Radio sky surveys with LOFAR telescope

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The International Low-Frequency Array (LOFAR) was designed as a highly efficient radio interferometer to perform sky surveys in the poorly explored low-frequency part of the electromagnetic spectrum. We briefly describe the instrument and review some recent observational results from the first and shallow Multifrequency Snapshot Sky Survey, as well as from the current much deeper LOFAR Two-metre Sky Survey. These results show the enormous potential of LOFAR for studying active galactic nuclei and star-forming galaxies, intergalactic magnetic fields, and cosmic ray propagation processes in galactic disks. We also mention LOFAR deep surveys and subarcsecond resolution surveys possible in future.

1 Introduction

LOFAR is the largest radio telescope operating at the lowest frequencies that can be observed from Earth. It opens up a window on one of the last poorly explored regions of the electromagnetic spectrum from 10 MHz to 240 MHz. Currently it consists of 52 ultra-modern antenna stations spread throughout Europe and connected by a high-speed fibre optic network. LOFAR works as an interferometer, combining the signals from a number of individual antenna dipoles and using powerful computers to process the radio signals as if they come from a virtual 'dish' of about 1300 km in diameter.

LOFAR has been designed, built and operated by ASTRON (the Netherlands Institute for Radio Astronomy). Polish astronomers have a significant share in this project: three LOFAR stations built in 2015 are now used 24/7 in Łazy (near Kraków, managed by the Jagiellonian University), Bałdy (near Olsztyn, University of Warmia and Mazury), and Borówiec (near Poznań, Space Research Centre of the Polish Academy of Sciences). Fast, dedicated Internet connections over the PIONIER network are provided by the Supercomputing and Networking Centre in Poznań to feed the signal from Polish station to the correlator in Groningen, The innovative digital system along with very long baselines makes LOFAR an excellent tool for studying radio sources at the highest sensitivity, spatial and spectral resolution achieved in this frequency regime to date (van Haarlem et al., 2013).

Problems with signal calibration due to high influence of the Earth ionosphere at low radio frequencies forced LOFAR users to develop and apply non-standard and computationally intensive methods, like advanced directional-dependent calibration techniques. Another unique feature of LOFAR is that it has no moving parts. Pointing the station beam in a given direction at the sky is achieved by software introducing time delays to the individual dipole antennas, which can see the entire sky. This allows the antenna station to look at different directions to the sky at the same time by using different sets of delays. The only limitation is the bandwidth of digital connections with the correlator and the capacity of modern computers. Thus LOFAR is an excellent and efficient instrument for making sky surveys.

2 MSSS Survey

The first LOFAR survey of the entire northern sky – the Multifrequency Snapshot Sky Survey (MSSS) – has already been completed (Heald et al., 2015). Although the survey is of relatively low spatial resolution ($\approx 3'$) and moderate sensitivity (of about 15–25 mJy beam^{-1}), it can be used to study extended objects in the sky such as nearby galaxies. The project, which was led by the Kraków group (Chyży et al., 2018), consisted of studying the low-frequency spectra of nearby galaxies.

We compiled a sample of over a hundred galaxies exhibiting different amounts of star-forming activity, for which we constructed integrated spectra over a wide radio range (Fig. 1). They show only weak curvatures manifesting small flattenings, not related to galaxy inclination.

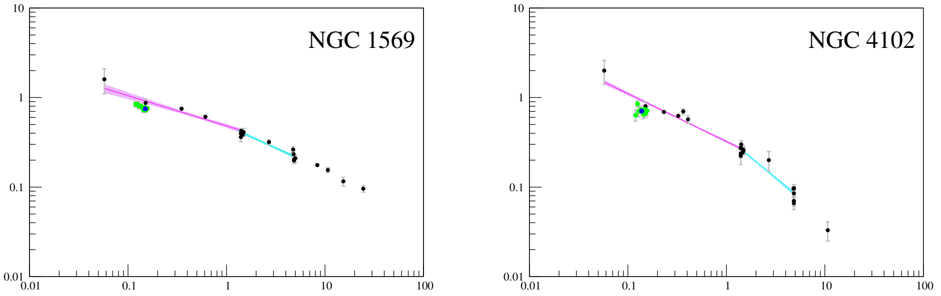

Fig. 1: Two examples of radio spectra of nearby galaxies from the MSSS survey. The flux densities from eight individual MSSS spectral bands are in green, the interpolated MSSS flux densities at 150 MHz are in blue, other published measurements are in black. The pink and black lines represent the low- and high-frequency power-law fits respectively, excluding points with possible contribution of thermal emission.

