allow all antennas to be used simultaneously. This provides two complementary approaches that provide jumps in the low-band sensitivity: 1) with $2\times$ as many active LBA elements, we have $\sim 2\times$ as many sources bright enough to characterize and correct ionospheric distortions (low-risk approach) and 2) with simultaneous LBA+HBA information, we can apply the ionospheric corrections derived from the

HBA, where more calibrator sources are available, to the LBA data (this is an innovative but riskier approach). Furthermore, DUPLLO will enable the distribution of a single-clock signal to all Dutch LOFAR stations, which greatly increases the robustness and precision of ionospheric calibration by separating these effects from clock errors. Using this three-pronged approach, DUPLLO will provide a step function in LOFAR's capabilities in the $10-90$ MHz range (Figure 1.2): At ~ 60 MHz, we aim for sensitivities of 1 mJy/beam rms noise (in an 8-hr integration, and even during non-ideal ionospheric conditions), and at ~ 30 MHz, we aim for 5 mJy/beam rms noise. For most fields, this will improve the sensitivity by a factor of roughly five compared to the current system. Just as importantly, the greatly enhanced calibration afforded by DUPLLO will enormously improve the fidelity of the images, which presently suffer from ionosphere-induced artifacts. As a significant bonus, DUPLLO will also provide a 24/7 system for cosmic ray, lightning and transient triggering; currently that is only possible in dedicated observations, but with the new system it will be possible to continuously feed the LOFAR Transient Buffer Boards with raw antenna data from both the LBAs and HBAs. Additionally, the increased computational capacity at the stations can also be used to form more beams on sky — though at the expense of running both LBA and HBA simultaneously, since the data transfer rate to each station is limited to 10 Gbit/s. This can be used to double the survey speed and provide matching between the field-of-view of Dutch and international stations.

COBALT 2.0 (Version 2.0 of the Correlator and Beam-former for the LOFAR Telescope): COBALT2.0, a CPU/GPU computing cluster that is the central 'brain' of LOFAR, is already running and provides an order-of-magnitude increase in computational capacity compared to its predecessor. Extensions to the correlator/beam-former code allow much more flexible options for parallel observations, which can use different station sets and provide imaging and high-time-resolution beam-formed data in parallel. This will allow LOFAR to use more of the information that is already arriving from the stations at COBALT2.0 and to run multiple science cases commensally.

TMSS (Telescope Manager Specification System): TMSS will be a brand-new software application for the specification, administration, and scheduling of LOFAR observations. Its realisation is crucial, as it will enable the required support for LOFAR2.0 use cases, while also streamlining LOFAR operations and improving the adaptability and maintainability of software for future extensions. This is being realized by a team of software engineers and telescope scientists who are very committed to make the project a success. TMSS is an important component of the Telescope Manager of LOFAR2.0, the system that will control all aspects of the telescope, including proposal handling, observation execution, and system monitoring.

LOFAR4SW (LOFAR for Space Weather): Many of the technologies upon which we increasingly rely, such as satellite communication and navigation systems, can be strongly affected by conditions in interplanetary space, driven by the solar wind carrying with it the interplanetary magnetic field (IMF), and large ejections of solar material known as Coronal Mass Ejections (CMEs). Full-time monitoring of this highly variable space weather is essential to both advance our physical understanding of it and improve the models used for the forecasts necessary for technology operators to mitigate its effects. LOFAR4SW is a design project which aims to use the existing LOFAR hardware as an independent system for space weather purposes, in parallel with radio astronomical observations. The design foresees an extra independent datastream both for the LBA and HBA bands. A key part of the design is to include a second analogue beam for the HBA tiles, to enable them to be pointed in independent directions for simultaneous astronomy and space weather purposes.

INTERNATIONAL BASELINES. The ≈ 2000 km baselines of the International LOFAR telescope are a unique feature of the telescope; and furthermore are expected to remain a unique capability well into the future. These long baselines of LOFAR have for the first time allowed sub-arcsecond resolution imaging at metre wavelength; and it is expected that the next decade will see the full exploitation of this unique capability. Numerous technical challenges have had to be overcome to enable LOFAR international baseline imaging. A number of proof of concept international baseline science results of individual objects have been published over the last decade. More recently however an automated imaging pipeline allowing imaging over wide areas has been developed. During 2021 a ‘paper splash’ of new astronomical results using international LOFAR baselines will appear with most of these new results using the new pipeline.

Recent imaging pipeline development for international baselines has concentrated on two imaging modes: either (1) Separately making multiple small area sub-images at hundreds of positions within the whole field of view, with these positions generally chosen to be centred on compact sources identified in Netherlands resolution imaging; or (2) Imaging the whole international station field of view at international baseline resolution. Large scale exploitation of these techniques (in particular the second) is presently limited by the amount of computer processing required. In the near and medium term future as algorithms improve and as more computer resources become available it is expected that International LOFAR imaging will become a standard technique made use of by all LOFAR users in the coming years. Given that there is significant collecting area in the international stations such international baseline imaging will provide the highest sensitivity for compact source imaging with LOFAR. In addition the international baselines will also allow the most accurate astrometry and the ability to study the sub-arcsecond structure of sources at metre wavelength.

At LBA frequencies the expected full inclusion of the large area Nenufar array at Nancay in the coming years will improve total sensitivity and also make international baseline imaging more robust by adding a second ’superstation’ to the international array in addition to the LOFAR core. Further increases in sensitivity for both LBA and HBA in the coming years are expected from the planned inclusion of new stations (such as the planned Bologna station) and other possible stations in Europe (and perhaps even beyond) that might be locally funded.

The expected increase in science return from international baselines over the coming decade as we move into the LOFAR 2.0 era is expected to come about via a synergy between ongoing efforts (new stations, enhanced computer resources and algorithms) and the specific technical upgrades made as part of the LOFAR 2.0 upgrade. The specific LOFAR 2.0 aspects include the possibility to use the additional LOFAR 2.0 electronics at international stations to form multiple HBA station beams which can then be correlated with Dutch station data so that the field of view of the international baseline more closely matches that of the Dutch stations. This technique will allow the possibility to speed up large area HBA imaging surveys at sub-arcsecond resolution.

The impact of the LOFAR 2.0 technical upgrade on international baseline imaging is however likely to have most impact at LBA frequencies. Firstly, the doubling in sensitivity of Dutch LBA stations and hence the increase in sensitivity of Dutch to international baselines will improve the robustness of international baseline imaging. Secondly, of even more impact, will be the ability to do joint LBA + HBA imaging using the whole ILT at full sensitivity using all of the dipoles in the ILT at once. HBA to LBA phase transfer is expected to be essential to achieving thermal noise limited international baseline LBA imaging over large areas/all of the field of view (rather than only on individual bright compact sources as has already been demonstrated). Simultaneous HBA + LBA full sensitivity observations at international stations will also have impact when using international stations without cross correlation, for instance for probing variations in the ionosphere on thousand km scales and being used to study spatially varying Interplanetary Scintillation and for single station uses such as solar or pulsar monitoring.

Because the potential astrophysical impact of the full exploitation of the international baselines is so wide (both by providing the ultimate LOFAR compact source sensitivity and its ultimate spatial resolution) the different astrophysics themed chapters of this science case incorporate the expected science impacts made possible by international baselines over the coming decade following the

LOFAR 2.0 upgrade. In addition to this Chapter 10 describes the scientific contributions to multiple fields of astrophysics that sub-arcsecond metre wave imaging surveys can make during the coming LOFAR 2.0 era.

LOFAR2.0 Specs

LOFAR2.0 provides simultaneous access to both LBA and HBA data or, optionally, increased FoV for one of the antenna sets. With COBALT2.0, the set of available imaging and beam-formed modes are expanded and can more flexibly run in parallel. The configurability of LOFAR is incredibly flexible in terms of the possible trade-offs between time and frequency resolution as well as sensitivity/bandwidth and FoV[141, 153]. Here we outline only some of the possibilities, to give an overall impression.

LOFAR2.0 imaging can reach 30 μJy/beam (HBA) and 1 mJy/beam (LBA) sensitivity in 8-hr synthesis observations that use the full EU array, with corresponding angular resolution of $0.2''$ (HBA) and $0.5''$ (LBA) and corresponding FoV of $\sim$ 12 deg^2. The standard imaging data products provide full Stokes parameters with 1-s integrations and 3-kHz channels, but higher time/frequency resolution is possible within the constraints of the total maximum $\sim$ 50 Gb/s output data rate from COBALT2.0. For example, visibilities with 10-ms integration time are achievable for up to a dozen stations, and sub-kHz channels can be synthesized given a longer integration time.

LOFAR beam-formed modes provide voltage tied-array beam data (with 5.12 μs and 195.3-kHz resolution) for up to a dozen beams, or up to hundreds of tied-array beams if the time/frequency resolution is downgraded and only Stokes I is stored. With COBALT2.0 the flexibility in forming sub-arrays and running in parallel to imaging observations is significantly increased. Standard tied-array observations combine either the 6 Superterp or 24 Core stations to provide 0.5° or $3'$ (FWHM) beams, respectively. In a 1-hr integration, a full-Core tied-array beam can reach an rms noise level of 0.1 mJy (HBA) and 1 mJy (LBA). Sub-arrays and 'fly's eye' mode allow one to also record multiple station subsets simultaneously; e.g., the full complement of international stations, each pointing in a different direction. With online re-digitization of the data to 8-bit samples, the FoV or time/frequency resolution can also be increased in general.

Additional technical details can also be found in the following tables and figures An overview of the LOFAR stations and antennas is given in Table 1.1. The LOFAR LBA and HBA sensitivities, for a variety of central frequencies, are quoted in Table 1.2.

Table 1.1: Overview of stations and antennas

Station Configurations	# of Stations	LBA dipoles	HBA tiles	Max. baseline (km)
Superterp	6	96	2×24	0.24
NL Core Stations	24	96	2×24	3.5
NL Remote Stations	14	96	48	121.0
International Stations	14	96	96	$\sim$ 2000

The 6 stations comprising the central Superterp are a subset of the total 24 Core stations. Note that the tabulated baseline lengths represent unprojected values. Both the LBA dipoles and the HBA tiles are dual polarization.

LOFAR2.0 Science

The breadth of astrophysics that is currently being studied with LOFAR is impressive. For example, LOFAR-enabled science includes: cutting-edge limits on the signal from the 'Epoch of

Table 1.2: LOFAR sensitivities

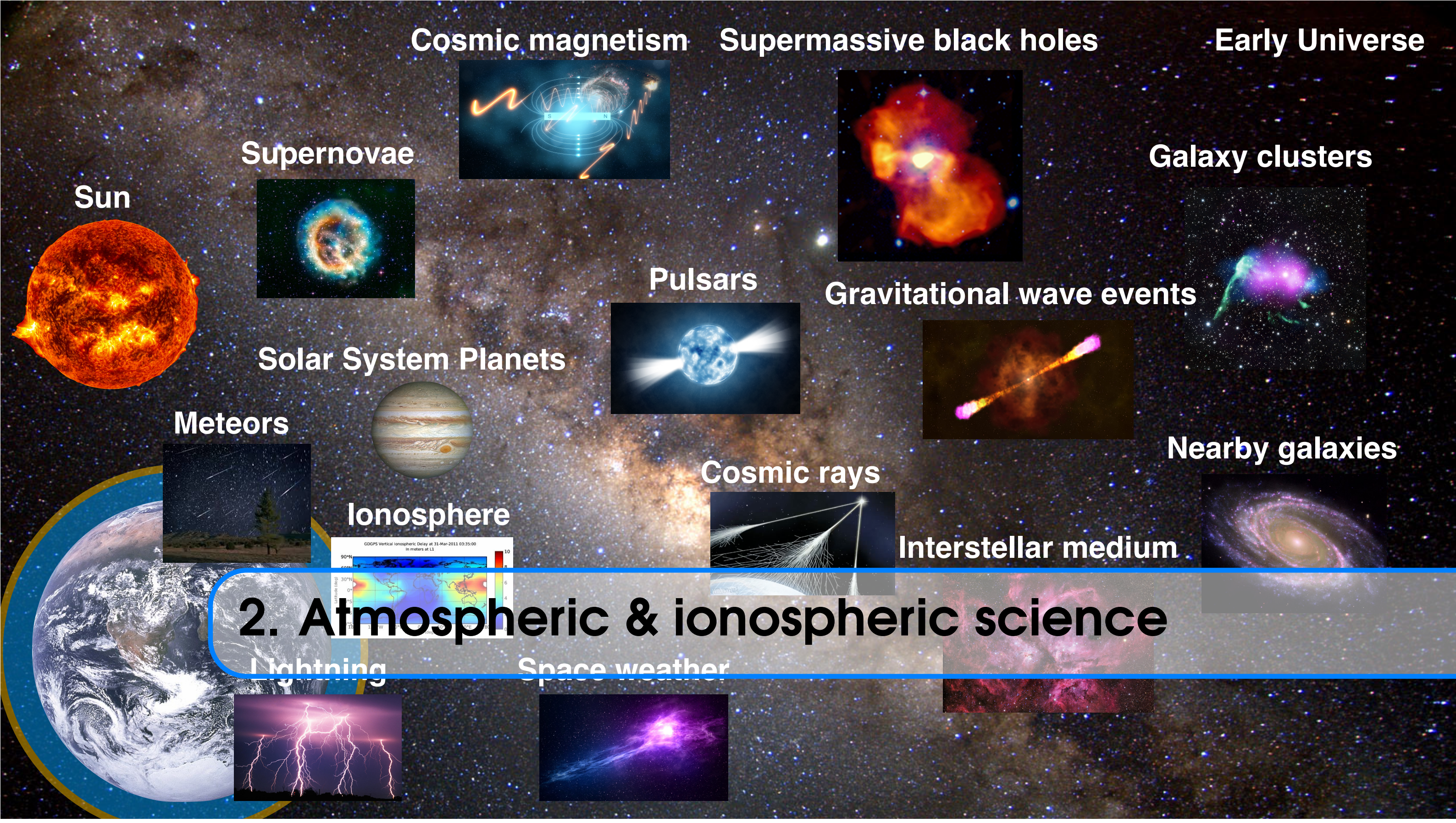
Freq. (MHz)	λ (m)	Sensitivity Superterp (mJy)	NL Core (mJy)	Full NL (mJy)	Full EU (mJy)
15	20.0	...	...	...	...
30	10.0	36	9.0	5.7	3.8
45	6.67	29	7.4	4.7	3.1
60	5.00	25	6.2	3.9	2.6
75	4.00	44	10.8	6.8	4.5
120	2.50	1.5	0.38	0.30	0.20
150	2.00	1.3	0.31	0.24	0.16
180	1.67	1.5	0.38	0.30	0.20
200	1.50	(2.5)	(0.62)	(0.48)	(0.32)
210	1.43	(2.5)	(0.62)	(0.48)	(0.32)
240	1.25	(5.6)	(1.4)	(1.1)	(0.73)

The quoted sensitivities are for image noise calculated assuming 8 hours of integration and an effective bandwidth of 3.66 MHz (20 subbands). The sensitivities are based on the zenith SEFD's derived from 3C295 in the Galactic halo[153]. These values assume a factor of 1.3 loss in sensitivity due to time-variable station projection losses for a declination of 30 degrees, as well as a factor 1.5 to take into account losses for "robust" weighting of the visibilities, as compared to natural weighting. Values for 15 MHz have not yet been determined awaiting a good station calibration. Similarly values at 200, 210, and 240 MHz should be viewed as preliminary and are expected to improve as the station calibration is improved. The procedure for determining these values along with associated caveats are discussed in more detail in van Haarlem et al. (2013)[153].

Reionization' when the first stars reionized the Universe[88]; unique insights into the composition of the mysterious cosmic rays[17] and the electrodynamics of pulsars[62]; discovery of unpredicted structures in the Milky Way's interstellar medium[69]; and powerful new measurements of the energetics involved in galaxy and galaxy cluster mergers[65]. Beyond the realm of astrophysics, LOFAR has also proven to be a very promising instrument for studying lightning in the Earth's atmosphere[53], turbulence in the Earth's ionosphere[89], and our active Sun[94]. There are over 400 LOFAR publications to date[2] and hundreds of astronomers involved in the LOFAR science teams.

In the following chapters we give an overview of the science that will be done with LOFAR2.0. We discuss science topics starting nearby in our own Earth's atmosphere all the way out to the distant reaches of the early Universe.

[2] `https://old.astron.nl/radio-observatory/lofar-science/lofar-papers/lofar-papers`



2. Atmospheric & ionospheric science

2.1 Lightning

Brian Hare

Amazingly, lightning is still poorly understood. Despite occurring in less than a second, a single lightning flash can propagate over 10's of kilometers, driven by a myriad of meter-scale high-energy processes, none of which are understood. For example, balloon-borne measurements of electric fields have consistently shown that thunderstorm electric fields are an order-of-magnitude smaller than dielectric breakdown. As a result, it is entirely not understood how lightning initiates. After initiation there is an initial stage where the lightning flash extends from a single point into a mature discharge. This stage is exceptionally difficult to observe, and thus is highly controversial in the field. It is known to emit high-energy bursts of gamma-rays that can saturate orbiting observatories, but how this occurs is also not understood. After the initial stage, the lightning flash continues to extend and propagate through the cloud, but its behavior is highly chaotic down to meter-scales, and thus very difficult to probe. LOFAR is the first instrument capable of imaging lightning with the meter-scale resolution needed to reveal the physics behind the basic lightning processes. Unlike any other lightning instrument, LOFAR can record the full raw-voltage traces from the antennas with nanosecond timing accuracy. This facility, combined with the 10 km long baselines, gives LOFAR unprecedented accuracy and resolution. We have used this unprecedented detail to discover entirely new structures on the lightning channels we call needles [53], which we may help solve why individual lightning flashes connect to the ground multiple times. We have also discovered that the radio emission from negatively-charged lightning channels comes in bursts, and the emission region of those bursts is nearly point-like [54]. This has had strong implications for understanding how lightning even emits VHF radiation in the first place, which is amazingly not known. Recent LOFAR observations, however, are starting to show how the radio emission from lightning varies with altitude; theory predicts this change should occur smoothly as response to pressure, LOFAR is showing however that it is more like a phase change and that lightning propagates very differently at high altitudes than low altitudes (work still in progress!).

Highlight 1 LOFAR is the first instrument capable of revealing the meter-scale physics that drives all fundamental lightning processes.

LOFAR 2.0 represents a significant step forward in the lightning science that can be performed with LOFAR. Simultaneous LBA and HBA observations will allow exploration of the frequency spectra of lighting radio emission over a wide band, which should significantly help constrain the physics behind lightning radio emission and propagation. Furthermore, we know that lightning propagation tends to emit bursts of X-rays, which tend to be coincident with higher frequency current pulses in laboratory sparks. Thus, higher frequency observations with HBAs, combined with standard LBA lightning mapping, gives the best opportunity to explore how lightning emits X-rays. In addition, the enhanced station-level electronics will allow for a new continuous observation mode that can observe every flash in a thunderstorm instead of just single flashes at a time. We know that lightning can behave very different in different climates, which limits the science that can be done with the Dutch LOFAR stations. It is possible that international stations could be used to explore lightning in environments that are not accessible to the Dutch stations.

Goal 1 Our end goal with LOFAR is to probe and understand every lightning process, including initiation, propagation, and everything in-between.

