LOFAR – Low Frequency ARray

Short Scientific-Technical Description

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An international telescope

While LOFAR started as a national project in the Netherlands, consortia of institutes and researchers in several other countries soon placed orders to build one or more LOFAR antenna stations there. The enormous range of distances between the stations yield unique capabilities for detailed images of the sky.

The collaboration was consolidated with an MoU signed in 2010 in the presence of H.M. Queen Beatrix, and establishment of the International LOFAR Telescope (ILT) as a foundation under Dutch law. After a decade, the ILT has grown to encompass nine countries. Next to the Netherlands (38 stations), these are Germany (six stations), Poland (three stations), France, Ireland, Latvia, Sweden, and the United Kingdom (one station each); stations in Italy and Bulgaria are funded to be built soon. Still more countries are considering to join as well

LOFAR as a European Research Infrastructure Consortium

LOFAR, designed and built by ASTRON in the Netherlands, is a distributed research infrastructure enabling world-leading radio astronomical research. During a decade of continuous operation, it has grown to a pan-European scale, with a diverse and expanding set of partners (presently in nine countries).

The partnership has initiated LOFAR2.0 – a major upgrade to deliver excellent, innovative science throughout the present decade and beyond. The LOFAR2.0 upgrade addresses a range of cutting-edge science use cases, compiled in close interaction with the research community. LOFAR2.0 is designed to be impactful and complementary to other major science facilities in the landscape of this decade; this gives urgency to the establishment of the LOFAR ERIC (European Research Infrastructure Consortium).

The LOFAR ERIC will provide the optimal vehicle, clearly positioning this major facility in the partner countries and in the European landscape. Maintaining the common vision and policies requires appropriately aggregated long-term membership and funding stability. The partners aim for the LOFAR ERIC to jointly purchase the LOFAR2.0 hardware. The LOFAR

ERIC can then conduct timely and coherent rollout to the distributed stations, testing, and operations phases.

A working group of Ministerial and science delegates from all current partner countries in the ILT has been formed. The Netherlands is the intended host country. Under the leadership of the Netherlands Ministry of Education, Culture, and Science, the Interim LOFAR ERIC Council has submitted to the European Commission the first-stage application to form LOFAR ERIC, with a view to establish it in 2023.

Science with LOFAR

The revolutionary multi-beaming capabilities of the LOFAR telescope allow astronomers to engage in multiple lines of research at once: they can look back billions of years to a time before the first stars and galaxies were formed (the so-called 'Dark Ages'), they can survey vast areas of the low-frequency radio sky, and they can be constantly on the lookout for radio transients originating from some of the most energetic explosions in the universe.

The Epoch of re-ionisation

The Epoch of Reionization (EoR) is the period during which the neutral gas in the Universe was completely ionised by the first stars and galaxies. This important event occurred when the Universe was a few hundred million years old (about a twentieth of its current age) and is critical in understanding how the first stars and galaxies formed. Observations of the 21cm (1420 MHz) line, red-shifted to frequencies between 70 and 200 MHz, are a unique probe of this era. LOFAR is the key pathfinder to investigate how to solve the calibration and imaging challenges at these low frequencies. Once these are solved, several thousand hours of LOFAR observations (a few peta-bytes of data) are needed to detect the very faint hydrogen signals.

Deep Extragalactic Surveys

The International LOFAR Telescope offers a transformational increase in radio survey speed compared to existing radio telescopes, as well as opening up one of the few poorly explored regions of the electromagnetic spectrum. For these reasons, an important goal that has driven the development of LOFAR since its inception is to explore the low-frequency radio sky through surveys, in order to advance our understanding of the formation and evolution of galaxies, clusters and active galactic nuclei (AGN).

The LOFAR Surveys Key Science Project has planned a wedding-cake survey strategy, with three tiers of observations, to be carried out over the next 5 years. Tier-1 is the widest tier, and includes low-band (LBA) and high-band (HBA) observations across the whole northern sky. Deeper Tier-2 and Tier-3 observations cover smaller areas, focusing on fields with the highest quality multi-wavelength datasets available across a broad range of the electromagnetic spectrum.

Reducing LOFAR radio data is a major challenge. This is due to the enormous data rates, bright sources far away from the pointing centre dominating the signal, radio frequency interference from radio, TV and planes and the corrupting influence of the ionosphere. The breakthrough idea was 'facet-calibration' and enables us to produce, for the first time ever, thermal noise limited maps at low frequencies with an angular resolution of ~5 arc seconds from 8 hours of data.