We suggest that such spectral curvatures can arise from synchrotron and inverse Compton energy losses of CREs, and their propagation across galaxies.

3 LoTSS survey

Recently, an international team comprising more than 200 astronomers from 18 countries published the first phase (Data Release 1) of the new LOFAR Two-metre Sky Survey (LoTSS). The newly released mosaicked images cover 20% of the northern sky with $6''$ resolution and unprecedented sensitivity of about 70 μJy per beam in the 120-168 MHz band. The survey has been expanded on daily basis (Fig. 2).

A special issue of the Astronomy & Astrophysics journal was dedicated to the first twenty-six research papers describing the survey and its first results (Shimwell et al., 2017). Scientists from two Polish universities: the Jagiellonian University in Kraków (five people) and the Nicolaus Copernicus University in Toruń (two people), took an active part in this big radio event, contributing several articles. The survey reveals hundreds of thousands of previously undetected galaxies and accurately maps the known ones, shedding new light on many research areas, as the physics of black holes, evolution of galaxy clusters, and processes occurring in the galactic interstellar medium.

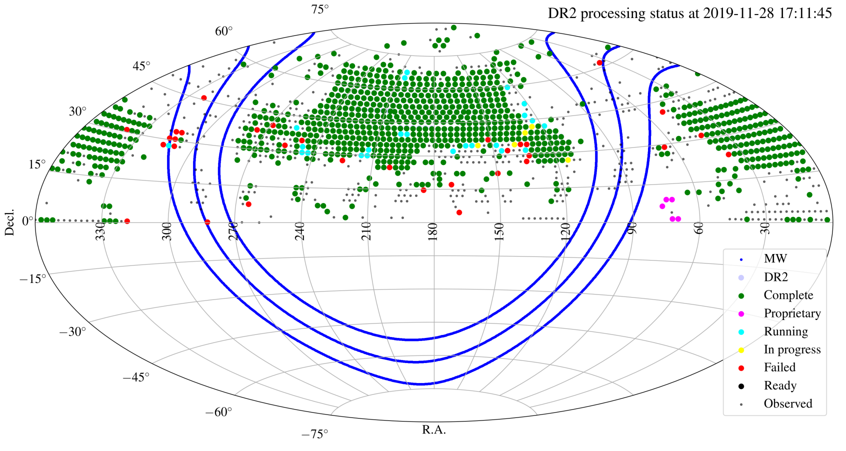

Fig. 2: The current status of LoTSS processing (Data Release 2). Fields in green were observed and their reduced data are available for analysis. Credit: Surveys Team.

3.1 Active galaxies

Data products of the LoTSS survey includes sky images/mosaics and the catalogue of sources detected automatically by the Python Blob Detector and Source Finder (PyBDSF). The catalogue consists of 318,520 radio sources (Williams et al., 2019). It was enhanced by identifying optical (Pan-STARRS) or infrared (WISE) counterparts of host galaxies using a cross-fit probability factor or visual inspection for complex sources. In the second case, a special platform in the Zooniverse project, called LOFAR Galaxy Zoo, was constructed to facilitate the identification process.

Over 230 thousands of sources have its counterparts in optical or infrared surveys. For these objects photometric redshifts were estimated and galaxy host properties provided (Duncan et al., 2019). The catalogue is available from `https://lofar-surveys.org` and constitutes an original and rich source for scientific investigation.

Basing on the LoTSS catalogue Hardcastle et al. (2019) presented an analysis of 23,000 radio-loud Active Galactic Nuclei (AGNs) from the celestial region known as the HETDEX Spring Field. The sources were studied on the life diagram: radio-power versus linear size, and then compared with an analytical model of source evolution. For strong sources, the observed objects correspond well with the model and most of actual sources are at an advanced age. However, the weaker ones do not fit well the model, which positively suggests some additional population of weaker and smaller sources, with perhaps different fuelling mechanisms of the AGNs.