2.2 Meteor showers

Cees Bassa, Mark Kuiack, Tammo Jan Dijkema

Interplanetary dust particles – meteoroids – that enter the Earth's atmosphere at high velocity are visible as meteors due to the ablation of the meteoroid by collisions with air molecules in the upper atmosphere. An ionized plasma trail is generated by these collisions, which can persist for several minutes and can reflect terrestrial radio emission (e.g. [0]). Over the past few years, intrinsic, non-thermal radio emission from large meteors (fireballs) has been detected at low radio frequencies (~ 40 MHz) using all-sky imaging with the Long Wavelength Array (LWA; [0, 105, 107]). The emission mechanism of this emission is not fully understood – one possible explanation is the radiation of Langmuir waves from the plasma in the ionization trail interacting with the ionosphere [106]. So far the radio emission from meteors has not been independently confirmed with other instruments. A survey with the Murchison Widefield Array (MWA; [176]) does not show radio emission from meteors at 72–103 MHz, which is consistent with the hypothesis that the emission follows a power law and is brighter at lower frequencies.

Recent LOFAR observations of the Perseids, Geminids and Quadrantids meteor showers using the AARTFAAC all-sky imaging mode [119] and beamformed observations from LOFAR remote stations between 30 and 60 MHz confirms the presence of radio emission for normal, non-fireball, meteors. Optical video observations from the CAMS (Cameras for Allsky Meteor Surveillance; [70, 121]) network in the Netherlands, as well as meteor radar reflections from the Belgian RAdio Meteor Stations (BRAMS; [0]) shows many coincident optical meteors and radio meteor reflections with the LOFAR detections. The LOFAR AARTFAAC images show that the radio emission is co-located with the ionized trails seen in video observations, but typically extends to lower altitudes in the atmosphere. For some of the brighter meteors, the radio emission trail remains visible for tens of seconds and disperses due to high altitude winds. The beamformed observations show that the radio emission seen with LOFAR is a mix of broadband emission as well as narrow band, reflected, emission from terrestial transmitters. Work is ongoing to determine whether the broadband emission is intrinsic to the meteor, or possible reflected emission from astronomical sources.

Highlight 2 With the AARTFAAC all-sky imaging mode, LOFAR provides unprecedented spatial resolution and sensitivity to characterize radio emission from meteors.

The LOFAR 2.0 upgrade to double the instantaneous LBA collecting area and enable simultaneous LBA and HBA observations will increase the sensitivity of LOFAR for research into radio emission from meteor showers. The all-sky imaging capability of AARTFAAC will be supported with LOFAR 2.0, and an upgrade of the AARTFAAC correlator is considered, which will increase baselines and sensitivity by including all 24 LOFAR core stations as well as process more bandwidth. The improved sensitivity and longer baselines will provide LOFAR with the unique capability of resolving and independently determining the distances to meteors through 3D near-field imaging. This allows the detection of many more fainter meteors, and studying the effect of high altitude winds on meteor trails, even in daylight. With the dense coverage of the optical video cameras provided by the CAMS network, operational on every clear night, as well as the BRAMS meteor radar in Belgium, LOFAR will be the ultimate instrument for studying low-frequency radio emission from meteor showers.

Goal 2 Determine the origin of radio emission meteors and image them in 3D.

2.3 The ionosphere

Hanna Rothkaehl & Maaijke Mevius

The ionosphere is an ionised layer in the upper atmosphere between 50 and 2000 km above the Earth's surface, which gets ionised through UV radiation from the Sun in daytime, with recombination occurring overnight. Solar flux density, geomagnetic field conditions, and density fluctuations in the lower atmosphere propagating upwards all cause strong variations and turbulence in the ionosphere, affecting global satellite positioning systems, aviation, and satellite and HF communication. Radio waves passing through this magnetised plasma are affected in various ways, through scintillation, absorption, dispersive delay, as well as rotation of the polarisation angle via Faraday rotation. LOFAR is very sensitive to all of these effects: Absorption structures can be imaged directly [87]; single station data beamformed on a bright calibrator, e.g. CasA, provides large bandwidth, high time resolution data on scintillation; combining the scintillation patterns of all core stations gives information on the moving structures above the LOFAR core [44]. The wide geographical spread of LOFAR stations enables conditions across much of Europe to be investigated, and data taken to date often show features seen only by one station (e.g., long-duration structure is sometimes seen in data taken by the stations in Sweden and Latvia, but not elsewhere). The wide bandwidth enables features to be seen in the dynamic spectrum which would be invisible to the discrete-frequency observations common in ionospheric scintillation research. Dispersive delays, observed as differential phase errors or position shifts of sources in standard interferometric observations, give information on larger scale structures in the ionosphere, such as small- and medium- scale Travelling Ionospheric Disturbances (TIDs) [89], [30]. Measurement of differential Faraday rotation gives access to higher order effects [30] and Faraday rotation of polarised sources provides an independent test of absolute Total Electron Content (TEC) models. [118].

Highlight 3 The wide bandwidth of LOFAR is a unique capability to enable the more-accurate modelling of ionospheric scintillation, alongside determination of refractive and other effects from interferometric measurements.

Simultaneous observing across the LBA and HBA bands enables multi-octave dynamic spectra of ionospheric scintillation to be taken ([43], enabling the link between plasma structures and corresponding intensity and phase perturbations to be probed, a better understanding of the ionospheric conditions giving rise to the scintillation, and the refinement of radio wave propagation models. Furthermore, this bandwidth considerably improves the accuracy of TEC measurements, and third-order effects, related to the vertical electron density distribution, can be observed in the lower part of the LBA band. The LOFAR4SW extension to the LOFAR2.0 upgrade enables the ionosphere to be monitored continually, allowing the ionospheric response to space weather effects to be observed and studied over a large part of Europe.

> **Goal 3** Accurately model radio wave propagation effects through the ionosphere across Europe.

3. Our Solar System

3.1 The Sun

Pietro Zucca

The release of magnetic energy in the solar corona is often accompanied by the acceleration of particles that emit light across the electromagnetic spectrum, from gamma rays through to radio. The quiet Sun always glows in radio emission, while escaping electron beams and fast CMEs often light up in the radio wavelengths, with the wide bandwidth of LOFAR able to provide imaging spectroscopy of the sources as they propagate up through the upper corona. LOFAR measures such events in extremely high resolution, providing diagnostics of particle acceleration, transport, and escape into the heliosphere, as well as the characteristics of the radio wave propagation itself. The high frequency and time resolution observations of solar radio bursts possible with LOFAR provide an excellent means of studying fine structure in the radio bursts, probing the turbulent density environment of the corona (e.g., [175], [80], [174]). In addition, the evolution of solar transients from the Sun through the solar corona, and the physical characteristics of the shock region and related radio emission, can be performed with unprecedented detail thanks to LOFAR (see e.g., [81]). The small-scale coronal structures necessitate using simultaneous high temporal/spectral cadence beamformed observations and high spatial resolution interferometric observations, to localise smaller-scale solar structures. Investigations of the source size of radio bursts using remote baselines are ongoing (See e.g., [99]).

Highlight 4 The spectroscopic detail and high-resolution imaging of solar radio bursts possible with LOFAR is leading to new insights into the fundamental physics of the solar corona.

Simultaneous observing across the LBA and HBA bands will enable the full tracking of solar radio bursts and CMEs from closer to their origin in the low solar corona out into the upper corona with unprecedented spectral and spatial resolutions. Solar radio burst activity and CMEs are highly unpredictable, which makes regular monitoring of the Sun essential to be able to catch events as they happen; the biggest solar flare of the current solar cycle was missed by LOFAR and the second biggest only half observed by LOFAR due to limited observing time. The LOFAR4SW extension to the LOFAR2.0 upgrade will enable such monitoring to take place in parallel with regular radio astronomy observations. International stations offer great individual sensitivity and longitudinal coverage which enables detailed spectroscopic observations of the Sun to be made over a longer duration each day.

> **Goal 4** Fully investigate the fine structures and the emission mechanism of solar radio bursts and quantify the role of wave propagation effects from the low solar corona to its upper regions.

3.2 The heliosphere & space weather

Richard Fallows

Measurement of interplanetary scintillation (IPS - e.g. [25]) due to small-scale density structure in the solar wind is the main ground-based technique available to monitor the solar wind throughout the inner heliosphere (e.g. [67]), with observations now being used to improve space weather models [68]. LOFAR offers unique capabilities in this area, which are only now being explored to their full potential: The number of international stations and long baselines between them is key to greater accuracy in these measurements; the wide bandwidth means that changes in scattering structure (e.g., weak- to strong-scattering, large-scale structure) invisible to single-frequency instruments can be observed, and the scattering better modeled to find the underlying small-scale turbulent density structure; the many baselines, especially internationally, enables accurate solar wind velocity estimation and direct sampling of the spatial density structure giving rise to the scintillation. The latter is particularly intriguing as this structure is generally thought to be anisotropic, elongated in the direction of the IMF: Assessment of the strength and direction of the IMF, especially within a CME, is of vital importance in assessing the potential impact upon the Earth's magnetosphere, and a LOFAR observation of IPS tracking the passage of a CME shows strong rotation of the spatial pattern as the CME passes. The dispersion and rotation measures from observations of pulsars close to the Sun also contain solar wind and CME density and magnetic field information: The frequency range observed by LOFAR allows the precision necessary for these parameters to be disentangled from interstellar and ionospheric effects, and work to achieve this is ongoing [146].

> **Highlight 5** LOFAR is at the forefront of ground-based space weather research and on the cusp of demonstrating crucial remote-sensing measurements of the magnetic field of a CME.

Regular monitoring of conditions in the interplanetary medium is essential to be able to (a) have observations already running and in place to observe sudden, unpredictable, events such as CMEs, and (b) fully observe and ultimately model, or constrain the possible outcomes from existing models, the full passage and evolution of space weather events through the inner heliosphere. The LOFAR4SW extension to the LOFAR2.0 upgrade, particularly if applied to international stations, will enable such monitoring to take place in parallel with regular radio astronomy observations. Simultaneous observing across the LBA and HBA bands will expand the breadth of scattering conditions visible in a single observation, to better assess directly the transition between weak and strong scattering and the validity of the weak scattering assumption inherent in modeling interplanetary scintillation across this transition. It also further increases the accuracy of dispersion and rotation measures calculated from observations of pulsars, to the level which makes direct measurement of the all-important interplanetary magnetic field a much-more realistic prospect.

> **Goal 5** Improve and constrain space weather models through the improved understanding of the solar wind and CMEs and their evolution and interaction through the inner heliosphere.

3.3 Planetary radio emission

Jean-Mathias Griessmeier

In the solar system, planets are known to emit radio waves via thermal blackbody radiation, cyclotron emission from Jupiter's magnetosphere, synchrotron emision from Jupiter's radiatio belts, and atmospheric lightning discharges.

Jupiter's decametric emission results from its auroral regions and interactions of the Galilean satellites with the planet's magnetic field. This results in various small scale ($<$1") radio sources at various positions on or around the planetary disk (of average size 40"): the auroral oval and the magnetic footpoints of the field lines connecting with the satellites [166].

Terrestrial lightning is characterized not only by its visible flash, but also accompanied by a brief burst of radio emission (cf. Section 2.1). Spacecraft observations have shown that lightning also occurs on other planets of the solar system, with clear detection of lightning on Saturn and Uranus [18, 72, 161, 167, 168], with emission at least up to a frequency of 40 MHz. However, because of the limited reach and lifetime of satellite missions, the amount of available data is rather limited. Recently, first ground-based observations became available, complementing the satellite observations. Ground-based observation of lightning on solar system planets required a very sensitive low frequency telescope. Lightning radio emission was detected at the giant Ukrainian radio telescope UTR-2 [0, 0, 74, 165], and was also observed by the WSRT and with LOFAR [0, 0]. Lightning may have an important role in the atmospheric chemistry (production of non-equilibrium trace organic constituents, potentially important for biological processes).

> **Highlight 6** Jupiter's decametric emission is studied in fine detail with low-frequency radio telescopes, including LOFAR. More recently, planetary lightning has also been shown to be detectable with ground-based low-frequency radio telescopes, such as LOFAR.

One of the upgrades of the LOFAR2.0 project is to double the sensitivity in the LBA band. For planetary lightning studies, this is a crucial parameter: for bursty emission, sensitivity cannot be traded for integration time easily. In addition, the long baselines of LOFAR should allow to spatially resolve the emission with high-quality calibration (transfer of the calibration solution from the HBA band to the LBA band).

For Jupiter's decametric emission, long baselines LBA observations will allow to determine the location and motion of source regions along magnetic field lines; this will allow the to image a planetary magnetosphere for the first time at low-radio frequencies. The scientific outcome is potentially very large [166], especially when combined with data from HST (in the UV) and Juno (in the UV and radio domain) observations [79]. Although Jupiter's radio emission is intense (up to 10^{5-6} Jy), it is sporadic (with emission timescales of msec to sec). High-quality calibration is required to allow the localization of the source relative to Jupiter. For this, the capabilities of LOFAR 2.0 (calibration transfer from HBA, and inclusion of NenuFAR in the LBA range) will be crucial.

Long baselines simultaneous LBA and HBA observations will also allow us to study the fine structure of Jupiter radiation belts on a broad spectrum with exceptionally high resolution [46].

With Saturn lightning at the limit of what is feasible with current LOFAR, LOFAR2.0 will allow to observe not only the brightest radio bursts, but also fainter ones. With double the sensitivity, one can also decrease the integration time by a factor of four, giving access to the sub-structure within a lightning discharge, allowing to study the energetics of Saturn's lightning, which still poses important questions [45]. In addition, the long baselines of LOFAR should allow to spatially resolve the emission: Saturn has an angular size of approximately 17", whereas LOFAR can achieve an angular resolution of 1-2" using the long baselines with the international stations, giving access to spatial information. However, this requires very careful calibration in the LBA band (either in beamformed or imaging mode). Observations on LOFAR's international baselines are rendered very challenging by the different state of ionosphere above the various locations; in addition, the station clocks are independent from each other. In this respect, LOFAR2.0 will be a major step forward: ionospheric calibration will be simplified by the simultaneous use of HBA and LBA fields, which allows the transfer of the HBA solution to the LBA observations. LOFAR2.0 will also offer a common clock for all NL stations, which will further facilitate long baseline imaging. This will be greatly faciliated by combining LOFAR's international baselines with NenuFAR [0] in the so-called "superstation mode".

> **Goal 6** Using international baselines in the LBA frequency range, LOFAR2.0 will provide spatially resolved observations of Jupiter's magnetosphere, Jupiter's radiation belts, as well as lightning in the atmosphere of Saturn.

4. The Milky Way

4.1 Stellar, brown dwarf, and star-planet interaction radio emission

Harish Vedantham, Joe Callingham

Low-frequency radio observations are a crucial probe of plasma in stellar coronae, planetary atmospheres and the plasma interactions between stars and their exoplanets. Radio observations constrain 'extrasolar space weather' that plays a crucial role in determining exoplanetary atmospheric properties and habitability. (i) On the stellar end, observations of coherent radio emission can constrain coronal structure that form the boundary conditions to models of stellar wind pressure on exoplanet atmospheres. Radio observations are also the only unambiguous tracer of coronal mass ejections and relativistic particle beams (so called energetic particle events) that impulsively erode exoplanet atmospheres. (ii) On the exoplanet end, radio observations of cyclotron emission provide a direct measure of magnetic fields that control atmospheric escape (see §4.2 below). (iii) Finally, radio observations powered by star-planet interaction in the sub-Alfvénic regime (similar to the Jupiter-Io interaction) can be used to discover rocky exoplanets around low-mass stars and determine the magnitude of Joule-heating of their atmospheres due to plasma current flowing between the star and the planet.

Recent LOFAR observations have demonstrated LOFAR's unique capabilities. [157] used LOFAR HBA observations to discover the first compelling evidence for radio emission from star-planet interaction. [158] used LOFAR HBA observations to achieve the first discovery of a sub-stellar object (cold brown dwarfs in this case) using radio data alone. Finally, [149] used LOFAR LBA beam-formed observations to achieve the first albeit tentative detection of cyclotron emission from an exoplanet— the gas giant Tau Bootes b.

> **Highlight 7** LOFAR provided the first compelling evidence for radio emission from star-planet plasma interaction similar to that seen between Jupiter and Io

Highlight 8 LOFAR achieved the first discovery of a brown dwarf with radio data alone showing that it can detect objects too cold and distant to be found in existing infrared surveys.

The LOFAR2.0 upgrade will allow the community to capitalize on these early discoveries towards a mature scientific program on three fronts: (i) thermal noise limited imaging at LBA frequencies will allow the measurement of magnetic fields of stellar and sub-stellar objects down to tens of Gauss that has not been probed before. (ii) Simultaneous LBA+HBA observations will allow observations of swept frequency radio bursts (so-called Type-III and -II events) associated with coronal ejections from Sun-like stars and the plasma disturbances their create in the interplanetary medium. The broad bandwidth is necessary to separate a bonafide type-III frequency sweeps with unrelated 'spike-bursts' that are of a similar duration but are not swept-frequency in nature [156]. (iii) The simultaneous LOFAR4SW beam will allow long-term monitoring of LOFAR-detected stars to search for periodic modulation generated by close-by exoplanets. An unambiguous detection of exoplanets, while scientifically exciting, will require hundreds of hours of observations (per star) that can be achieved using the LOFAR4SW parallel data-stream without affecting standard LOFAR observations.

Goal 7 Discover the first signature of energetic particle event on a Sun-like star (type-III radio burst).

Goal 8 Discover the first population of terrestrial exoplanets around low-mass stars by exploiting the modulation of stellar radio emission at the planetary orbital period.

4.2 Exoplanets

Philippe Zarka

Six solar system planets are magnetized and possess a magnetosphere, in which complex plasma processes accelerate electrons, producing strong low-frequency radio emissions detected in 5 cases [170]. These so-called auroral emissions result from the super-Alfvénic solar wind-magnetosphere interaction and, for at least part of the Jovian radio emissions, to magnetosphere-ionosphere currents. In addition Jupiter's magnetic field is in sub-Alfvénic interaction with at least 3 of its Galilean moons, also inducing strong radio emissions [86]. Physical information from all these systems was merged into a radio-magnetic scaling law that relates the emitted radio power to the incident Poynting flux on the obstacle [169, 171, 172], leading to predict that hot Jupiters are strong radio emitters, and that close-in exoplanets should experience a giant Io-Jupiter-like interaction with their parent star.

Highlight 9 Long-predicted SPI and hot Jupiters radio emission start showing up in LOFAR HBA and LBA observations.

After several unconfirmed tentative detections, recent LOFAR HBA imaging observations (from the LoTSS survey) provided hints of star-planet interaction (SPI) for the system GJ 1151 [157], but the presence of the planet is still controversial [113]. In parallel recent LOFAR LBA LF beamformed observations calibrated on Jupiter provided a tentative detection of the exoplanet τ Bootes b, still to be confirmed [149].

While SPI corresponds to radio emission of energetic electrons in the stellar magnetic field, cyclotron Maser radio emission of exoplanet origin is limited at high frequencies by the amplitude of the exoplanetary magnetic field, and thus far more likely in the LBA range. The sensitivity jump from LOFAR to LOFAR 2.0 in the LBA range, with more antennas, improved calibration and inclusion of NenuFAR, will hopefully lead to many detections. The number of detections is very important: all 6 solar system planetary magnetospheres, although emerging from the same physics, display very different characteristics (size, dynamics, reconnection sites, electron energies...). Which characteristics are fundamental ? Which are particularities ? Detection of dozens of exoplanets in radio will answer this question and by opening the new field of comparative exo-magnetospheric physics. The expected breakthrough in our understanding can be compared to the revolution the discovery of hot Jupiters brought to the field of planetary formation.

Radio detection is also the best way to access exoplanets' magnetic moments (thus interior structure) and rotation (hence spin-orbit synchronization) [64]. This knowledge will help understanding the complex and controversial role of the magnetic field in atmospheric escape (a magnetic field protects a planet's atmosphere from the loss due to the direct impact of the stellar wind, but it may actually enhance atmospheric loss on semi-open field lines connected to the stellar wind magnetic field [51]). This will put constraints on planetary habitability. Radio detection can also provide information about exoplanet's orbital inclination, plasma environment, and the energetics of the star-planet interaction [64].