A key aim of the project is to study the properties of shocks and turbulence in merging, low-redshift galaxy clusters. The facet calibration technique has resulting in some of the most sensitive and high-resolution low-frequency images that have ever been produced. These images are highlighting new insights whilst revealing many new questions into how particles are accelerated within the intra-cluster medium (ICM). An excellent example is the LOFAR image of the `Sausage cluster', enabling the most precise characterisation of a cluster shock ever.

Transient sources and pulsars

The cosmic lighthouses known as 'pulsars' shine brightest in long-wavelength radio light, making LOFAR an ideal telescope for studying them. With its huge sensitivity and enormous computational power, LOFAR has already discovered 50 new pulsars, including a pair of millisecond pulsars, as part of its all sky survey, LOFAR Tied-Array All-Sky Survey (LOTAAS), and dedicated searches.

The exceptional sensitivity and wide bandwidth have also enabled LOFAR to make detailed studies of the emission properties of the largest ever samples of normal and millisecond pulsars. Pulsars also provide us with excellent probes of the ionised interstellar medium and magnetic fields and at LOFAR frequencies it is revealing new information on how they vary as a function of space and time through detailed studies of individual objects and precision timing observations

LOFAR has also been used in combination with the XMM-Newton X-ray telescope to reveal the perplexing relationship between the radio and X-ray emission from two pulsars which show variable radio emission. High-energy astrophysical sources such as pulsars and black holes can also be associated with ejections of matter and energy at close to the speed of light. Such relativistic outbursts have a characteristic signature in the radio band, and LOFAR has been used to both search for new events, utilising its enormous field of view, and to follow-up events first detected with other facilities such as orbiting X-ray telescopes and Advanced LIGO (Laser Interferometer Gravitational-Wave Observatory).

In the past year astronomers have discovered LOFAR's first 'blind' (previously unknown) transient, in the direction of the north celestial pole, and measured the low-frequency spectrum of radio emission from a nearby black hole, V404 Cyg, in outburst and followed-up the first detection of gravitational waves.

Ultra-high energy cosmic rays

Astroparticle physicists have known for a long time that there are extremely energetic particles (ionised atomic nuclei, i.e. atomic nuclei without surrounding electrons) that travel through our Universe. These particles carry macroscopic energies of tens of Joules, concentrated in one elementary particle. These particles have energies many thousand times bigger than what can be achieved in man-made accelerators.

How and where nature accelerates these highest-energy particles in the Universe is an open question. The favourite explanation is that they are being accelerated by exploding stars (in so-called supernova explosions) in our Milky Way and by supermassive black holes at the centre of other galaxies.

In these active galaxies, a black hole is swallowing material and ejecting jets at velocities close to the speed of light. It is commonly assumed that up to a certain energy cosmic rays are accelerated in our Milky Way and at the highest energies they are originating in other galaxies, i.e. they are of an extragalactic origin.

LOFAR offers the unique possibility to study the origin of high-energy cosmic rays through the detection of sharp pulses of radio emission that are associated with air showers, caused by the interaction of cosmic rays with the Earth's atmosphere.

A key method to explore the origin of cosmic rays is to measure their properties at Earth, such as their arrival direction, their (kinetic) energy, and the type of particle, often expressed in terms of the atomic mass. In recent publications, it has been shown that these properties are measured with unprecedented precision with LOFAR. The technique to measure the properties of cosmic rays through the recording of MHz radio pulses has been established by LOFAR and is now routinely used to explore the origin of cosmic rays. First LOFAR data are already constraining astrophysical models of the origin of cosmic rays. The data give new insights into the transition region from an origin of cosmic rays in our Milky Way to extragalactic sources.

Solar science and space weather

The Sun's activity appears not only in the well-known 11-year Sunspot cycle but also in short duration eruptions as flares and coronal mass ejections (CMEs). Such eruptive events can harmfully influence our Earth's environment and technical civilisation and are usually called Space Weather. These events are accompanied with an enhanced radio emission of the Sun especially in the frequency range (30-240 MHz) covered by LOFAR.

Hence, LOFAR is of great interest for solar physicists, since LOFAR with its spectroscopic and imaging capabilities is well suited for studying active processes in the Sun's corona. This is the reason why the Key Science Project "Solar Physics and Space Weather with LOFAR" was founded. During LOFAR's commissioning phase and the first cycles of regular observations, the solar KSP performed observations of the Sun together with ASTRON.

An example is presented in the figure below, showing the propagation of a type III burst source along the coronal magnetic field (white lines) through the corona. This example impressively demonstrates that LOFAR can really work as a dynamic spectroscopic radio imager of the Sun and is able to track fast motions