With LOFAR one can also study magnetic fields in the intergalactic medium using Faraday rotation effects. Such an attempt was made by O'Sullivan et al. (2019), who studied a giant radio source J1235+5317, located behind several cosmic web filaments of size of about 1 Mpc each. Polarized emission from the lobes and

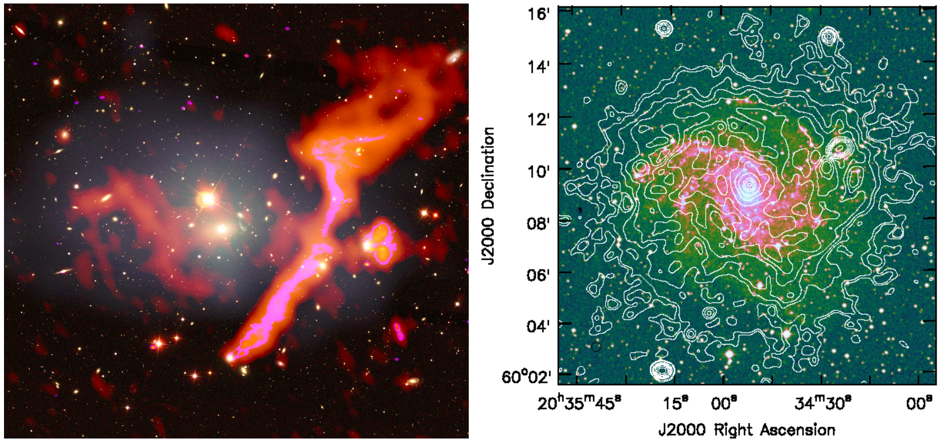

Fig. 3: Left: The galaxy cluster Abell 1314 (seen in the centre) is probably in the merging process. Non-thermal radio emission detected with LOFAR is shown in red and pink, and thermal X-ray emission detected with the Chandra telescope is shown in gray, overlaid on the optical image. Credit: Amanda Wilber/LOFAR Surveys Team. Right: LORAR radio emission of NGC 6946 at 144 MHz overlaid on optical emission (Piotrowska et al. in prep.).

a difference in their Faraday rotation measure of $2.5 \pm 0.1\,\mathrm{rad\,m^{-1}}$ were detected. However, the probability that the difference is due to primordial magnetic fields remaining after the early phases of the Universe appeared to be rather small – only about 5%. Thus a larger statistical sample of similar sources is needed to better assess intergalactic magnetic fields, while the concept has been actually proved.

3.2 Galaxy groups and clusters

The LoTSS survey sparked off systematic radio studies of groups of galaxies (Nikiel-Wroczyński et al., 2019). It turns out that 63% of known groups have their counterparts in the LoTSS catalogue. On the other hand, 14% of them reveal extended emission. Several systems exhibit relatively strong magnetic fields, which can suggest that they affect the dynamics of the gas within the group and influence the evolution of such systems.

A large team of radio astronomers examined galaxy clusters in the LoTSS survey. Of most interest it seems to be the diffused emission of clusters, which comes in the form of extended envelopes (halos) around the cluster centres and radio relics at their edges. These structures are produced by gravitational interaction and merging of clusters, leading to large-scale shock waves, which in turn accelerate cosmic ray electrons (CREs). Studies of synchrotron emission of such CREs give an insight into the dynamics and evolution of clusters.

An example of such research is the analysis of radio emission of the Abell 1314 cluster (Wilber et al., 2019). It is probably just merging, showing an extended radio envelope which initiates mechanisms to accelerate CREs in the large 800 kpc tail of the radio galaxy IC 711 (Fig. 3 left panel).