> **Goal 9** With increased low-frequency sensitivity, detect several exoplanetary radio emissions, enabling comparative exo-magnetospheric physics and constraining magnetic moments, atmospheric escape and habitability.

For all these detailed quantitative measurements, long enough series of observations of selected targets are important because emission periodicity is the key to its interpretation. As planetary radio emissions are often sporadic [170], and non-uniformly distributed in the time-frequency plane, the capability to measure dynamic spectra of the targets of interest is crucial. Beyond beamformed observations, subject to various pollutions and risks of false positives [149], restoring dynamic spectra from calibrated visibilities is an essential capability. It was incorporated to LoTSS in the form of the DynSpecMS package developed in Meudon, that proved efficient on stellar bursts [19]. Its application to a low frequency survey should be systematic.

Beyond hot Jupiters, predicted stronger magnetosphere-ionosphere coupling and radio emission intensity has been predicted for planets orbiting at a few AU of strong X-UV emitting stars [101] (which is also the habitable zone range of solar type stars). Distinguishing between an emission produced in the exoplanet's magnetosphere and induced emission in the corona of its parent star requires high angular resolution measurements. The sub arcsecond resolution provided by LOFAR 2.0 will allow us to identify the emission source for systems closer than 5-10 pc. In case of detections of emission from binary systems such as τ Bootes [149] or CR Draconis [19], high angular resolution measurements will also allow to identify which component is emitting. Direct detection and localization of radio signals from exoplanets and/or star-planet plasma interactions will be an exciting first in astronomy.

> **Goal 10** Angularly resolve the radio source in nearby exoplanetary systems: star or planet ?

4.3 Supernova remnants

Jacco Vink

Supernova explosions provide the dominant source of energy for the interstellar medium. These explosions create multi-parsec sized shells, supernova remnants (SNRs), which emit non-thermal emission with a relatively steep spectral index—$\alpha \approx -0.5$—and which, when combined with gamma-ray emission, provides insights into particle acceleration properties and magnetic-fields of SNRs.

The Galactic SNR population provides us information on the Galactic supernova rate—thought to be 2–3 per century and the locations of active starformation. Moreover, the non-thermal emission provides insights into the acceleration of relativistic electrons. Currently, there are about ~ 300 SNRs identified in the Milky Way, but based on a likely lifetime of $\sim 50,000$–100,000 yr, we expect the Galaxy to contain about 1000-3000 SNRs. Combining the properties of non-thermal radio, X-ray and gamma-ray emission also provides us with insights into the cosmic-ray acceleration properties of SNR shocks and the internal magnetic-field energy density. These magnetic fields are likely amplified by the accelerated particles, but their strengths and turbulence are also an important ingredient for efficient cosmic-ray acceleration. Understanding cosmic-ray acceleration by SNRs is important as SNRs are thought to be responsible for the bulk of the cosmic rays in the Galaxy, but we still do not understand if and how SNRs are capable of accelerating cosmic rays beyond 10^{14} eV.

Due to their steep spectra SNRs are best searched for at low radio frequencies, where they become more prominent than HII regions. Moreover, the multi-channel nature of the LOFAR receivers are ideal for distinguishing HII regions and SNRs. Indeed, a LOFAR HBA study of a Galactic field around $l = 54°$ resulted in the discovery of a relatively young SNR [37], easily identified in a field riddled with HII regions.

When it comes to individual SNRs, low-frequency studies provide new insights into the nature of the objects. For example, for the bright SNR Cas A LOFAR LBA observations made it possible to precisely map the freely-expanding, unshocked supernova material, by means of free-free absorption of cool electrons. This provided new insights into the dynamics and explosion mass of this important SNRs [3]. A similar study of the SNR of SN1572 (Tycho's SNR, or Cas B), did not reveal interior emission, but likely a limb-brightened shell of cold electrons immediately outside the shock. This shell likely originates from mass loss by the progenitor system [5]. This is of interest, because SN1572 was a Type Ia supernova. One of the models for Type Ia supernovae is the merging of two white dwarfs. But such a system would not give rise to pre-supernova mass loss.

Finally, the low-frequency spectra can be used to probe to study the spectral shape of non-thermal emission. Some models for cosmic-ray acceleration predict curved non-thermal spectra. But there may also be spectral index variations accross the SNR, which leads to deviations from a power-law shape. LOFAR has indeed found evidence for both spectral index variations accross SNRs, as well as spectral curvature. See for example [4].

Highlight 10 The LBA band of LOFAR allow us to probe cool electrons through free-free absorption studies. This can be used to probe gas that is not yet shocked by either the forward or inward shocks of supernova remnants.

4.4 Pulsar wind nebulae

Jacco Vink

Pulsars create electron-positron pairs in their magnetosphere, which can escape the magnetosphere through the open magnetic-field lines piercing the pulsar's light cylinder. This creates a relativistic wind of electrons/positron (electrons for short). Either in the wind itself, or in the termination shock the electrons are accelerated, forming a non-thermal population of electrons. After passing the termination shock these accelerated, relativistic electrons create a nebula of relativistic electrons called a pulsar wind nebula (PWN). This PWN contains most of the energy released caused by the spinning-down of the pulsar. As such it provides a record of the total rotational energy loss over the $\sim 10^6$ yr lifetime of the pulsar.

The pulsar is created during a supernova explosion. As a result the PWNe and SNR are created at the same time. But not all SNRs contain energetic pulsars (and Type Ia SNR contain no neutron stars at all), so only a minority of SNRs contain PWNe. On the other hand, PWNe have a longer lifetime than SNRs. So many PWNe are known without being surrounded by SNR shells. A famous example of a PWN inside an SNR is the Crab Nebula. In fact, the Crab Nebula is unusual as the non-thermal radio emission originates from the PWN, without a trace of a SNR shell surrounding it. The electrons/positrons eventually escape the PWN or the PWNe is dissolved. This releases these particles in the interstellar medium. Currently, the presence and spectrum of positron cosmic rays is puzzling. The positrons may be a hint of dark matter annihilation. But more likely is that the positrons originate from nearby PWNe. To fully understand the origin of cosmic-ray positrons it important to have a census of nearby PWNe, and obtain observational information on how and when they escape the PWNe.

The acceleration of electrons/positrons is in itself also important. PWNe are the most nearby examples of shock acceleration in relativistic outflows, and provide information that may also be relevant for acceleration in AGN jets. Currently there are two open questions regarding the acceleration in PWNe: 1) How come that PWNe are energetically dominated by relativistic electrons, rather than by magnetic-field energy density? (This is known as the sigma-problem.) 2) What is the Lorentz factor Γ of the wind? The Γ of the wind is usually assumed to be $\Gamma \sim 10^6$, but that implies that the PWNe contains few "accelerated" electrons with $\Gamma \ll 10^6$. This is at odds with the near power-law shape of radio spectra down to ~ 100 Hz, which is caused by electrons with much lower Lorentz factors. In fact, it natural to assume that the non-thermal spectrum is at low energies terminated in a thermal bump, which should also be reflected in the synchrotron spectral shape. The contradiction between low-frequency radio spectra and the high Lorentz factor wind is in some models [e.g. 90] solved by postulating two populations of electrons, one originating from the high Lorentz factor wind, and another population either caused by "relic" electrons from past activity, or having another acceleration origin.

Not many LOFAR studies yet exist of PWNe, but an indication of what lies ahead can be found in two studies. The hints of a thermal synchrotron bump were investigated for the PWN G54.1+0.3, but no evidence for it were found, nor was there a hint of a surrounding SNR [37]. The Crab Nebula (Tau A) was mapped by LOFAR LBA data as part of an effort to map all "A-type" radio sources [31]. Interestingly, the map of Crab Nebula provided an hint that the torus —coincident with the termination shock— was less prominent at below 100 MHz than around 1 GHz. Although one cannot rule out some artefacts and systematic errors at these low frequencies, the change in morphology may indeed hint at two different populations of relativistic electrons/positrons.

Highlight 11 With the LBA band of LOFAR we are finally able to probe and map the lowest frequency and reveal whether the non-thermal spectrum is terminated by a thermal synchrotron bump.

4.5 The life cycle of the interstellar medium

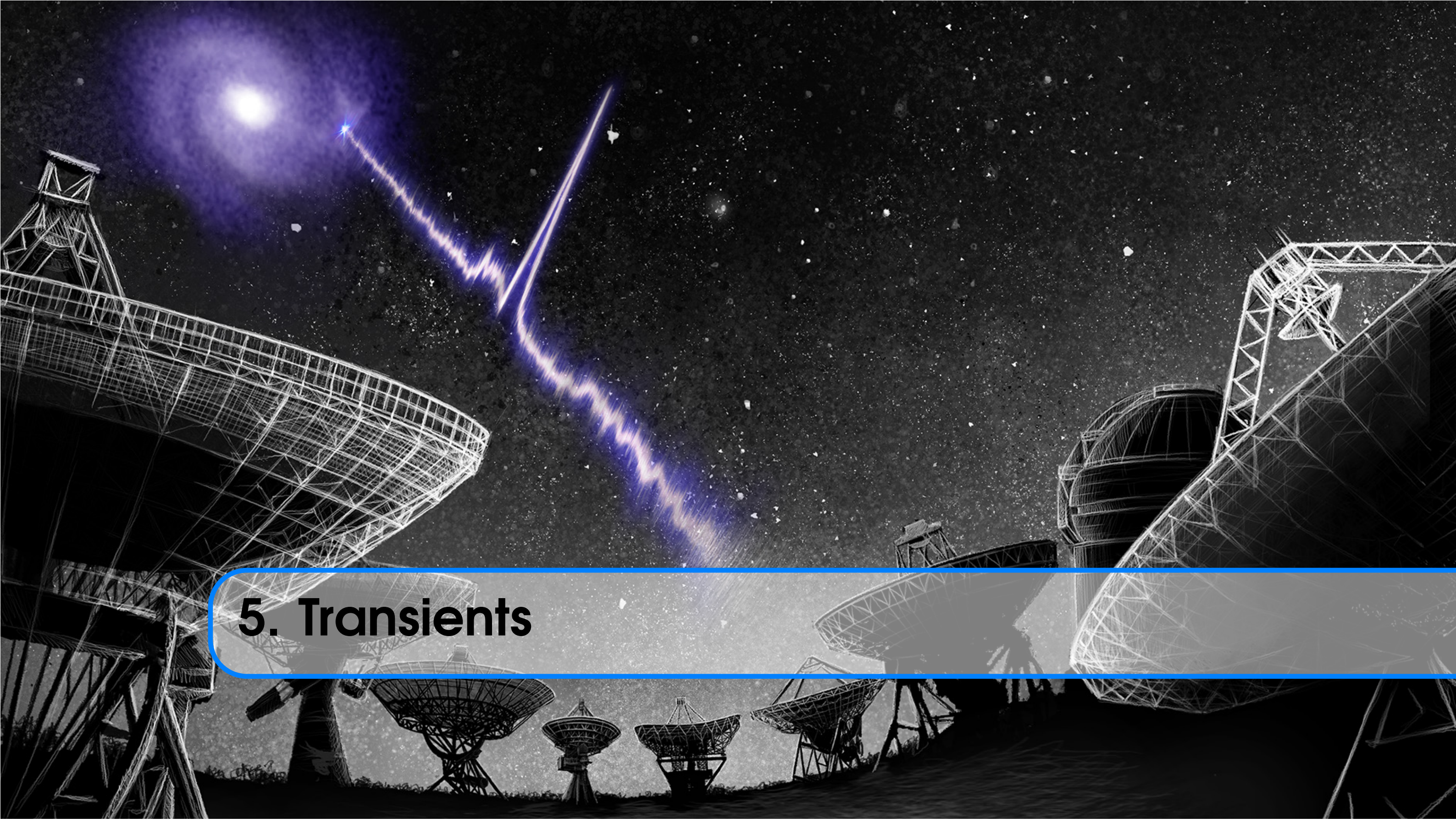
Pedro Salas, Kimberly Emig, Xander Tielens & Raymond Oonk

The interstellar medium (ISM) is the gas, dust, radiation and charged particles that lie between the stars in a galaxy. The coldest gas in the ISM provides the fuel for star formation. Conversely, stars ionize, heat, stir and enrich the ISM, through their radiation, winds and explosions, collectively known as stellar feedback. This interplay between star formation and the ISM gives rise to a feedback cycle and is one of the key drivers of galaxy evolution. One of the consequences of stellar feedback is the stratification of the gas into distinct phases, e.g., cold neutral clouds – the cold neutral medium (CNM) – and warm ionized gas in discrete HII regions and extended throughout the galactic disk – the warm ionized medium (WIM). LOFAR is unique in its ability to detect these gas phases through radio continuum and spectral line observations at the lowest frequencies observable from Earth. At LOFAR frequencies moderately dense ($n_e \sim 1$–100 cm^{-3}) ionized gas becomes opaque. Observations of opaque ionized gas can be used to determine its properties (e.g., density, temperature and size) and to perform cosmic ray tomography. LOFAR can also readily observe spectral lines from hydrogen and carbon in the form of radio recombination lines (RRLs), which trace warm ionized and cold neutral gases, respectively. Currently, LOFAR is the only telescope capable of observing low-frequency RRLs with the spectral and spatial resolution necessary to separate different components of the ISM, identify which objects are associated with the gas, and measure the gas kinematics. Observations with LOFAR have shown that it is possible to detect RRLs from carbon down to 11 MHz [125] and to use extragalactic sources to perform pinhole studies of the gas in our own Galaxy [108]. LOFAR HBA and LBA observations have for the first time enabled a precise determination of the temperature and density of cold neutral gas in the Perseus arm of the Galaxy [109] and to map these properties on pc scales [126]. LOFAR is enabling complementary studies of the ISM in high redshift galaxies, with the first detection of RRLs on a $z \sim 1.2$ galaxy [39].

Highlight 12 LOFAR is enabling detailed studies of the ISM in the Milky Way on unprecedented scales and is opening up a new window to study the ISM across cosmic time through RRLs.

Measuring the properties of the neutral and ionized gases using RRLs and radio continuum requires deep integrations and a high spectral dynamic range – RRLs have peak amplitudes which are $\sim 10^{-4}$ the continuum level – using both the HBA and LBA. LOFAR2.0 will enable large surveys of RRLs because of the following aspects: (i) For studies of the Milky Way tied-array observations are preferred due to the large angular scales involved. The larger field-of-view will increase the survey speed, and the use of a single clock for the NL stations will result in higher-quality and higher-sensitivity RRL cubes. (ii) For extragalactic observations, where imaging observations are preferred, the increased sensitivity of the LBA will result in a higher detection rate for RRLs in other galaxies. (iii) Simultaneous HBA+LBA observations will enable the detection of RRLs over a wide frequency range, which is a must to determine the properties of the ISM of the host galaxy. RRL observations with LOFAR2.0 will enable a completely new perspective into the life cycle of galaxies across cosmic time, similar to what ALMA has made possible through observations of the redshifted 158 μm [CII] line.

Goal 11 Chart the physical properties and kinematics of the cold neutral and ionized gas phases in our Galaxy and throughout cosmic time using radio recombination line observations.



5. Transients

5.1 Pulsars

Jason Hessels & Ben Stappers, Caterina Tiburzi

Pulsars are highly magnetised neutron stars that produce beams of radio waves that sweep across the sky like a cosmic lighthouse. These radio pulsations allow us to study the properties and evolution of neutron stars, which are some of the most extreme objects in the Universe. Using the technique of pulsar 'timing', we can constrain the neutron star equation of state, test Einstein's theory of gravity and detect low-frequency gravitational waves with the Pulsar Timing Arrays (PTAs). However, to date the success of PTAs has been compromised by the disturbances introduced by Galactic plasma such as the ionized interstellar medium and Solar wind while pulsar's radiation propagates. In the last years, LOFAR and its international stations proved to be cutting-edge telescopes to characterize the ionized interstellar medium [36], frequency-dependent dispersion phenomena [35] and the Solar wind [145, 146] within the context of pulsar timing and PTAs, having the benefit of a uniquely high-quality, highly-cadenced dataset on more than 100 pulsars covering a timespan of more than 7 years. Pulsars are exceptionally steep-spectrum radio sources. LOFAR is a unique pulsar telescope because of its high sensitivity across the lowest 4 octaves of the radio band, and its ability to provide voltage tied-array data for multiple sources at once. LOFAR has discovered close to 100 radio pulsars to date[128]. LOFAR pulsar discoveries include a record-breaking slow 23.5-sec pulsar, which may be a magnetar descendent[143], and a 1.41-ms pulsar that is the fastest-spinner in the Galactic field[6]. We have also used LOFAR in tandem with the X-ray telescope *XMM-Newton* to demonstrate broadband moding, in which a pulsar rapidly changes between two distinct and characteristic emission modes[62].

> **Highlight 13** LOFAR has discovered both the fastest- and slowest-spinning radio pulsars in the Galactic field.

With LOFAR2.0 we will perform an ultra-deep pulsar survey by targeting compact, highly polarised sources found in LOFAR imaging surveys like LoTSS. We aim to find the most exotic radio millisecond pulsars, and to use them as probes of gravity and dense matter physics. The NL single clock will provide higher-quality and higher-sensitivity tied-array observations. COBALT2.0 allows the parallel observing modes that are needed to conduct such observations commensally during deep imaging surveys. The LOFAR stations, especially the large International stations, are sensitive telescopes in their own right. By using sub-arrays, we can also monitor dozens of pulsars in parallel and use these pulsar timing data to measure neutron star orbits, probe the interstellar medium, and measure the density and magnetization of the solar wind (see also §3.2).

> **Goal 12** Discover a sub-millisecond pulsar that strongly constrains the neutron star equation-of-state.

5.2 Fast radio bursts

Jason Hessels

Fast radio bursts (FRBs) are millisecond-duration radio flashes of extragalactic origin. They are billions to trillions of times more luminous compared to Galactic pulsars. FRBs are a compelling astrophysical mystery: what produces these astoundingly bright but ephemeral signals? Both repeating and apparently non-repeating FRBs have been discovered, but are they all created by the same type of astrophysical source? FRBs provide a novel view of extreme astrophysics in action. They are also unique probes of the magnetised and ionised material within and between galaxies. LOFAR's high sensitivity, broad band, and access to full-polarimetric voltage data make it a powerful telescope for targeting known repeating FRBs. Using coherent dedispersion, one can achieve optimal time resolution. LOFAR's wide field-of-view also allows it to potentially discover new FRBs, some of which may be invisible at higher radio frequencies, and to shadow ongoing higher-frequency experiments like CHIME/FRB. FRB 20180916B is a famous and well-studied source because it is exceptionally nearby[84] the first FRB to show a periodicity in its observed activity[22]. It is also the first FRB to be detected at LOFAR frequencies[112, 115], and has been seen down to the very edge of the HBA band at 110 MHz — suggesting that LBA detections are also possible[115]. These observations demonstrate that there is very little absorption in the local environment of the source, and that the periodic activity is delayed towards lower radio frequencies. Both are critical clues for understanding the nature of their prototypical source.

> **Highlight 14** LOFAR is the first and only telescope to detect repeating FRBs at low frequencies, and this has strongly constrained their local environments.

LOFAR2.0 will give a major step in our ability to detect FRBs. Using COBALT2.0, sub-arrays and parallel observing will vastly increase the field-of-view compared to previous pulsar/FRB surveys[73, 128], and allow us to target many repeating sources at once. By using the international stations to shadow CHIME/FRB, we aim to localise newly discovered FRBs to $\sim 10-50$ milliarcseconds, which is comparable to the resolution of the *Hubble Space Telescope* and allows one to determine not only the host galaxy of an FRB, but also its exact galactic neighbourhood. Importantly, it appears that some FRBs are better detectable at low radio frequencies. Understanding the low-frequency properties of FRBs is key to constraining their local environments, emission physics and whether there is a single or multiple sub-populations of physical distinct FRB progenitors. The simultaneous LBA+HBA observing afforded by LOFAR2.0 will allow unprecedented studies of their broad-band spectra, which is a key observable in understanding their emission mechanism and for using them as cosmological probes. Lastly, LOFAR's low frequencies may allow for the discovery of high-redshift FRBs by doing deep, targeted observations of, e.g., the northernmost EUCLID field.

Goal 13 Use LOFAR to localise nearby FRBs to 10-milliarcsecond precision, and then identify their stellar companions using the European Extremely Large Telescope.

5.3 EM counterparts to gravitational wave events

Antonia Rowlinson & Ralph Wijers

The detection of gravitational waves from merging neutron stars and black holes, confirming a long standing prediction of Einstein's GR, has been one of the biggest recent breakthroughs in physics and astronomy, probing the physics of extreme gravity and dense matter. Besides being probes of fundamental physics, these objects also hold great promise for becoming precision tests of cosmology, stellar evolution, and the physics of fluid flows and magnetic fields in extreme conditions. In order to unlock that promise most fully, it is necessary to detect these same events also in electromagnetic radiation: it may offer a direct redshift measurement of the source, as well as probe the properties from any ordinary or even very exotic matter participating in the merger event, thereby testing much more physics, and possibly more precisely testing it, than by using the gravitational-wave signal alone.

LOFAR offers some unique capabilities for moving science forward in this area. First of all, its wide field of view with good sensitivity are essential given the large error boxes of gravitational-wave events and that the objects are fairly distant, hence faint. Furthermore, at low radio frequencies there is a strong possibility of detecting coherently emitted radiation, and some models predict that mergers involving at least one neutron star or magnetar might produce a flash of prompt coherent emission. Almost only LOFAR could find this, and if it did, it would be very telling about the physics of the underlying outflow and central engine. LOFAR's fast and automated response to triggers is also essential functionality for this science. At late times (weeks to years) after the merger, the more 'normal' emission from the mildly relativistic outflow from the merger would become visible. This would provide good measurements of the total energy and mass ejected from the merger and, combined with earlier data at other wavelengths, about the shock physics and the collimation of the outflow. Thus far, the number of attempts at followup have been limited, both because LOFAR's rapid response triggers were still under development until recently and because the number of suitable GW events (at least one NS, error box well defined and in the North) has been limited.

5.4 Supernovae

Deepika Venkattu, Peter Lundqvist & Miguel Pérez-Torres

Supernovae are the explosive end stages of stellar evolution. With the enormous energies linked to them, these powerful transients have been extensively studied. Supernovae have a huge impact on their environs and our understanding of these catastrophic events increases our knowledge of a host of topics, not the least of which is stellar and galactic evolution. They are important laboratories for understanding shock physics and radiative processes and are connected with the transfer of heavy elements through the Interstellar Medium (ISM), and effectively with life on earth. Type Ia supernovae or thermonuclear supernovae are famously used as standard candles in cosmology. A subset of core-collapse supernovae, the broad-lined Type Ic are now known to be associated with long gamma-ray bursts. Despite being fascinating topics that have been studied for millennia, and with wide-ranging applications, supernovae still pose unanswered questions, for example, on their progenitor systems and explosion mechanisms.

In the radio, we typically see the synchrotron emission from the interaction of the supernovae ejecta with the dense circumstellar material, dependant on the pre-supernova mass-loss rates and wind speeds of progenitor stars. While an understandable issue for supernovae at low frequencies is the major role of absorption such as synchrotron self-absorption (SSA) and free-free absorption (FFA) or a combination thereof, the increased sensitivity levels of LOFAR would still give a better chance of detection. Also, the fact that we have not been able to study supernovae at such low frequencies so far opens up many possibilities for understanding new mechanisms.

Highlight 15 By its ability to peer further and detect fainter emission, LOFAR can find more supernovae and their remnants [37] in various stages after explosion, bridging the gap between our current knowledge of mature supernovae and young supernova remnants (SNR).

With LOFAR 2.0, the ability to access the lowest frequencies opens up a completely uncharted territory for supernovae science. We now expect to have the ability to look at hitherto unseen processes that might peak at low frequencies from supernovae radio emission. There is a possibility of studying processes like the Razin-Tsytovich effect, to confirm or constrain modelling beginning from the standard radio model all the way to current cutting-edge models of radio supernovae. For example, an early LOFAR study of the M82 nucleus does not detect SN 2008iz in contrast to standard radio supernovae model predictions [155].

The advances in data processing capabilities, especially with respect to the international LOFAR stations, that accompanies LOFAR 2.0 means that *routine* production of sub-arcsecond resolution images with 8 hours integration of LOFAR-VLBI will be a reality. This is important for transient science since this would now complement higher frequency VLBI data to produce the most sensitive images at the highest resolution available. The expected ability to combine LBA and HBA images opens up a unique band of frequencies to probe supernovae emission and absorption processes. It is also possible that at later epochs, the low frequency light curves of supernovae display changes that help us study the impact of the progenitor system. For example, the late time downturn in radio fluxes of SN 1993J could possibly be due to a change in mass-loss rate caused by mass accretion efficiency changes of the companion star in the progenitor binary system [78].

A lofty goal with LOFAR 2.0 would be transient triggering at low frequencies to type supernovae in the radio, rather than the current system of follow-up from optical detections. This would help discover hidden supernovae that are dust-obscured (hence making optical discovery impossible), for example in luminous and ultra-luminous infra-red galaxies. A DUPLLO survey that follows a few years after LoTSS would also be beneficial for this particular science case. Comparing DUPLLO and LoTSS data would also be useful for many cases, like detecting radio supernovae from differences between the two epochs, and removing confusion with other compact objects.

Goal 14 Explore uncharted territory, understand new physics that might dominate low frequency radio emission from supernovae using high resolution sub-arcsecond images.

5.5 GRB afterglows

Antonia Rowlinson & Ralph Wijers

5.6 Exploring the transient parameter space

Jason Hessels, Antonia Rowlinson & Ralph Wijers

Exploration of new astrophysical parameter space — whether it be new parts of the electromagnetic spectrum, new messengers or new depths of sensitivity, or timescales — has led to many transformational insights. The discoveries of quasars, pulsars and cosmic microwave background are just a few examples from the past century.

Modern astrophysics is increasingly developing our ability to explore the "time-domain", in which we track the variations of astrophysical objects over timescales of nanoseconds to centuries. Adding this temporal dimension to our toolbox is changing the way we view the Universe. For instance, gamma-ray bursts trace the most energetic explosions since the Big Bang; fast radio bursts remain an enigmatic phenomenon but are already allowing us to trace baryonic matter and magnetic fields in intergalactic space; and gravitational wave events point to mergers of black holes and neutron stars, in which exotic nucleosynthesis of heavy elements can take place.

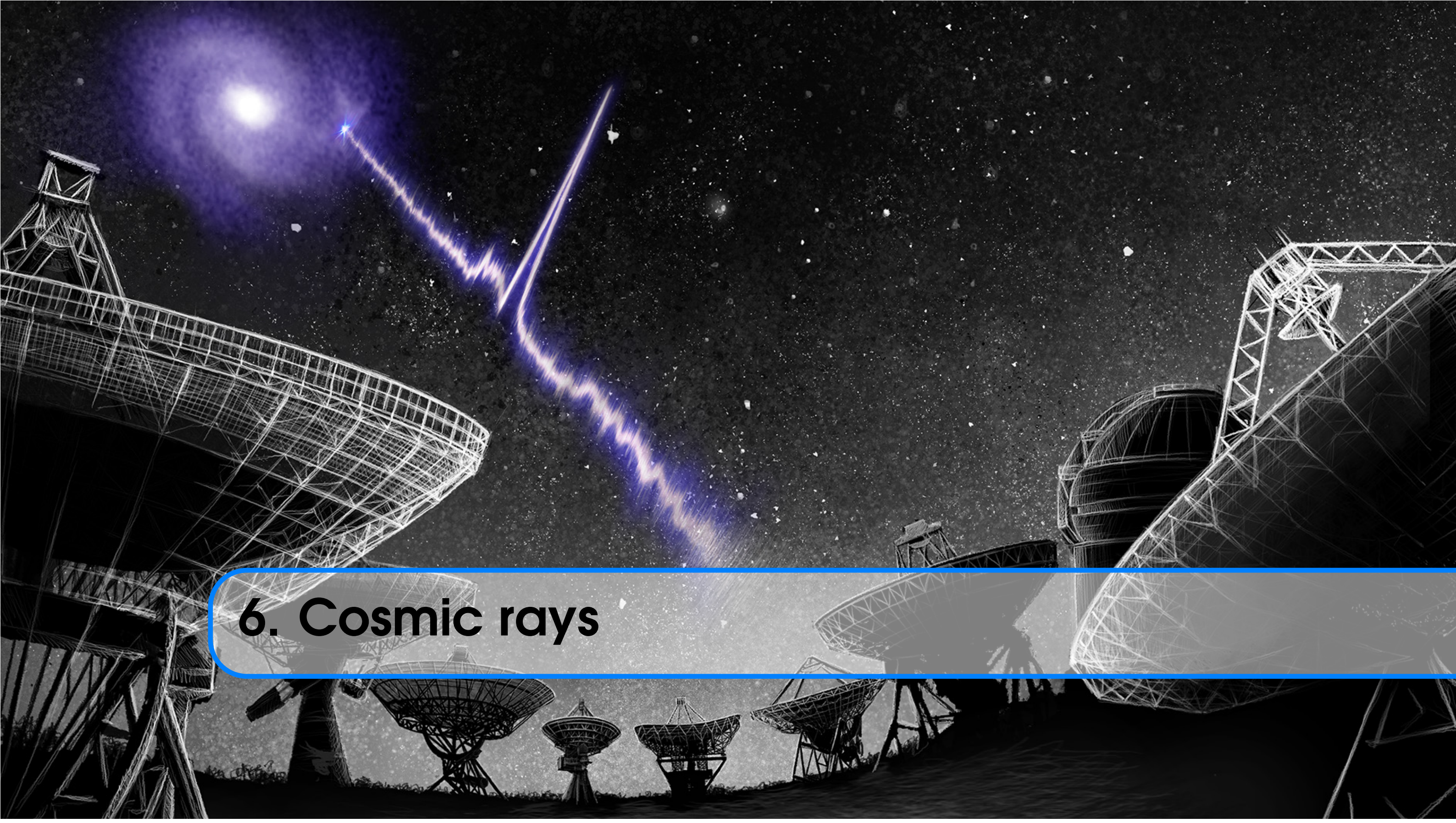
LOFAR is exploring the lowest 4 octaves of the radio window visible from Earth, with unprecedented sensitivity and spatial resolution compared to previous radio telescopes. LOFAR's flexible beam-former and correlator, COBALT2.0, provides observing modes that span time scales of microseconds upwards. Using the transient buffer boards at the LOFAR stations, nanosecond time resolution can be achieved. LOFAR's wide-field LBA and HBA surveys are reaching depths that are orders-of-magnitude beyond the state-of-the-art, and also provide full polarimetric information.

LOFAR's beam-formed modes have enabled the discovery of both the fastest-spinning and slowest-spinning radio pulsars in the Galactic field; these modes have also enabled the first ultra-low-frequency fast radio burst detections. AARTFAAC has detected radio emission from meteors and continues to scan the sky for bright but rare transients. The Stewart et al. transient, found in early LOFAR monitoring of the North Celestial Pole remains an enigma, but suggests that there is an underlying population of such signals.

> **Highlight 16** LOFAR has discovered surprisingly low-frequency emission from fast radio bursts and discovered unexpected transient stellar radio emission.

Massively parallel observations, both beam-formed and imaging, will enable us to explore new regions of transient parameter space by trading field-of-view for sensitivity and time resolution. Fast-imaging (10-ms integrations) is virtually unexplored at low radio frequencies. An enhanced AARTFAAC system, no longer limited by confusion, could go an order-of-magnitude beyond the current state-of-the-art.

> **Goal 15** By pushing to ultra-low frequencies of 10 – 50 MHz with high-sensitivity, we aim to discover exotic radio transients whose emission mechanism and associated spectrum has thus far hidden them from higher-frequency radio observations



6. Cosmic rays

6.1 Galactic cosmic rays

Stijn Buitink

Cosmic rays are the most energetic particles that exist in the Universe. Despite intensive studies with observatories around the world, there are still many open questions about their origin and the physics behind the acceleration processes. LOFAR can detect the nanosecond-scale radio pulses that are emitted when high-energy cosmic rays collide on molecules in the Earth's atmosphere and create avalanches of secondary particles called *air showers* [130].

Radio detection of air showers was still a relatively young and unexplored field when LOFAR observations started. Nowadays, the technique is widely used in cosmic-ray observatories around the world. LOFAR played a large role in this revolution. The large antenna density in the LOFAR core allowed for precise characterisation of the emission characteristics: the shape of the shower front [27], the polarisation of the radio signal [131, 132], and the frequency spectrum [97, 100]. It was conclusively shown that the emission mechanism is now understood and can be simulated in Monte Carlo codes with very high precision.

Highlight 17 LOFAR has played a crucial role in the rapid development of radio detection of air showers into an established and widely used technique.

Since cosmic rays are charged particles, their trajectories are deflected by magnetic fields and their arrival directions on Earth do not point back to the sources. This makes the identification of cosmic-ray sources a daunting puzzle. A crucial measurement is the mass composition of cosmic rays. This can be determined indirectly by studying the penetration depth of air showers in the atmosphere. LOFAR was able to perform atmospheric depth measurements with a resolution that exceeds other state-of-the-art observation techniques [16]. These measurements led to the first high-precision radio-based mass composition study of cosmic rays in the galactic-extragalactic transition region.

Highlight 18 LOFAR measured shower depths with a precision exceeding traditional observation methods, which was the basis for a study of cosmic-ray mass composition in the transition region [17].

Currently, air shower observations with LOFAR are performed intermittently running in the background of other astronomical observations. The effective duty cycle of high quality observations is small because of technical limitations. With the LOFAR2.0 upgrade, low+high band cosmic-ray observations will run constantly in the background. The air-shower detection rate is boosted even further by a recently finished expansion of the particle detector array used for triggering. In addition, a smarter triggering algorithm is being developed that combines signals from the particle detectors and the antennas.

Together, these innovations will lead to an increase in detection rate by more than an order of magnitude, while at the same time extending the energy range at the lower and higher end. Finally, the possibility to simultaneously observe in the low and high band will lead to more accurate reconstruction of the cosmic-ray energy and mass.

Goal 16 Order-of-magnitude improvement in detection rate and reconstruction quality to search for origin of high-energy cosmic rays.

6.2 Ultra-high-energy cosmic rays

Stijn Buitink

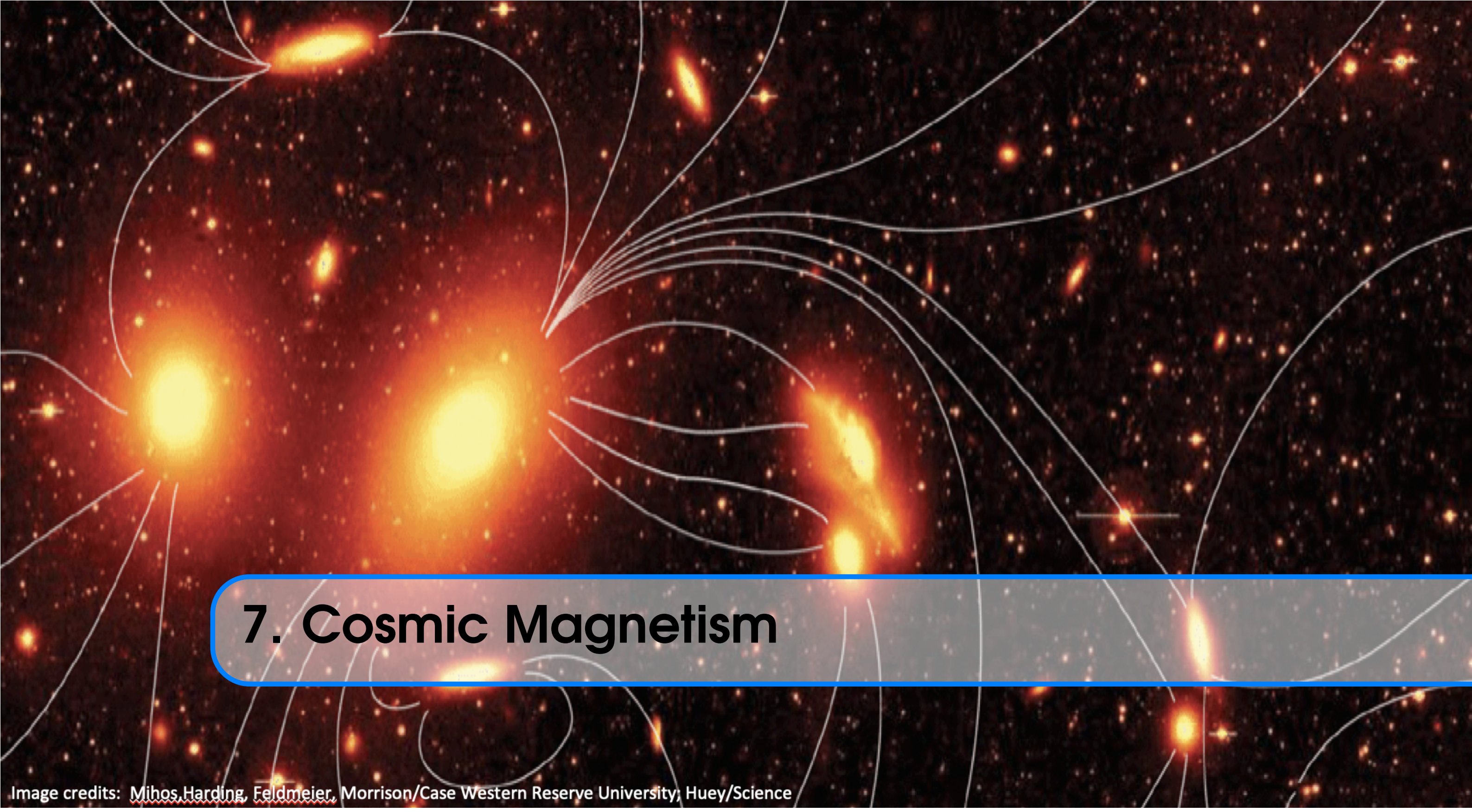
At the highest energies the flux of cosmic rays decreases below one particle per square kilometer per century. In order to study particles with energies close to - or even exceeding - the observed cutoff around 10^{20} eV, huge detector volumes are needed. The visible surface of the Moon has an area of millions of square kilometers and can act as a giant cosmic-ray detector. Radio telescopes can be used to search for the short radio flashes of ultra-high energy cosmic rays or neutrinos hitting the Moon. This provides a unique possibility to study the most powerful accelerators in the Universe or even exotic physics like super-heavy dark matter.

Using the LOFAR core, fifty tied-array beams can be formed simultaneously to cover the surface of the Moon. Each beam has to be monitored in real-time for the occurrence of short radio pulses. This needs to be done against a background of anthropogenic noise while correcting for signal distortions caused by the ionosphere. An observation pipeline was developed to perform the complete analysis in real-time on a GPU cluster [0].

Highlight 19 A GPU-based detection system was developed to search for impacts of ultra-high energy particles on the Moon

Lunar cosmic-ray observations will benefit from the increased bandwidth and computational power of LOFAR 2.0. Observations will be fine-tuned further to decrease the energy threshold and achieve sensitivity to the flux of ultra-high energy cosmic rays. LOFAR will be able to reach unprecedented sensitivity above 10^{21} eV and probe a previously unexplored parameter space, possibly leading to first detection of a lunar cosmic-ray pulse.