3.3 Nearby galaxies

Nearby galaxies appear different at low radio frequencies than at higher ones and in the optical bands. An example is NGC 6946 in Fig. 3 (right panel), in which the radio emission seen with LOFAR at 144 MHz is much more extended than the optical emission, and the arm-interarm contrast is lower at low radio frequencies. Similar behaviour was also observed with LOFAR for M 51 galaxy (Mulcahy et al., 2014). This is most likely due to different CRE properties in different parts of the galactic disk as well as to the nature of synchrotron radiation. Because CREs, radiating at low radio frequencies, are of relatively low energy – according to the synchrotron formula:

$$\nu_c \propto E^2 B, \tag{1}$$

where ν_c is the critical frequency of radiation, E is the energy of CREs, and B is the magnetic field strength, the synchrotron lifetime

$$\tau \propto E^{-1/2} B^{-3/2} \tag{2}$$

for such CREs is longer. They can therefore travel by diffusion further from their acceleration zones in the spiral arms to the interarm regions and galactic outskirts than the higher-energy CRE, which radiate at higher frequencies.

Another interesting effect that can be studied in galaxies using LOFAR is the radio–far-infrared (FIR) correlation. This relation is known to be linear for galaxies of various radio luminosities and redshift. Fig. 4 presents radio-FIR relation constructed for different regions of NGC 6946. We used Hershel 100μm and LOFAR 138 MHz data. There is a significant difference in the slope of the correlations obtained for the arm and interarm regions. A similar relationship constructed at 1400 MHz does not show such a strong brake in the slope, although a weak sublinear trend for the interarm regions is also observed. The CRE diffusion can again account for such a broken radio-FIR relationship. LOFAR is therefore a unique tool in studying and modelling cosmic ray transport in galaxies.

LOFAR can be also of help in understanding other processes that are apparently stronger at low frequencies e.g. thermal absorption and ionization losses of CREs. Radio emission could be used to estimate the star formation rate of galaxies as well, apart from the other well-known star formation tracers (Heesen et al., 2019).

4 Deep fields and future surveys

The images, calibration software, and catalogues of LoTSS DR1 have been publicly available since February 2019. Next release of the survey data (DR2) will be available soon, covering a larger portion of the sky and providing a catalogue of about 2 mln sources, the largest one in radio astronomy so far.

LOFAR is also used for deep surveys (with sensitivity of about 20 μJy per $6'' \times 6''$ beam) of several sky fields to probe properties and evolution of star-forming and active galaxies in the distant Universe, as well as to study in greater detail nearby galaxies and clusters. Several LOFAR deep fields will become public this year.

LOFAR paves the way for the Square Kilometre Array (SKA), which will be the largest and most sensitive radio telescope in the world. Recently it has been proposed to perform a survey of the entire sky with outstanding subarcsecond resolution. First

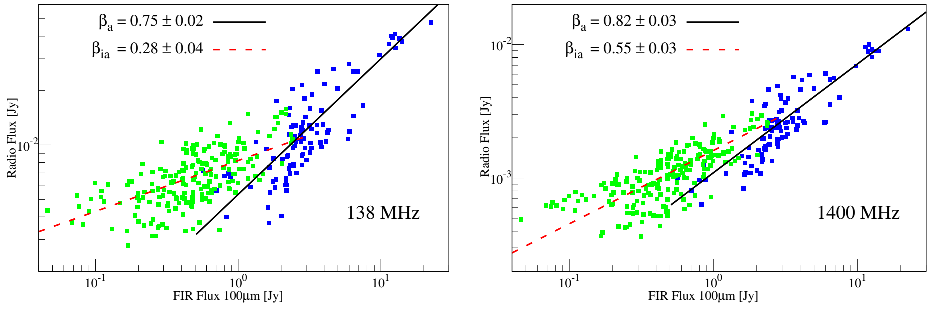

Fig. 4: Radio – FIR relation for regions within NGC 6946 at 138 MHz and 1400 MHz: blue dots denote star-forming regions in the spiral arms; green dots mark interarm regions. The slopes in the power law fitted to the data points are also given for the arms and interarm regions (β_a and β_{ia} respectively, Piotrowska et al. in prep.)

experiments indicate that this is possible while using international stations, including those in Poland. Such upgrading of the LOFAR telescope, especially at frequencies below 100 MHz, will give us an instrument unsurpassed even in the SKA era.

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