Goal 17 Achieve unprecedented sensitivity to the most energetic particles in the Universe.



7. Cosmic Magnetism

7.1 The magnetized Milky Way

Marijke Haverkorn

The linear polarisation of synchrotron emission in the Milky Way gives unique information about the structure and strength of Galactic magnetic fields, due to frequency-dependent depolarisation effects and Faraday rotation. Depolarisation becomes increasingly severe at decreasing frequencies, so that at the lowest frequencies, any polarised signal probes the magnetized interstellar gas in the local Solar neighborhood.

Detecting diffuse polarised synchrotron emission with LOFAR has allowed characterizing interstellar magnetized turbulence om parsec scales [66], estimating magnetic field strengths and identifying magnetized structures in the Solar neighborhood [69, 150], and finding correlations between magnetized structures and other interstellar tracers such as dust and neutral hydrogen [152, 173]. In addition, Faraday rotation of LOFAR-detected signals of extragalactic polarised point sources [151] and pulsars [139] constrains the 3D structure of the Galactic magnetic field.

A completely complementary way to probe Galactic magnetic fields with low-frequency radio observations, is through free-free absorption in Galactic HII regions [0]. Measurements of this absorption (typically below ~ 100 MHz) provide an estimate of synchrotron emission along a localized pathl ength which is only part of the line-of-sight through the Galaxy [102, 142]. These emissivities can be used to constrain models of the Galactic magnetic field [116, 117].

> **Highlight 20** LOFAR high-resolution polarimetric imaging allows quantification of the connection between magetized structure and interstellar gas in the Solar neighborhood.

The LOFAR2.0 LBAs will enable us to probe polarisation of Galactic synchrotron emission at the lowest frequencies, to assess the amount of depolarisation. This is until now uncharted territory. Locations with complete depolarisation will provide limits to the magnetic field structure in the nearby interstellar gas, while any polarisation structures detected allow us to obtain Faraday spectra in unprecedented Faraday depth resolution below 0.01 rad m^{-2} if we can detect polarisation across the LBA band, indicating unique detail in Faraday rotation in e.g. the Local Bubble wall [2], or even in the hot ionized medium inside the Local Bubble.

The first LOFAR LBA study of free-free absorption in HII regions has detected a handful of HII regions in absorption in the inner Galaxy (Polderman, 2021, PhD thesis). The increased sensitivity in LOFAR2.0 by more than an order of magnitude, combined with the higher resolution, will make both weaker and smaller (in angular diameter, so farther away) HII regions accessible to this analysis. This will allow probing into the mesa-scale structure of the Galaxy, possibly enabling detection of emissivity differences between spiral arms and interarms regions.

Map out magnetic field structure in around the Local Bubble using LBA Faraday spectra over the northern sky.

7.2 Magnetic fields in other galaxies

Volker Heesen

Nearby galaxies are the ideal laboratory to study the influence of magnetic fields on galaxy evolution in the Universe. Low-frequency radio continuum observations are particularly well suited to study magnetic fields as they trace the non-thermal synchrotron emission from cosmic ray electrons spiralling around magnetic field lines. LOFAR is particularly well adept to study outflows and winds in nearby edge-on galaxies [56, 92, 96], where the oldest cosmic-ray electrons become visible that illuminate the magnetic field. Magnetic field scale heights are $\gtrsim 15$ kpc, larger than the typical scale heights of 6 kpc that are observed at GHz-frequencies [76], highlighting the unique potential of LOFAR. The role that cosmic rays and magnetic fields play in these outflows is the subject of many theoretical works, from hydrodynamical descriptions [41, 127] over local [47] to global MHD simulations [110], but is only poorly constrained observationally [61].

Magnetic fields in galaxies may be regulated by the small-scale dynamo where the turbulent energy density is in approximate equilibrium with the magnetic energy density. Radial profiles of energy densities and pixel-by-pixel plots show an excess of magnetic fields in galaxy outskirts and areas of low star formation [7, 9, 10]. Such observations can be compared with magnetohydrodynamical (MHD) models, which require, albeit sophisticated, still several simplifications which applicability needs to be verified [111]. What has become clear though is that magnetic fields have high field strengths $\sim 10\ \mu$G, so that they are dynamically important in the gaseous interstellar medium. With LOFAR we can access areas where turbulence from star-formation in the atomic and molecular gas is sub-dominant [7], and we can explore other amplification mechanisms such as the magneto-rotational instability [50].

Highlight 21 With the LOFAR Two-metre Sky Survey we studied the distribution of cosmic rays and magnetic fields in a sample of 45 nearby galaxies on a scale of a few 100 parsec [60].

With LOFAR2.0, using international baselines, we will be able to go much further and and study radio continuum at a resolution of 50 pc, comparable to the cloud scale in the interstellar medium. This then will allow us to probe the influence of magnetic fields on the turbulence within and stability of star-forming regions, a crucial ingredient to many theories of star formation [48, 75, 77]. The high angular resolution will also facilitate a better modelling of confusing background sources, allowing us to trace the faintest diffuse emission in the halo, to explore magnetic fields in outflows, winds and accretion flows that connect galaxies with the circum-galactic medium – the proposed reservoir of the 'missing baryons' in the Universe [148].

Goal 18 With deep combined observations with LOFAR HBA and LBA using international baselines we can reveal magnetic field properties at cloud scale and search for magnetic fields in the ionized baryons of the elusive circum-galactic medium.

We will also search for magnetic fields in outflows using the Faraday rotation of polarised background sources such as radio galaxies [63]. These observations have the potential to unlock the conundrum of the interchange between star formation, stellar feedback, magnetic fields and cosmic rays. Theory suggests that the balance between magnetic field amplification and outflows advecting magnetic fields may lead to equipartition magnetic fields in galaxies. Such a balancing of forces has wider implications for galaxy formation as cosmic rays can provide them with a maximum stability curve along which galaxies are stable with respect to outflows [28].

7.3 The magnetised cosmic web

Shane O'Sullivan

The origin of magnetic fields in the Universe is one of the major unsolved problems in astrophysics. Radio observations can illuminate the presence of magnetic fields directly through synchrotron radiation from relativistic plasmas and, more generally, through the Faraday rotation of linearly polarized light as it propagates through magnetised plasma along the line of sight. Both these methods have been pursued to investigate the signature of weak magnetic fields in the diffuse ionised gas that is expected to permeate the cosmic web [14, 103]. Recent LOFAR Faraday rotation observations have provided some of the most robust upper limits on the average magnetisation of the Universe of less than a few nanoGauss [104]. Lower limits on the magnetisation of the Universe of $\sim 10^{-8}$ nG have been provided by γ-ray observations, meaning that our current ignorance spans $\sim$8 orders of magnitude.

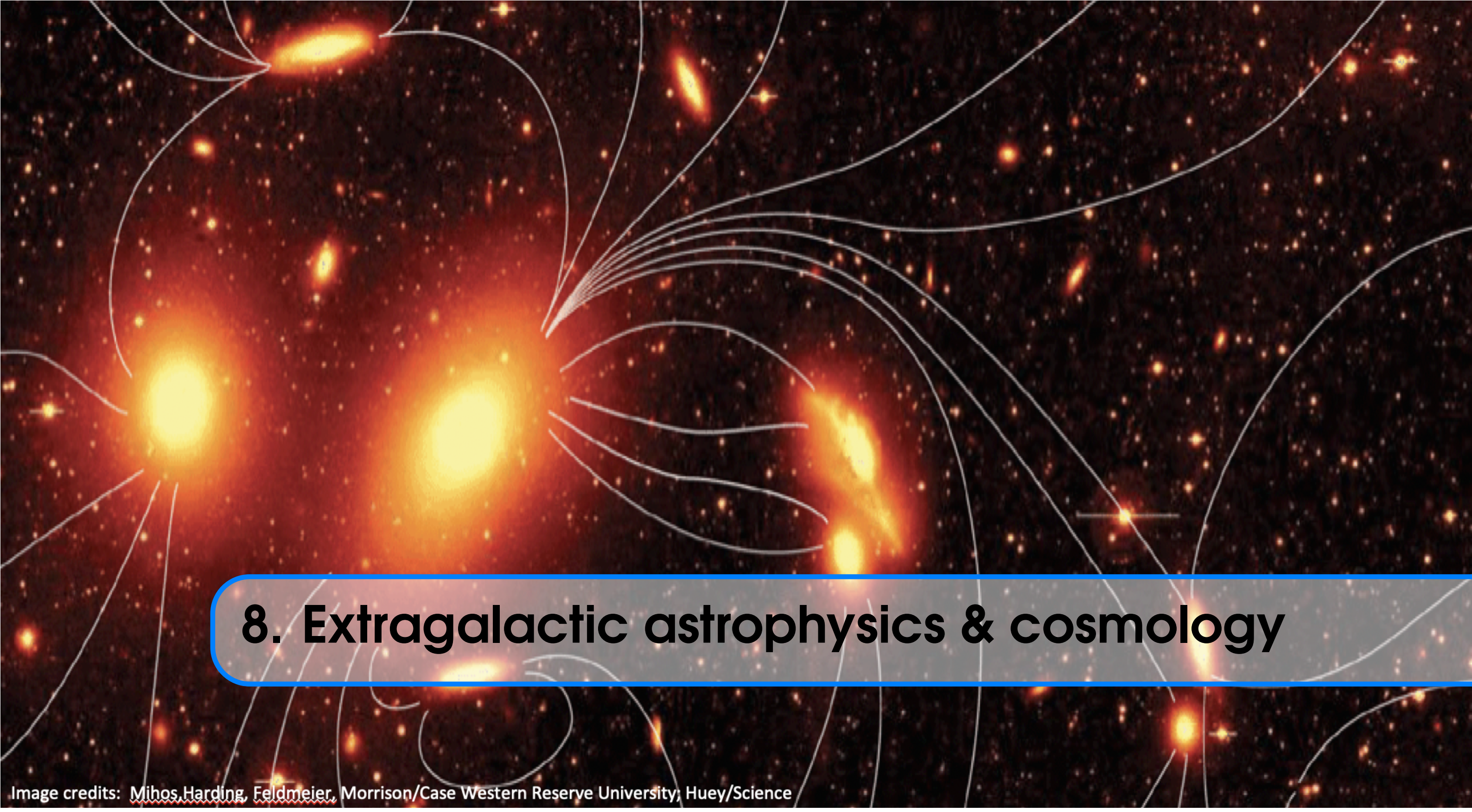
> **Highlight 22** LOFAR Faraday rotation observations have placed an upper limit of 4 nG on the cosmological co-moving magnetic field strength on Mpc scales [104].

Determining the magnetisation of cosmic voids and filaments is important because the fields in these regions are not as strongly modified from their original state as those in dense environments such as the intracluster and interstellar media. This means that they can be more straightforwardly compared with predictions from cosmological MHD simulations of different magnetogenesis scenarios. For example, recent LOFAR observations provided evidence against a model of strong primordial fields but was consistent with weaker primordial fields and an 'astrophysical' origin (i.e. a scenario where the magnetic fields are ejected into the large scale structure at later times through AGN and/or galactic outflows). Recently, a stacking analysis of diffuse radio emission at low frequencies has claimed the detection of strong magnetic fields ($\sim$10s of nG) related to synchrotron emission produced in the filaments between cosmic over-densities [160].

> **Goal 19** Use LOFAR HBA and LBA observations to generate the most accurate Faraday rotation measure grid in the northern sky, coupled with the study of diffuse synchrotron emission from cosmic filaments, to constrain the properties of the magnetised cosmic web.

LOFAR 2.0 is the ideal instrument to push the boundaries of this field, due to the exceptional angular resolution provided by the international stations, the high sensitivity to optically thin synchrotron emission with both the HBA and LBA, and the extremely accurate Faraday rotation measurements (e.g. a factor of $\sim$100 better than radio telescopes at centimetre wavelengths). In particular, these capabilities will enable the construction of the largest catalog of discrete radio sources with the most accurate Faraday rotation measures (i.e. an RM Grid) across the northern sky. Among other things, this RM Grid will allow us to push well into the sub-nG regime, providing the most stringent constraints to date on the magnetisation of the Universe.

Furthermore, the high angular resolution of LOFAR, coupled with the sensitivity to extended structures, provides an unrivalled ability to identify the host galaxies of the radio-loud AGN that make up the RM Grid. The redshifts of these galaxies will then enable robust investigations of how magnetic fields in cosmic filaments and voids are evolving with cosmic time. While these studies provide the most robust quantification of the typical magnetisation of the cosmic web, they will be complemented by efforts to obtain direct detections of the synchrotron emission generated locally at the cosmic filaments. These complementary approaches will provide a step-change in our understanding of the origin and evolution of magnetic fields in the cosmic web.



8. Extragalactic astrophysics & cosmology

8.1 Nearby galaxies

Krzysztof Chyzy & John Conway

The radio emission from normal star-forming galaxies traces the underlying distributions of thermal and relativistic plasmas, cosmic-ray (CR) electrons, and magnetic fields, thus providing vital information about the physical processes at work in galaxies. First LOFAR observations revealed that galaxies appear larger at low frequencies and have less arm-interarm contrast in their emission than at higher frequencies, indicating propagation of CR electrons from spiral arms into interarm regions [92, 95]. Spectra of galaxies at low frequencies are hard to interpret but contain invaluable data about several coexisting processes: injection of synchrotron emitting electrons, absorption by thermal plasma, CRs transport and various energy losses. In some starburst galaxies, like M 82, we observe spectral flattening that can be attributed to thermal absorption. In weakly star-forming galaxies, free-free absorption can be observed only locally, in compact regions, or at frequencies as low as the LOFAR LBA band [23]. In some galaxies, the propagation of CRs is particularly strong, manifested by an altered (sublinear) radio-infrared relation. This is to be observed at low frequencies due to long synchrotron lifetimes of CR electrons [8]. LOFAR is thus an excellent tool to study the evolution of a relativistic plasma in the interstellar medium.

> **Highlight 23** LOFAR galaxies appear larger and smoother than at higher frequencies, indicating the propagation and evolution of CR electrons.

Increased sensitivity of LOFAR2.0 would enable unique searches for very extended synchrotron emission in outer galactic disks, halos, and areas entering the intergalactic space. Multifrequency radio data and spatially resolved spectral index studies would then constrain modelling of CR-transport, the values of diffusion coefficient or escape time, and their dependence on galaxy parameters. High-sensitivity LBA observations would enable, for the first time, identification of free-free absorption and ionization processes that may prevail in very low-frequency spectra. Discrete/compact objects could be similarly examined in galaxies by LOFAR-IB, providing critical insight into the physical conditions controlling the evolution of star formation in galaxies. The enhanced sensitivity of LOFAR2.0 will enable targeting thousands of nearby galaxies spanning a very wide range of galactic star formation rate (SFR). Their emission will be used to construct a reliable dust-unbiased SFR indicator, largely free from the thermal component present at higher frequencies [59]. When properly calibrated, such a radio tracer, which is independent from optical and infrared ones, can be particularly useful for inferring SFR in objects of the distant Universe.

> **Goal 20** Use detected synchrotron emission to determine the transport and cooling of CRs in galactic outflows into the intergalactic space.

> **Goal 21** Perform high-quality imaging with LOFAR HBA and LBA to distinguish tiny effects of thermal absorption and CR ionization losses and allow galaxy radio spectra to be fully explained.

8.2 Detailed studies of low-redshift AGN and AGN physics

Raffaella Morganti & Martin Hardcastle

Radio emission from active galaxies (AGN) is driven by powerful jets that are generated from close to the central supermassive black holes but can propagate out to very large (megaparsec-scale) distances. The synchrotron emission from these jets appears at all frequencies from radio up to X-ray but they are brighest at the low radio frequencies probed by LOFAR. Though the physics of the jets and the structures they generate is of great interest in itself, it is perhaps even more important to understand the environmental impact of radio AGN which is now universally thought to be the main 'AGN feedback' process controlling the growth of the most massive galaxies at the present day. To do this we need detailed studies both of individual radio-loud AGN and of populations so that we can understand their physics, the mechanisms by which they interact with their external environments, and their lifecycles from birth through to death and beyond. LOFAR's low operating frequency, high resolution and, critically, its extremely good ability to image extended structures make it unique as an instrument for the study of these objects, which can be among the most spectacular in the LOFAR sky, and much work has been done both on individual objects and on hitherto poorly studied populations such as remnant and restarting sources ([13, 20, 58, 82]). Because of their brightness and the fact that they normally contain compact structure, radio AGN are also excellent targets for the international baselines, allowing a comparison with high-frequency observations [55].

> **Highlight 24** LOFAR observations of large samples of AGN have provided a step change in our understanding of their lifecycles and thus their environmental impact [52, 133].

In the LOFAR 2.0 era we expect advances to come in two key areas:

1. Routine availability of high-quality imaging spanning LBA and HBA frequencies (and the inclusion of LBA data in sensitive surveys) will allow us to study the radio synchrotron spectrum of large numbers of resolved sources. Resolved spectral index studies are a key diagnostic of source ages and thus of their lifetime of activity, duty cycle and so on [93]. Up to now these studies have often been limited by the quality of multifrequency radio data, but LOFAR 2.0 will make high-quality low frequency spectral mapping available on a sample basis. LBA observations may well reveal steep-spectrum structure that indicates previous epochs of activity and is invisible to the HBA.
2. The increased availability and usability of the international baselines will allow us to move to a situation where sub-arcsec (sub-kpc) resolution imaging is routinely incorporated in radio AGN studies. Whereas most AGN in the sky are unresolved at 6 arcsec, all but a small

fraction can be resolved with the international baselines, greatly expanding the scope of sample studies and allowing us to understand source environmental impact on the sub-galactic scale. In the same way, individual studies of the physics of particular objects will routinely benefit from high-resolution imaging of compact features such as jets and hotspots, probing as yet poorly understood physics of high-energy particle acceleration.

Goal 22 Develop a full understanding of the evolution and lifecycle of the radio AGN population with broad-band, high-resolution imaging on a sample basis.

8.3 Evolution of AGN and star forming galaxy populations

Philip Best

Understanding the evolution of galaxies, from the end of the 'dark ages' through to the complexity and variety of systems we observe in the local Universe, remains a primary goal of astrophysics. To achieve this, it is essential to measure the evolution of the cosmic star-formation rate density as a function of cosmic time and to determine the distribution of that star-formation amongst the galaxy population (as a function of stellar mass, galaxy morphology, environment, etc) at each redshift. These critical measurements require large, unbiased samples of star-forming galaxies across cosmic time, using sensitive observations over sufficiently wide sky areas to overcome cosmic variance. Low-frequency radio emission traces recent supernova explosions, and hence star-formation, and crucially it does so in a manner independent of dust. LOFAR's combination of high sensitivity and wide field-of-view therefore make it ideal to tackle this goal; its high angular resolution is also critical, as it limits source confusion (unlike surveys with Herschel, for example). LOFAR surveys are already identifying hundreds of thousands of star-forming galaxies, with the deepest surveys having the sensitivity to detect star-formation rates of tens of solar masses per at the peak epoch of galaxy formation ($z \sim 2$), and thus probing 'typical' star-forming galaxies at that epoch. The vast majority of these star-forming galaxiea are unresolved at Dutch resolution - in the LOFAR 2.0 era with routine international baseline imaging the sizes and internal structures of such galaxies can be determined- Such observations will constrain star-formation per unit area in these galaxies, and in the most extreme objects, trace internal free-free absorption.

Another crucial piece in the picture is the role that AGN play in regulating star formation in their host galaxies. The growth of supermassive black holes at the hearts of massive galaxies is associated with large outflows of energy, either in the form of radiation ('radiative' or 'quasar-like' AGN) or jets ('radiatively-inefficient' or 'jet-mode' AGN), both of which can have a substantial effect on the evolution of the host galaxy [57]. LOFAR surveys offer the sensitivity to detect jet-mode AGN, and study the relationships between jet-mode activity, massive galaxies, and the quenching of star formation, out to highest redshifts where the peak of both star formation and AGN activity occurs. These surveys can also identify obscured (Type-2) 'radio-quiet' AGN, quantifying the fraction of these as a function of luminosity and redshift, and providing the first complete cosmic census of black hole growth.

LOFAR is already having an impact in both of these areas, using data from both the wide-area LoTSS survey [134, 135], and the LoTSS Deep Fields [124, 144].

Highlight 25 Comparison of ultra-deep LOFAR imaging in the Elais-N1 field with the available multi-wavelength data has led to a new calibration of the radio luminosity to SFR relation, and demonstrated a clear dependence of this relation on stellar mass [138].

Highlight 26 LOFAR has shown a ubiquity of radio jets in the most massive galaxies in the local Universe [123], and measured the kinetic luminosity function of jets out to $z \sim 0.7$ [52].

LOFAR2.0 offers considerable prospects to expand on the current state-of-the-art. The higher observing efficiency and larger field-of-view for HBA observations will allow still deeper and wider surveys, probing down to the current confusion limit over sufficient cosmic volume to include all environments from rich clusters to voids. The routine inclusion of a large number of international baselines in the analysis will enable sub-arcsecond imaging, removing confusion limitations, and improving source cross-matching with the multi-wavelength ancillary data. Within the present HBA LoTSS survey 92% of sources are unresolved at Dutch only resolution (LoTSS Data Release 2, Shimwell et al 2021, in preparation) but with the addition of international baselines test observations show (Sweijen et al 2021, in preparation) all but a small fraction are resolved. High angular resolution imaging using the international baselines will therefore be a key to improving source classification, distinguishing between compact AGN (unresolved cores), star-forming galaxies (extended emission) and large-scale AGN (jet structures). International baseline HBA and LBA imaging will also allow us to determine the size distribution of AGN which in turn constrains the distribution of 'jet-mode' AGN lifetimes.

Robust deep LBA observations at both Dutch and international resolutun will enable us to improve our physical understanding of both the radio luminosity to star-formation rate relation (for star-forming galaxies) and the radio luminosity to jet-power relation (for jet-mode AGN) in the low redshift Universe, each of which is critical if these are to be employed at high redshifts.

Goal 23 Determine how the distribution of cosmic star-formation rate density depends upon redshift, stellar mass, environment and galaxy morphology, in a manner unbiased by dust.

Goal 24 Quantify the energetics of both jet-mode and quasar-mode AGN feedback in galaxy evolution across cosmic time.

8.4 Clusters and cluster halo sources

Gianfranco Brunetti, Marcus Bruggen Reinout van Weeren & Huub Röttgering

Cluster merging processes are the most energetic events known in the Universe since the Big Bang. This enormous amount of energy is converted into heat, kinetic energy and non-thermal plasma. So-called radio 'halos', 'relics' are rare (only $\sim 10^2$ known examples), Mpc-scale, steep-spectrum sources associated with shocks and turbulence in clusters [15, 154]. They trace the energetics and merger history of the cluster's interactions, an essential process related to structure formation in the Universe. Another important energy source that heats the cluster plasma is the AGN associated with the central brightest cluster galaxy. Heating by this AGN can offset the radiative cooling losses of the cluster gas, having a profound impact on the evolution of clusters [42].

Highlight 27 LOFAR discovered the first example of radio emission from a magnetized filament of the cosmic web located between to galaxy clusters [49].

Highlight 28 Using LoTSS, LOFAR carried out the first systematic survey of the most distant galaxy clusters [34]. This revealed that these clusters contain a population of ultra-relativistic particles and have surprisingly strong magnetic fields.

The unique depth and low observing frequency of LBA and HBA LOFAR2.0 surveys will result in the discovery of hundreds more diffuse cluster radio sources out to $z = 1$. This enables us to address the questions: (i) what is the impact of AGN activity on the hosting galaxy cluster? (ii) by which mechanisms are cosmic rays accelerated? (iii) are theoretical models able to predict the population of radio halos and radio relics revealed by the LOFAR2.0 surveys? Furthermore, low frequencies also trace plasma that has been re-energized through compression or other phenomena. Sources we know in this category likely represent just the tip of the iceberg but can have spectral indices as steep as $\alpha = -4$ [33]. The high angular resolution and ultra-low frequency coverage offered by LOFAR2.0 makes it the only instrument able to characterise this population.

Goal 25 Determine the history of AGN heating in clusters by tracing fossil plasma from previous episodes of AGN activity

Goal 26 Uncover the predicted population of ultra-steep spectrum radio halos related to less energetic cluster-cluster merger events.

An exciting new prospect enabled by LOFAR 2.0 is the possibility of subarcseond resolution studies of the structure of high redshift clusters using HBA+LBA International baseline observations. While for local clusters key parameters related to the magnetic fields, shocks and particle acceleration have been measured, for distant clusters this has not yet been done. This is because there was simply no instrument on the planet that could image the z > 0.6 clusters at sub-arcsec resolution, at the relevant radio frequencies (<200 MHz). Combined with Euclid data that will contain about 50,000 northern galaxy clusters up to redshift 2 and which will span more than two orders of magnitude in mass (down to 1013.5 M), the 0.3 arcsec LOFAR surveys will enable us to address the following specifc questions:

- How does the fraction of clusters with diffuse radio emission depend on their mass and redshift? Does this follow the model predictions?

– How do the properties of the magnetic fields (strength, topology) evolve? And how do these relate to models of the origin and amplification of the fields?

– How do the properties of the cluster-wide shocks (geometry, size, Mach numbers) evolve?

– How do the properties of the merging clusters (mass ratios, impact parameters) evolve as can be deduced directly from the relic morphologies?

Goal 27 Use LOFAR 2.0 international baseline observations to study the internal structures of distant (z>0.6) clusters at subarcsecond resolution and hence trace physical properties which previously could only be studies in nearby clusters.

8.5 The most distant radio galaxies

George Miley

Distant radio galaxies are among the largest, most luminous, most massive and most beautiful objects in the Universe. They are energetic sources of radiation throughout the electromagnetic spectrum. The radio sources are believed to be powered by accretion of matter onto supermassive black holes in the nuclei of their host galaxies. Not only are distant radio galaxies fascinating objects in their own right, but they also have several properties that make them unique probes of the early Universe and the formation of galaxies and clusters.

An important characteristic of high-redshift radio galaxies (HzRGs) is the correlation that exists between the steepness of their radio source spectra and the redshift of the associated radio galaxies [12, 147]. Small radio sources with very steep spectral indices at low frequencies ($\alpha < -1$) below ~ 1 GHz tend to be associated with galaxies at high redshift. The exploitation of this empirical correlation has resulted in the discovery of most known radio galaxies with $z > 2$ (e.g. [29, 122]). The most distant presently known radio galaxy is TGSS J1530+1049, with $z = 5.72$, close to the end of the Epoch of Reionisation [129].

These distant $z > 2$ radio galaxies are frequently associated with groups and conglomerates of galaxies that are believed to be the progenitors of rich Abell clusters in the nearby Universe. These proto-clusters generally have sizes of > 3 Mpc and masses of $10^{14} - 10^{15}$ MSun, comparable to local rich clusters (e.g. [159]). The beauty and "messiness" of their images rival those of LOFAR images of local clusters (e.g. Abell 2256, Perseus Cluster). An example is the famous Spiderweb Proto-cluster at $z \sim 2$ [40, 91]. Establishing how these proto-clusters form and evolve into nearby clusters will be a fundamental area of astronomy and cosmology for decades to come.

> **Highlight 29** Because of its unprecedented performance at low radio frequencies, LOFAR2.0 will provide the largest ever compendium of active galaxies at and proto-clusters from $z > 2$ up to $z \sim 6$ and into the Epoch of Reionisation.

Figure 8.1 shows the wealth of diagnostics presently accessible for studying LOFAR high-redshift galaxies. ILT radio images of (proto-)clusters at various redshifts will investigate progenitors of tailed radio galaxies, radio halos and merger remnants and allow their relationship to the hot X-ray gas, optical/IR ionized gas and molecular diagnostics to be studied from $z \sim 6$ to the present day. In this way, LOFAR2.0 will be a powerful tool for disentangling the complicated processes that drive galaxy and cluster evolution.

The identification of radio galaxies at $z > 6$, i.e. within the Epoch of Reionisation would be particularly exciting, as providing a unique new tool for studying the early Universe. At these redshifts, the hyperfine 21 cm transition of neutral hydrogen would be observed at low frequencies by LOFAR2 as absorption lines in the radio spectra of luminous background radio galaxies (e.g. [21]). This would provide a unique new diagnostic for studying the earliest epoch of the observable Universe.

The quest to find distant radio galaxies and proto-clusters by finding and identifying rare ultra-steep spectrum sources was a prime driver for the initial construction of LOFAR. With its upgrade LOFAR2.0 will provide a combination of low-frequency sensitivity and resolution that is unrivalled for detecting ultra-steep spectrum radio sources. The planned large-sky surveys with LOFAR2.0 at $10 - 90$ MHz combined with the $115 - 160$ MHz HBA large-sky surveys will contain a treasure trove of several thousand rare small ultra-steep spectrum radio sources – most of which are distant powerful radio galaxies. Measurement of the sizes and morphologies of LOFAR ultra-steep spectrum sources with the ILT and studying their dependence on redshift will give new information about radio galaxy evolution and cosmology. Multiwavelength studies of these LOFAR galaxies and (proto)clusters will drive large observational programmes on leading optical, millimeter and X-ray telescopes.

> **Goal 28** Identify 100000 powerful radio galaxies and 10000 proto-clusters at $z > 2$ and use their diagnostics together with lower redshift objects to trace the evolution of galaxies and clusters from their formation during the EoR until the present day.

8.6 Gravitational lensing

Neal Jackson/John McKean

Table 1.
Diagnostics of the early Universe to be provided by LOFAR2 distant radio galaxies and proto-clusters

CONSTITUENT	OBSERVABLE	TYPICAL DIAGNOSTICS
Relativistic plasma	Radio luminosities, morphologies, sizes, polarisations	Magnetic field, ages, energetics, pressure, particle acceleration. Jet collimation and propagation
	X-ray continuum	Magnetic field, equipartition, pressures
Hot ionized gas $T_e \sim 10^7$–10^8 K $n_e \sim 10^{-1.5}$ cm^{-3}	Radio(de)polarisation	Density, magnetic field.
	X-rays	Temperature, density, mass
Warm ionized gas $T_e \sim 10^4$–10^5 K $n_e \sim 10^{0.5-1.5}$ cm^{-3}	UV-optical emission lines	Temperature, density, kinematics, mass, ionisation, metallicity, filling factor
	Nebular continuum	SED contamination
Cool atomic gas Epoch of Reionisation ($z > 6$) $T_s \sim 10^3$ K $n(HI) \sim 10^1$ cm^{-3}	HI absorption	Kinematics, column densities, spin temperature, sizes, mass
	UV-optical absorption lines	Kinematics, mass, column densities, metallicity
Molecular gas $T \sim 50$ - 500K $n(H_2) > 10^2$ cm^{-3}	(Sub)millimeter Lines (e.g. ALMA)	Temperature, density, mass
Dust $T \sim 50$ - 500K	UV-optical polarisation	Dust composition, scattering, mass, hidden quasar
	(Sub)millimeter continuum	Temperature, mass, heating source
Old stars $t > 1$ Gyr	Optical to near IR continuum	Age, mass, formation epoch
Young stars $t < 0.5$ Gyr	UV-optical	Star formation rates, ages, history
	Lyα	Star formation rate. Relation to AGN radio jet
Quasar (hidden or dormant)	UV-optical polarisation Broad lines	Luminosity
Supermassive black Hole (SMBH)	Extended radio, Quasar	Formation, evolution, activity timeline

Figure 8.1:

Strong gravitational lens systems, in which a background galaxy or quasar is multiply imaged by the action of a foreground galaxy or cluster, are important objects for astrophysics and cosmology. In cosmology, they give estimates of H_0 [163] and potentially w [26]. In astrophysics, they allow us to measure masses and mass distributions in the lens galaxy, which is very hard to do with stellar dynamics in $z = 0.5 - 1$ objects; the lens magnification allows us to observe very faint background objects at some combination of higher resolution and higher sensitivity; and the presence of a single source viewed along two separate lines of sight through the lensing galaxy allows us to determine information about physical properties within the lensing galaxy. Typical galaxy-mass lenses cause separation between multiple images of order $1''$-$2''$, so international LOFAR is a very well-matched instrument for studying these objects. In wide-field surveys such as LoTSS, we can also measure radio fluxes for optically-selected lenses using the magnification produced by lensing and, by comparing with fluxes in the submm, determine the physical origin of the radio emission in radio-quiet objects [140], McKean et al. 2020 submitted.

Use of multiple lines of sight to study lensing galaxies has been attempted in the optical waveband to determine dust content via differential reddening of the lensed images [98]. In the radio, differential polarization along the lines of sight can be used [83] to measure magnetic fields. In addition, radio absorption may be used to study molecular gas in lensing galaxies [162], and scattering along the line of sight broadens the size of radio components, a phenomenon observed with GHz-frequency VLBI in a number of radio lenses [11, 71, 85]. Differential scattering measurements can be used to deduce scattering measure and learn about the ionized columns in lensing galaxies. Low-frequency measurements are particularly important here because scattering effects have a λ^{-2} dependence, and mas-scale differential broadening has been seen e.g. where lines of sight pass through disks in late-type lens galaxies [11, 85]. Recently we have observed the

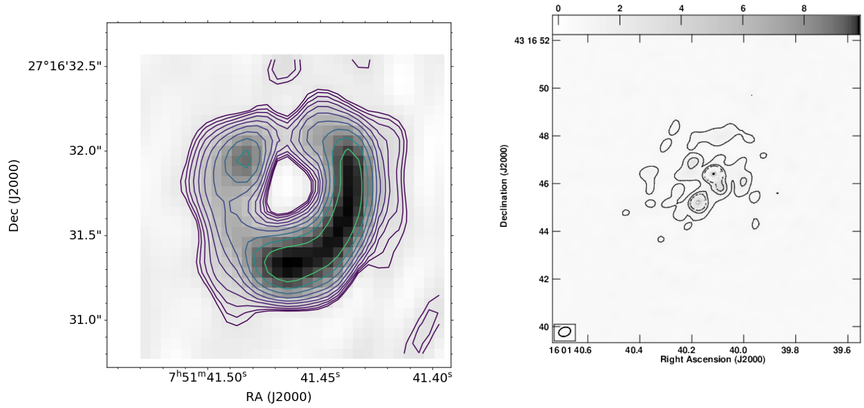


Figure 8.2: LOFAR-IB maps of two strong lenses: MG0751+2617 (left) and CLASS B1600+434 (right), both in HBA. MG0751 is a core-jet radio source lensed into an arc structure, and B1600 is a two-image lens produced by a spiral galaxy, in which the SE image is seen through the disk of the lens galaxy.

lens system CLASS B1600+434 (Badole et al. submitted) with LOFAR-IB at HBA, deriving limits on the lens galaxy scattering measure.

Highlight 30 With LOFAR-IB we have demonstrated the lowest-frequency high-resolution observations of gravitational lenses to date (Fig. 8.2), constraining the ionized columns in the lensing galaxy via scattering measure.

Highlight 31 High-sensitivity wide-field surveying with LoTSS has been used to measure radio fluxes for radio-quiet lenses in the footprint, thus investigating the physical origin of the radio emission in a way not possible if the objects were not magnified.

Because of the λ^{-2} dependence, we will be able to do a much better job in differential-scattering studies with the LBA, a regime currently closed to us pre-LOFAR 2.0 due to the difficulty of calibration of these relatively faint objects. LOFAR-2.0 opens up other possibilities in gravitational lensing studies. Using the LoTSS HBA survey will yield a large number of candidate new gravitational lens systems, most of which will be false positives. Spectral index discrimination will be possible using large-scale LBA surveys at faint flux levels, potentially aiding the first significant sample of new radio lenses in the last 20 years. In radio lenses which are already known, we can use lens models to recover intrinsic structure of the lensed radio source at different frequencies, and can therefore compare the spatial distribution of the low-frequency, steep-spectrum synchrotron components with the high radio frequency and optical/submm components, thereby elucidating the interaction between the radio plasma and molecular gas in the high-redshift background objects at much greater effective resolution than would otherwise be possible.

Goal 29 Measure properties of ionized components in a large number of distant galaxies via differential scattering in IB observations at low frequencies.

Goal 30 Use LOFAR-IB surveys at HBA and LBA to locate a new sample of radio lenses with efficient rejection of false positives.

8.7 Cosmological studies

Dominik Schwarz

Over the past decade, the concepts of cold dark matter (CDM), dark energy, a cosmological constant (Λ) in its simplest form, and an early cosmic epoch of inflationary expansion, are combined in the so-called ΛCDM model, which has been tested at per cent level accuracy by observations of the cosmic microwave background (CMB) radiation [114]. At the same time, observations of cosmic probes at smaller redshifts (supernova, gravitational lens systems, large-scale structure surveys) became much more accurate and tensions with respect to values inferred from CMB observations have been identified for the Hubble rate H_0 [120] and today's rms amplitude of matter density fluctuations S_8 [164]. While this marks impressive progress in observational cosmology, we still do not understand the nature of the dark components, which make up 95% of the energy density or the Universe. To unveil the nature of the dark components, we must study the evolution of cosmic structures with redshift and on all length scales, from the very first stars to the largest voids and filaments observed today.

Radio surveys play a unique role in this endeavour as they can probe the largest accessible scales over a huge range in redshift. The currently ongoing LoTSS [134, 135] and LoLSS [32] projects start to allow us to probe the statistical distribution and evolution of extragalactic radio sources.

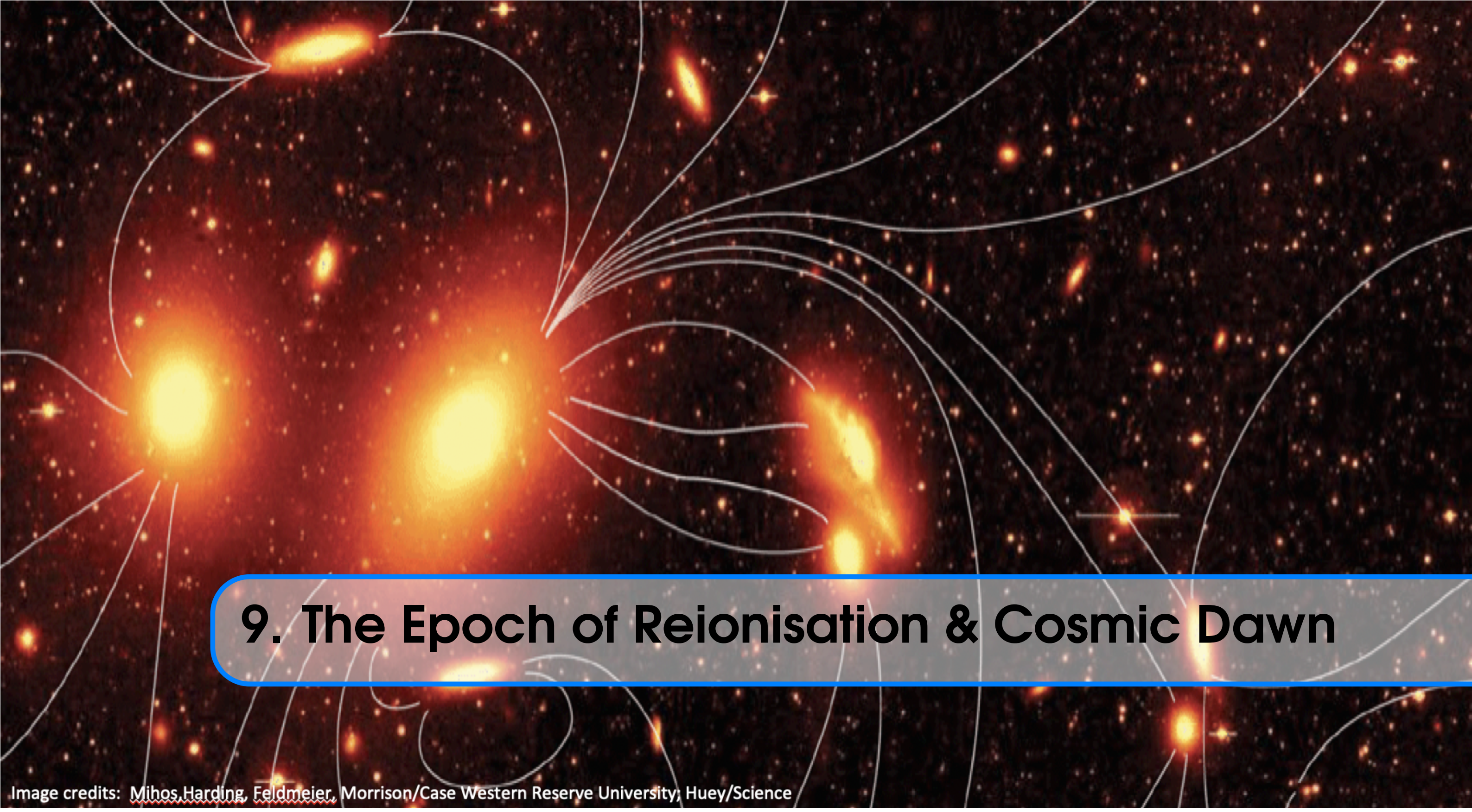
Highlight 32 The measured angular clustering of LoTSS-DR1 radio sources has been shown to be consistent with the Planck best-fit cosmology, which demonstrates that the systematic issues of low-frequency radio surveys can be handled [136]. For the first time, a positive correlation of the large-scale distribution of radio sources with the gravitational potential causing the lensing of CMB anisotropies has been detected at 5σ [1].

The upcoming LoTSS-DR2 will allow us for the first time to obtain competitive constraints on cosmological parameters from a radio survey. Together with spectroscopic follow up with the WAVE-LOFAR project (1 million of spectroscopic redshifts) and with final DR of LoTSS, LOFAR radio sources will therefore already before the LOFAR2.0 upgrade allow for a new and unique approach to the study of cosmic large-scale structure.

On the largest scales we expect to observe a radio counterpart of the dipole of the cosmic microwave background, which is believed to be dominated by a kinematic contribution. Existing wide area radio surveys (NVSS, SUMSS, WENSS, TGSS) find an excess dipole that points towards the same direction as the CMB dipole, but signals a non-kinematic contribution to the cosmic radio dipol [137].

LOFAR2.0 will allow to at least double the sensitivity for the lowest frequencies (the integration of NenuFAR could further boost the sensitivity), which suggests to focus on a high resolution LoLSS2.0 survey, starting after the peak of the next solar cycle (about at the time when the LOFAR2.0 construction and upgrade work will be completed). This will allow us to go as least as deep as for the LoTSS survey at the lowest frequencies, which will allow for the measurement of precise spectral slopes and the international baselines will allow morphological classification, which will then allow us to obtain several independent tracers of the large-scale structure. Together with a survey in the HBA high band (above 200 MHz), which will be enabled by largely improved RFI mitigation, LOFAR2.0 will be able to provide a high resolution, multi-radio-color, all-Stokes view of the Northern sky, including about 30 million radio sources or a source density of ~ 1 arcmin^{-2}. The separation of AGNs and SFGs is key to make use of cosmologcial multi-tracer techniques. While the source density of optical and infra-red survey will continue to outnumber the LOFAR2.0 surveys, extinction and thermal dust are not an issue and therefore we will be able to observe larger patches of the extragalactic universe than these other wavebands, which will allow us to make the most precise tests of ultra-large scale non-Gaussianity and the cosmic radio dipole.

Goal 31 Measure the ultra-large-scale power spectrum of AGNs and SFBs as a function of redshift to (i) constrain primordial non-Gaussianity and to (ii) resolve the nature of the cosmic radio dipole – thereby studying the origin of large-scale structures and testing the cosmological principle.



9. The Epoch of Reionisation & Cosmic Dawn

9.1 Epoch of Reionisation & Cosmic Dawn

Léon Koopmans, André Offringa & Garrelt Mellema

The study of the first stars, galaxies, black holes and intergalactic gas during the first billion years of the Universe is one of the leading science drivers of many 21st century telescopes. The building blocks of the present-day Universe were put in place during this period, and everything we see around us today is mostly the result of physical processes starting some 100 million years after the Big Bang. Over the past 20 years optical and submm telescopes have been able to detect more and more galaxies from the later parts of this era, which has been an impressive achievement. Through these studies we are learning much about how those early galaxies assembled and grew.

However, the emergence of the first galaxies not only initiated changes in the local conditions, it actually changed the state of the Universe on all scales, even the larges ones. These changes were caused by the radiation produced by the stars and accreting black holes inside the galaxies. This radiation ultimately permeated the entire Universe and changed the diffuse gas between the galaxies from cold and neutral to hot and ionized, a process known as Cosmic Reionization.

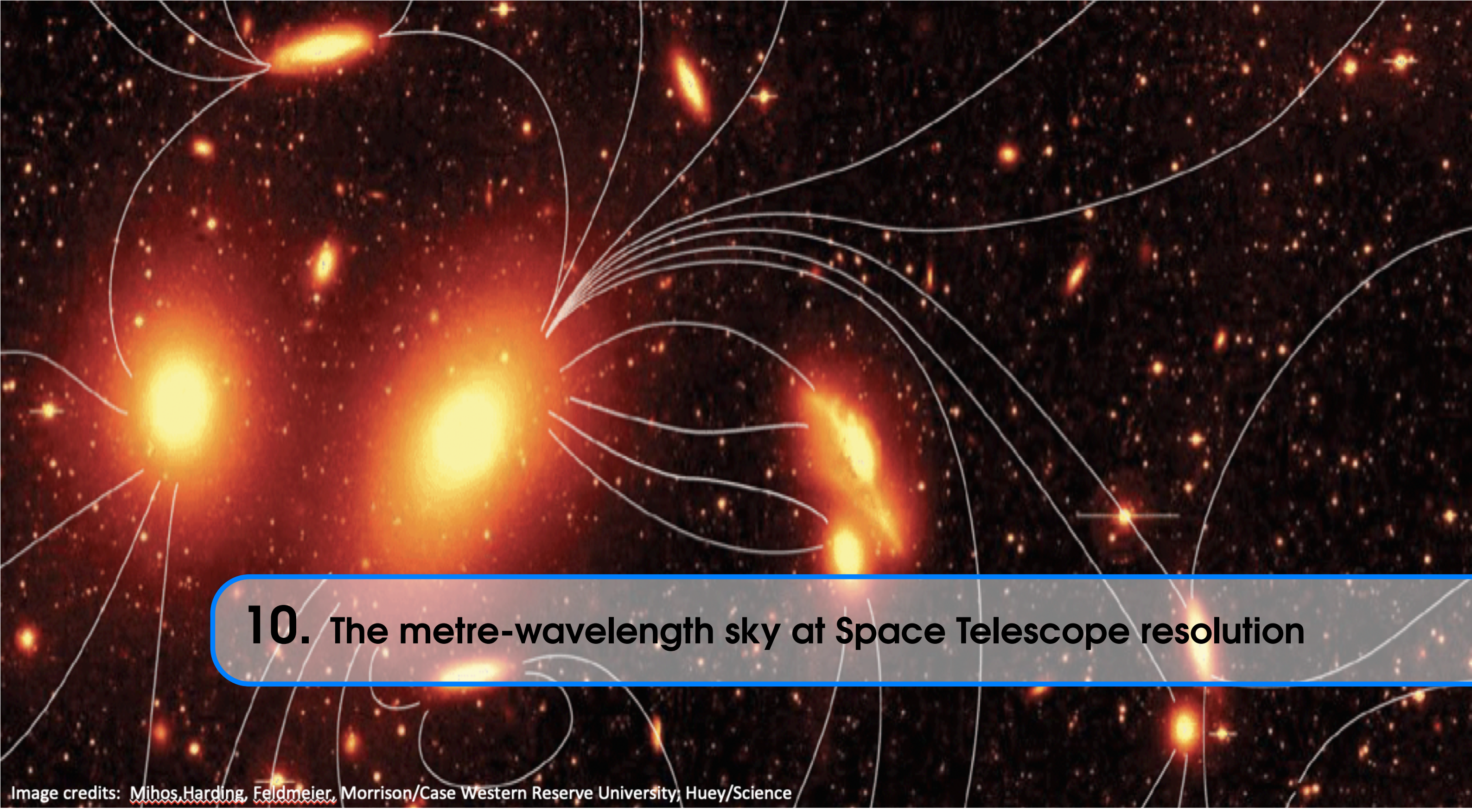
The best and most direct observational probe of this process is the 21-cm line of neutral hydrogen. By measuring this line from many different redshifts we can track the changes in the neutral hydrogen content in the Universe during the Epoch of Reionization, from fully neutral to completely ionized. The spatial distribution encodes the distribution of the galaxies which caused the process and also contains information about the density variations in the diffuse gas.

The 21-cm signal of hydrogen thus harbours the potential to unveil the physical processes of the Cosmic Dawn and Reionization, the underlying dark matter distribution, and much more, promising a transformational view of the evolving Universe during its infancy. This was a major inspiration for the construction of the first version of LOFAR, as well as for a range of other state-of-the-art radio telescopes such as the Murchison Widefield Array (MWA) in Western Australia and the Precision Array for Probing the Epoch of Reionization (PAPER) in South Africa, and the design and construction of the next-generation instrument such as HERA and the SKA.

Whereas the above-mentioned telescopes have sufficient sensitivity to detect the 21-cm signal during the Epoch of Reionization statistically, none have done so yet, because of many daunting challenges: the 21-cm signal fills the sky but its intensity is much fainter (>1000×) than emission from our own Milky Way and that from extra-Galactic radio sources. Besides these 'foregrounds', the 21-cm signal is contaminated by interference signals (e.g., transmitters, satellites), and signals from the sky are distorted by a time-varying ionosphere and observed with a time-varying and instrumentally polarised radio telescope. Hence the weak 21-cm signal is corrupted at levels far exceeding it. All these effects need to be accounted or corrected for (i.e. called "calibration"). LOFAR has been one of the premier instruments to detect the 21-cm signal from the EoR, and the latter constitutes one of its Key Science Programs. The LOFAR EoR KSP has yielded the deepest-ever limit on the strength of the 21-cm signal [ref] and is about to publish even deeper limits.

With LOFAR2.0, in particular the ability to combine the LBA and HBA frequency range and it's ability to observe a much larger field of view in the AARTFAAC mode (correlating dipoles and tiles, rather than stations), is a major step forward in LOFAR's ability to control instrumental, ionospheric and other systematics in 21-cm signal data, but also increase sensitivity on large scales where the 21-cm peaks, by enable much large volume ($>$25 times) to be survey at once. A pilot program in this mode, using only the LBA system of LOFAR, has recently been conducted (i.e. the ACE project). With LOFAR2.0 such observations can be extended to simultaneous observations of both Epoch of Reionization (HBA), and the Cosmic Dawn (LBA), which is also the observing mode of the upcoming SKA.

While the most direct approach to studying the EoR signal is via searching for red-shifted HI emission an alternative approach, if sufficiently high redshift radio galaxies can be identified, is to study HI in absorption against these sources. The potential constraints that can be imposed on EoR conditions by such absorption observations are described by [24]. Planned LOFAR 2.0 enabled broad band LBA+HBA continuum surveys will be an ideal tool (see Section 8.5) for searching for the necessary background sources, by using the fact that ultra-steep sources are preferentially detected at high redshifts. Future LOFAR 2.0 surveys are expected to detect thousands of ultra-steep extragalactic sources of which a subset are expected to have $z > 6$ and hence lie within the EoR. The redshifts of candidate sources can be confirmed by optical spectroscopy and then high spectral resolution LOFAR HI observations conducted. Such absorption searches, which are most likely occur at the top frequency end of the HBA band, will benefit from planned LOFAR 2.0 technical enhancements which will reduce the impact of radio interference at these frequencies.



10. The metre-wavelength sky at Space Telescope resolution

Leah Morabito, Neal Jackson, John Conway & Huub Röttgering

10.1 Introduction

Although radio astronomy began at metre wavelengths the desire for higher resolution soon drove its development to shorter wavelengths. Today several cm wavelength telescopes give tenths of an arc-second resolution; comparable to existing or planned space-based optical/infra-red telescopes (i.e. HST/JWST/Euclid), or to ground based telescopes using adaptive optics. At metre wavelengths LOFAR uniquely, using its international baselines, achieves comparable resolution (i.e approximately 0.3 arcsecond for HBA and 1.0 arcsecond for LBA). This resolution far exceeds that planned for SKA1-low and will remain a unique LOFAR capability well into the future.

The detailed registration and inter-comparison of sub-arcsecond structures within sources across the electromagnetic spectrum is increasingly vital for astrophysical interpretation. Telescopes from optical/infra-red, ranging through mm and centimetre, now completed by LOFAR at metre wavelengths, all give comparable sub-arcsecond resolution enabling multiband comparison. Such matched resolution observations allow spatially resolved studies of Spectral Energy Distributions - constraining different source emission components of starlight, dust, free-free and synchrotron. The detailed properties of each emission component in terms of its spectral slope and spectral turnovers can be used to constrain source astrophysical properties. Likewise the combination of matched resolution polarization information across wide radio frequency ranges allows for the determination of intrinsic polarisation strengths/orientations, Faraday rotation depths and depolarization properties, constraining the magnetic fields within sources and within foreground ionised gas.

A remarkable aspect of the International LOFAR telescope is that it uniquely combines sub-arcsecond resolution with a very wide field of view; enabling in principle the whole of the Northern hemisphere sky to be surveyed at sub-arcsecond resolution. LOFAR's low frequency of operation gives it a large instantaneous field of view, which in turn allows the sky to be surveyed with a few thousand pointings, while its very long baselines still allows sub-arcsecond resolution despite its low frequency. In comparison, while the VLA Sky survey (VLASS), operating at around 10 cm wavelength, is also surveying a large fraction of the sky it only achieves a spatial resolution of 2.5

arcsec. LOFAR at HBA frequencies improves on this resolution by a factor of > 8 while also being much deeper. It is clear that a future LOFAR DUPPLO enabled Northern sky HBA+LBA survey achieving, 0.3 - 1.0 arcsecond resolution, will have enormous legacy value. Such a survey has the incredible potential of opening up the radio regime to multi-wavelength studies in a way never seen before: imagine being able to search a database for matched-resolution sub-arcsecond resolution radio images of any source in the Northern sky.

Highlight 33 LOFAR is the only telescope to have achieved sub-arcsecond resolution at <200 MHz, enabling a variety of studies of spatially resolved active galactic nuclei and extreme star forming galaxies.

10.2 Future international baseline capabilities

It is expected that during the coming LOFAR 2.0 era LOFAR international baseline (IB) imaging will become fully automated with the goal of having intelligent pipeline scripts that can produce science ready images after simply selecting a pointing field to process. These pipelines will also employ more efficient processing algorithms and use increased computational resources so that IB data can be fully processed in less than the observing time - so keeping up with observations. The ultimate goal is that LOFAR 2.0 will automatically process all data, including IB data, collected via simultaneous LBA+ HBA observations, producing a set of images at multiple frequencies and spatial resolutions, corresponding to those provided by LOFAR core to the international baselines. This image set will by default include total intensity and full polarization information. Additionally, at least in specified directions, full spectral resolution (for spectral line studies) and high time resolution data products should also be available. It is envisioned that these data products will be produced for both PI defined pointed observations and for large area sky surveys.

The critical international baseline contributions to the above data product set will rest on the sustainability secured by implementing the LOFAR 2.0 upgrade at international stations. This upgrade will renew the ageing electronics at international stations, make these stations more robust against interference and maintain full interoperability with Dutch stations. In addition it is expected that in the future new LOFAR 2.0 international stations will be added to the array (especially in the case of new partners joining the LOFAR project). These new international stations will enhance uv coverage and potentially also resolution. An exciting long term prospect is to add stations to improve baseline coverage between Dutch baselines and the current shortest international baselines, so ensuring the robust characterisation of structure on all angular scales.

Specific LOFAR 2.0 technical improvements relevant for international baseline imaging include the option to double the field of view of HBA-only observation by forming two beams at international stations, so speeding large area HBA-only sky surveys. The largest specific LOFAR 2.0 impact will however come from the ability to conduct full sensitivity simultaneous LBA+HBA observations which use HBA to LBA phase transfer to correct ionospheric phases in the LBA data. Using this technique together with the ability to use all Dutch station dipoles and the addition of the NenuFAR telescope in France will completely transform LBA international baseline imaging. Such imaging is presently only possible toward the brightest compact sources but LOFAR 2.0 should enable LBA source location and imaging at international baseline resolution over the full station field of view.

The previous Chapters of this white paper describe in detail how the above LOFAR 2.0 IB capabilities can contribute to specific science areas. These impacts will arise from targeted observations, small surveys, or specialist observing modes, as well as from proposed future all-hemisphere HBA+ LBA survey observations. Below in Section 10.3 we first describe these sky survey impacts while in Section 10.4 other none survey impacts are presented.

10.3 Science Impacts of LOFAR 2.0 international baseline observing - Survey observations

Future all Northern sky HBA+LBA surveys, which by default fully process IB data, promise a huge scientific return. The huge legacy value of such data, and its unique combination of sky coverage, spatial resolution and sensitivity relative to other radio sky surveys is described above in Section 10.1.

At HBA frequencies, while the full IB processing of existing archived LoTSS survey data will already have a large science impact, new HBA IB data collected by LOFAR 2.0 surveys will be of higher quality - greatly enhancing discovery potential. In contrast to LoTSS the new survey can be designed from the beginning to fully integrate IB observations and processing; making use of all that has been learnt over the last decade. Given likely expansions in storage capacity this new survey data can be stored at higher time and frequency resolution allowing HBA IB resolution imaging without distortion and sensitivity loss over a much larger fraction of the sky. This advantage combined with using sky pointings interleaved in position with respect to those used by LOTSS will maximize the IB processed sky coverage - providing a higher detection rate of rare objects such as gravitational lenses. New HBA survey data will also benefit from new stations added to the array. Such additions give improved image reliability and point source sensitivity and, depending on new station locations, characterisation of intermediate scale structure or higher angular resolution. In areas of sky overlapping with already reduced LoTSS HBA IB observations the inter-comparison of the new and old IB surveys will allow compact source transient detection with maximum sensitivity. IB resolution imaging will eliminate for such transient searches confusion with host galaxy diffuse emission or (for finding Milky Way transients or other compact sources observed in the galactic plane) confusion from local galactic diffuse emission.

The LBA portion of a future LOFAR 2.0 dual band survey will be truly revolutionary for IB enabled science; producing for the first time a LBA frequencies an arcsecond resolution survey of the whole Northern sky (see Section 10.2). Furthermore all of these LBA images will be accurately registered with multiple frequency HBA survey images allowing the broad band radio spectra (and polarization properties) of millions of objects to be studied at sub-arcsecond resolution. It is again hard to anticipate all the potential science users of such a data set; as the entire northern sky has never before been surveyed at such resolution at such low radio frequencies, the potential for new discoveries is extremely high. Below we describe some of the specific known science goals that will be enabled by this revolutionary HBA+LBA survey at international baseline resolution.

– *Resolution and classification of Extragalactic Sources*– The vast majority i.e. >92% of sources detected in the current LoTSS Northern hemisphere survey (Shimwell et al 2021, in prep) are unresolved at the maximum Dutch LOFAR resolution of 6 arcseconds. IB-enabled imaging using future HBA+LBA survey data with resolution 0.3 to 1 arcsecond should resolve the vast majority of these extragalactic sources. The availability of such images will greatly aid the classification of sources into AGN or star-forming galaxies (Chapter 8.3).

– *Constraining AGN evolution*-. Since the advance speed of radio lobes is expected to show only modest variations the size distribution of radio-loud AGN depends primarily on the lifetime distribution of the AGN population. Accurate AGN size data can therefore be used to determine this lifetime distribution (Chapter 8.3), and hence determine a critical parameter in determining the energy input of AGN into galaxies and the intergalactic medium.

– *Detailed physics of AGN*– Once most of the AGN are resolved at multiple LOFAR frequencies, such data combined with matched resolution higher frequency radio data (from i.e. eMERLIN and JVLA) can be used to investigate the spatially resolved Spectral Energy Distributions (and multi-frequency polarization properties) of large numbers of AGN. Such studies include measuring spectral ages of sources, and so constraining in combination with source sizes, source expansion rate distributions.

– *High resolution Cosmic Magnetism Observations*– A large fraction of sources with currently detected polarization using Dutch LOFAR are resolved FRIII sources in which polarization is detected within their lobes/hotspots. Limits on differences in Faraday rotation measure between lobes are used to constrain the intergalactic field (see Chapter 7.3). Potentially via using IB polarisation can be detected in lobes/hotspots of the much larger population of AGNs that are unresolved by Dutch LOFAR - hence increasing the statistics of polarization detections and probing smaller LOS angular separations in foreground rotation measure.

– *Detailed physics of star-forming galaxies*– Virtually all but the nearest normal star-forming galaxies are unresolved at current Dutch.only LoTSS survey resolution. Resolving such sources allows measurement of star-formation density (i,e Star-formation rate per unit area). Low frequency spectral turnovers caused by free-free absorption mapped in starburst galaxies allow the ionised thermal gas component ins such sources to be traced. This in turn provides a measurement of star-formation which is independent of the empirical radio synchrotron to star-formation correlation.

– *Discovery and Study of Strong Gravitational Lenses*— The typical separation distance between multiple images in strong galaxy mass gravitational lenses is 1 to 2 arcseconds (Chapter 8.6) - wide area LOFAR IB observations are therefore ideal for detecting such lenses; in addition the wide frequency coverage of joint HBA+LBA IB observations will aid in identification of such lenses. Strong lens systems also provide the ability to study the propagation of radio waves from the same source through different parts of a lensing galaxy, allowing us to investigate the differential ionized columns by scattering and absorption (and eventually polarization effects); since these effects increase as λ^2, the use of the lowest frequencies is very important.

– *Compact sources in Galaxies*— IB observations of nearby galaxies, because they make use of all of LOFAR's collecing area, give the maximum sensitivity for the detection of compact sources within these galaxies. IB observations also eliminate the confusion with diffuse emission from the host galaxy. We expect IB data toward nearby galaxies to detect large populations of radio supernovae, supernova remnants and weak central AGN. There also exists a large discovery potential for finding new classes of compact sources in galaxies.

– *Stellar and exoplanet emission*— Analysis of existing LoTSS survey data at Dutch resolution is already revealing (see Section 4.1) stellar system radio emission via detection of circular polarized and/or variable emission associated in position with catalogued stars. IB observations, especially at LBA frequencies including the NenuFar station in France will maximize sensitivity and reduce confusion for detecting such stellar or exoplanet emission in survey data. In addition the IB location of emission to sub-arcsecond accuracy may prove vital to precisely identify (especially in multiple star systems) the star hosting the emission or exoplanet.

– *Transient sources*— In areas of sky overlapping with already reduced LOTSS HBA IB observations the inter-comparison of the two surveys will allow transients detection with maximum sensitivity. IB resolution imaging also eliminates for such transient searches confusion with host galaxy diffuse emission or (for Milky Way sources observed in the Galactic plane) local Galactic diffuse emission).

– *Cluster radio emission at high resolution* At Dutch resolution many radio emitting structures within clusters (i.e. shocks, and individual powering radio sources) remain unresolved, in particular at LBA resolution. Survey IB observations (see Chapter 8.4) will have sufficient resolution to reveal these structures in all detected clusters in the Northern Hemisphere, including for the first time distant clusters with $z > 0.6$.

Goal 32 Imaging the entire Northern sky at sub-arcsecond resolution with both the HBA and LBA will open a new discovery space and provide an immensely valuable legacy dataset for the entire astronomical community.

10.4 Science Impacts of LOFAR 2.0 international baseline observing - non-survey observations

The wide range of science that can be accomplished using IB data from all hemisphere survey observations is described above in Section 10.3. Also possible of course are dedicated long integration observations of individual objects or small samples of AGN, Galaxies and clusters etc. Additionally there are, as described below, other specific non-survey techniques and targeted observations producing high scientific impact from the inclusion of IB data.

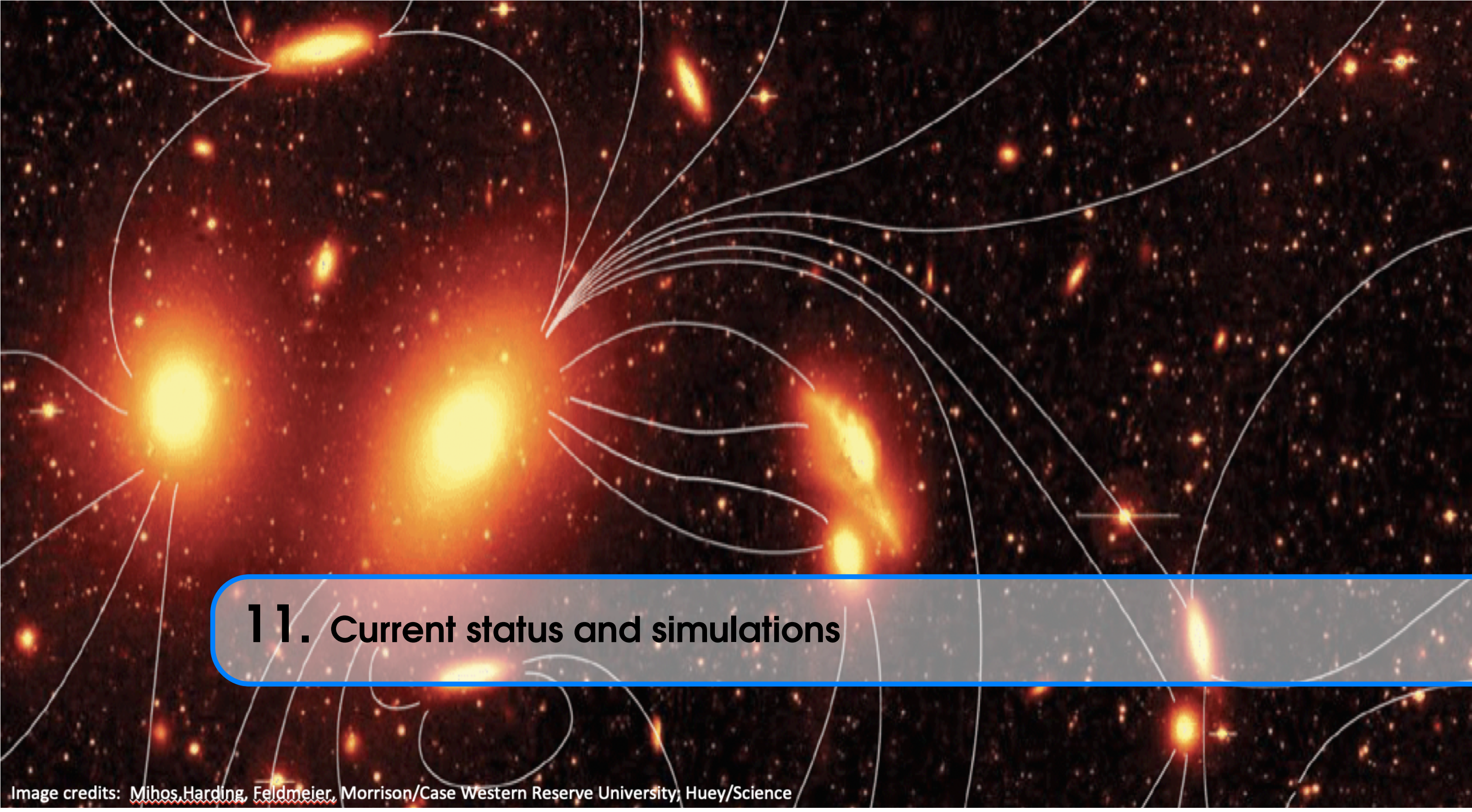
– *Space Weather studies.*– The specialized technique of Interplanetary Scintillation (IPS) makes use of HBA + LBA observations of strong scintillating sources at international stations to produce tomographic images of the interplanetary medium - providing a potentially transformative effect on this science area (see Chapter 3.2)

– *Solar System Planets*– Observations including IB data allow the accurate location and characterization of emission from solar system planetary systems. This Includes LBA IB imaging of Jupiter decametric emissions and of planetary lightning (see Chapter 3.3).

– *Nearby stars and exoplanets* – (Chapters 4.1 and 4.2). The full use of IB data gives, for deep targeted searches for exoplanet emission toward nearby stars, use of the full collecting area of LOFAR's Dutch plus international stations (plus at LBA frequencies where exoplanet detection is most likely the collecting area of NenuFAR) - so giving maximum possible point source sensitivity. Additionally for any detections closer that about 10 pc IB imaging can localize the emission within the stellar system constraining its origin, i.e. whether it comes from an exoplanet, star or star-exoplanet interaction.

– *Transient sources* – Specific none survey transient applications of IB data include Fast Radio Burst studies (Chapter 5.2) by for instance simultaneously monitoring the positions of multiple known repeating bursts. IB observations have the advantage that, depending on signal to noise, detections can be located to 10 - 50 milliarcsecond accuracy - sufficient not only to identify their host galaxy but also their local galactic environment. Other IB applications include searches for radio detections of EM Counterparts of gravitational wave events (Chapter 5.3) and Gamma Ray Burst (GRB) afterglows (Chapter 5.5). In addition to maximizing point source sensitivity and minimising confusion LOFAR IB observations can again locate such sources in galaxies to better accuracy than at other wavebands. A final application specific to long rise time transients involves searching for compact LOFAR emission at positions of known historical Supernovae in nearby galaxies (Chapter 5.4) making use of IB resolution to avoid confusion with host galaxy diffuse emission.

Goal 33 Beyond contributing to hemisphere survey observations LOFAR 2.0 International baselines can also be used to achieve unique scientific results in such diverse areas as Space Weather, Planets in our solar system Planets, targeted searches for Exoplanet and Stellar emission and Transient observations. Within the latter area are included specific projects to monitor recurrent sources (such as repeating Fast Radio Bursts) or to follow-up and precisely locate transients detected via other wavelengths or messengers.



11. Current status and simulations

Francesco de Gasperin, Henrik Edler

11.1 Calibration strategies

In the past 10 years, the LOFAR community worked towards the definition of reliable calibration strategies for low-frequency data taken in various observing modes. In this chapter, we will focus on interferometric observations. This led to the development of a set of pipelines that can automatically reduce both HBA and LBA data to an intermediate level, where all non direction-dependent systematic errors are corrected [the so-called "PreFactor" pipeline][]. Further refinement in the calibration aimed at removing direction-dependent effects were developed independently for HBA [using principally KillMS for calibration and DDFacet for imaging][] as well as the upper half of the LBA band [using DP3 for calibration and a combination of WSClean and DDFacet for imaging][]deGasperin2021. Both series of pipelines were optimised for the use of only Dutch stations, so that a set of *ad hoc* strategies were developed to include the international stations [see previous chapter and][].

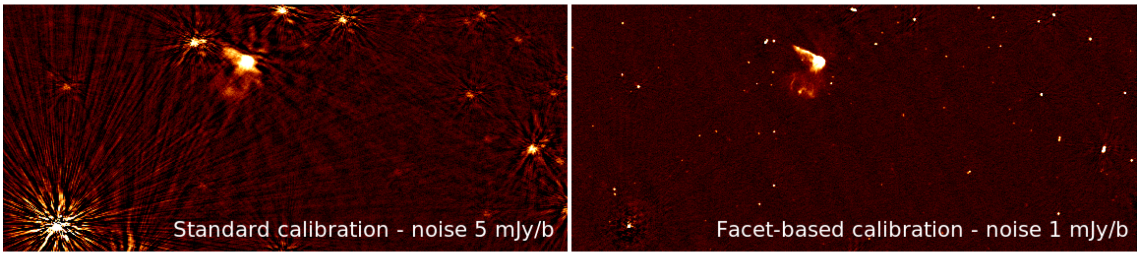


Figure 11.1: The region around the “Toothbrush” galaxy cluster at 42 MHz (λ = 7 m). This comparison shows the impact of the calibration techniques described in this section.

11.1.1 Imaging at tens of MHz with LOFAR

Currently, the calibration and imaging strategy adopted to reduce LOFAR LBA data are able to reach thermal noise level in mild to medium ionospheric conditions and only in the upper region of the LBA band (> 30 MHz; see Fig. 11.1). The calibration pipeline relies on a standard observing mode where the available bandwidth is divided among a calibrator and one or more target fields. This is used to transfer the instrumental systematic effects derived using the calibrator data to the other beams and correct them. No common strategy has been so far developed to include the international stations.

The process for the calibration is divided into a series of macro-steps:

Pre-processing: The data are downloaded from the LOFAR Long Term Archive, averaged in time and frequency, rescaled and divided into the various targets.

Calibrator calibration : The calibrator data are analysed in a series of steps, each aimed at isolating one systematic effect, including: polarisation mis-alignment, Faraday rotation, bandpass, clock delay, and ionospheric delay.

Solution transfer: Some of the solutions of the previous step are transferred to the target beams and data are combined in frequency and divided in time in chunks of one hour. Multiple observations can also be combined together for the subsequent steps.

Direction independent calibration : The 1-hr chunks of data are calibrated against a global sky model obtained from archival surveys (NVSS, WENSS, TGSS, and VLSSr). The Faraday rotation is estimated and removed, as well as the second a order beam error. Any emission coming from strong sources outside of the primary beam is removed.

Direction dependent calibration : Bright and compact sources are located across the field of view. Their flux is isolated, subtracting the rest of the field and a series of calibration steps are performed (phase and, if the source has enough signal-to-noise ratio, also amplitudes). This process is repeated in series. Finally the entire field-of-view is Voronoi tessellated around these direction-dependent calibrators and imaged applying the correct solutions to each region.

Extraction (if needed) : Sometimes, one is interested only to a specific source or region of the large LOFAR field-of-view. In this final step we subtract the non relevant sources and self-calibrate the region of interest to enhance the image quality of the region. The procedure can also merge multiple pointings to allow for joint calibration and imaging.

The combination of these macro-steps is named Pipeline for LOFAR LBA (PiLL) and it is publicly available[1]. The pipeline is tuned to work in the most optimal frequency range (around 54 MHz) and both using LBA_OUTER mode, where the 50% of the dipole in the outskirts of the stations are used, or LBA_SPARSE, where a pseudo-random distribution of 50% of the dipoles across the station are used. The pipeline can be effortlessly reused if all dipoles are used, as planned with the DUPLLO upgrade.

11.1.2 LOFAR LBA Surveys

The LOFAR LBA Sky Survey (LoLSS) is covering the sky at Dec > 24 deg at 42–66 MHz, with the preliminary data release achieving 5 mJy beam^{-1} noise at a reduced resolution of 47 deGasperin2021. A reprocessing of the same data (Data Release 1) will be publicly release in 2022 and achieve 1 mJy beam^{-1} noise at 15 resolution. In addition, the experimental LoDeSS survey is now taking 14–30 MHz observations, providing a first, albeit shallow (15 mJy beam^{-1}), look at the decametre sky. Compared to LoTSS, the current LBA surveys are rather insensitive, even for sources with steep spectra. Therefore, most of the science cases relayed around either extremely rare sources ($\alpha \lesssim -2$), or to spectral studies of relatively bright sources. The vast majority ($\gtrsim 90\%$) of LoTSS detected sources remains invisible in the current LBA surveys.

[1] `https://github.com/revoltek/LiLF`.

The LOFAR 2.0 upgrade will increase the LBA survey speed by a factor of ~ 2 due to the higher sensitivity of the stations when all dipoles are in use and by another factor of ~ 2 due to the increased computing power at station level that doubles the available bandwidth. This will enable the possibility to reach $300-500\ \mu$Jy beam^{-1} across most of the northern sky with a dedicated survey and the 100 μJy level for a selected number of fields within a reasonable amount of time ($\sim$ 100 hrs per field). The use of international stations will become more relevant in this scenario as confusion limit will be at 300 μJy level.

11.2 Simulating LOFAR 2.0

The changes brought by the LOFAR 2.0 upgrade will impact the ultra-low frequency calibration of LOFAR in a multitude of ways: the upgraded LCUs will effectively double the dipole count for the Dutch stations, increasing the sensitivity by up to a factor of two and thus, allowing for more calibrator sources per sky area. The distributed White-rabbit clock system will strongly reduce clock delays and ease delay calibration or even render it obsolete for the Dutch baselines. A further change, with an impact that is harder to judge, is the new capability of simultaneous observations with LOFAR LBA and HBA. New, innovative calibration strategies could improve calibration of the low-band, exploiting the simultaneous information of the ionospheric effects also encoded in the data of the high-band, which operates in a higher signal-to-noise regime.

To explore these new possibilities for calibration, we developed a tool to create simulated LOFAR 2.0 observations, including systematic effects such as the direction-dependent ionospheric corruptions, instrumental delays as well as the primary beam and bandpass responses. Additionally, thermal noise can be added to the data at the level expected for LOFAR 2.0, extrapolated from empiric measurements of the current system. Using this code, we simulated a full 8 h simultaneous LBA and HBA observation with LOFAR 2.0 using the Dutch stations [38]. We performed a full calibration of the simulated data and considered two different possibilities to improve low-band calibration utilizing the simultaneous observation: the ionospheric TEC could be determined in HBA for a large number of directions, and then these solutions could be applied to the LBA data. Alternatively, the ionospheric parameters could be estimated using data of both LBA and HBA together. In the first scenario, the procedure is less complicated and does not require further advances in software. In the latter, a significantly larger bandwidth could be leveraged to more precisely fit the characteristic spectral behavior of the ionospheric delay. By comparing the calibration solutions to the corruptions used in the simulation, we found that the underlying ionospheric parameters could be determined most accurately when estimated jointly from both frequency bands of LOFAR. Contrary, the solution transfer approach is very susceptible to the presence of remaining, non-ionospheric phase errors in the HBA data. The presence of such residual errors shifts the estimated TEC by some amount, such that minimum of the χ^2 distribution in the HBA data is attained. However, if these TEC values are then applied to the LBA data, the phase-errors caused by the TEC-offset are amplified as ν^{-1} and do not, in general, coincide with the χ^2 minimum in LBA. Therefore, the solution-transfer method can only be used if the HBA data is free of any significant non-ionospheric phase errors.

II The LOFAR2.0 Use Cases

12. Use Case 1:

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