Probing the Magnetic Fields of Nearby Spiral Galaxies at Low Frequencies with LOFAR

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Abstract

While the Low Frequency Array (LOFAR) is still in its commissioning phase, early science results are starting to emerge. Two nearby galaxies, M51 and NGC4631, have been observed as part of the Magnetism Key Science Project’s (MKSP) effort to increase our understanding of the nature of weak magnetic fields in galaxies. LOFAR and the complexity of its calibration as well as the aims & goals of the MKSP are presented.

1 Introduction to the Low Frequency Array

LOFAR is a next generation radio telescope currently in its construction & commissioning phase. Its core is located in the Netherlands and the international stations are located in Germany, France, Sweden and the UK, with plans to expand to additional European countries. The LOFAR telescope consists of two distinct types of antennas, namely the Low Band Antenna (LBA) which operate between 10 and 90 MHz and the High Band Antenna (HBA) which operates between 120 MHz and 240 MHz. A single LBA antenna is able to see the entire sky and the telescope is pointed by forming beams at each station. Single HBA tiles (each of which contain 16 dipole pairs) have a large field of view but are not able to observe the entire sky (Stappers et al. 2011 & van Haarlem, Wise, et al. in prep). The data from all stations are then correlated at a central supercomputer.

LOFAR, due to its bandwidth and low frequency, can measure Faraday rotation measures (RM) with a very high precision. We will use “RM Synthesis” (Brentjens & de Bruyn 2005) and thereby detect weak magnetic fields and low electron densities in galaxies which are
unobservable at higher frequencies. The high RM precision of LOFAR will also help to study RMs from pulsars, stellar and AGN jets, and the lobes of radio galaxies with unprecedented accuracy.

2 Introduction to the MKSP

The main aim of the international LOFAR Key Science Project on Cosmic Magnetism in the Nearby Universe (MKSP) is to observe the magnetic fields in the Milky Way and nearby galaxies by observing total and polarized radio synchrotron emission at very low frequencies. Low-frequency radio emission traces low-energy cosmic-ray electrons which suffer less from energy losses and can propagate further away from their acceleration sites into regions with weak magnetic fields. Trying to detect polarization at these low frequencies is a challenge in itself and can be best done through RM Synthesis. RM Synthesis will allow the investigation of the 3-D structure of magnetic fields in the Milky Way and in nearby galaxies. We plan to use LOFAR to detect the radio emission in galaxies at distances of tens of kpc from the star-forming disks and study structures like extended gaseous halos of spiral and dwarf irregulars, or tails of interacting and stripped spirals. The MKSP encompasses several research groups focused on: the magnetic field of the Milky Way through continuum observations as well as pulsar Rotation Measures (RM); the magnetic fields of nearby galaxies and giant radio galaxies; intergalactic filaments & finally stellar jets.

RM Synthesis has already been used on LOFAR data to successfully detect polarization. Emission in Stokes Q & U was seen alternating for the pulsar PSRJ0218+4232 (Heald et al. 2011). RM Synthesis was performed and showed that the pulsar has a Faraday Depth of about 61 rad/m$^2$ which agrees with published data. Currently, efforts are concentrating on finding pulsars that could be used as polarized calibrators.

3 The calibration challenges of LOFAR data

The calibration and imaging of LOFAR data is a great challenge, in part because at these frequencies there can be large ionospheric phase variations which distort the observed brightness distribution in uncorrected images. An overview of the imaging pipeline can be seen in Heald et al. (2011). The ionospheric phase variations can be corrected for by iterative self calibration using bright radio sources in the field. Strong sources nearby can distort the target source. These problematic sources, however, can be subtracted from the uv data.

The LOFAR antennas detect the emission from bright sources even when located far away from the station beam pointing direction. This can distort the images of the target field. Most problematic are the very bright “A-Team” sources such as Cygnus A and Cassiopeia A. Fortunately, there is now software in place to subtract their distorting emission through a process called “demixing” (van der Tol, S. et al. 2007), which is done prior to calibration and is essential for all LBA observations.

Calibration with LOFAR is done through the program BBS which requires a Local Sky Model (LSM) which is extracted from a Global Sky Model (GSM) that is stored in the database. The initial GSM development will come about through the Multifrequency Snapshot Sky Survey (MSSS) (MSSS; Heald et al. in prep) which has started in October 2011. At present, skymodels are created from the WENSS or VLSS surveys. BBS calibrates the complex station gains using this LSM.
LOFAR has the novel ability in that it is able to observe two or more parts of the sky simultaneously. This has the advantage of continuously observing the target source and getting the maximum uv coverage whilst observing a calibrator. The total bandwidth is divided up by the number of sources observed, in these cases the on-source bandwidth is halved. The calibrator can be then easily calibrated and the obtained gain and phase solutions found can be transferred to the target observation.

4 Dual observations of 3C295 & M51

The spiral galaxy M51 was chosen to be observed by the MKSP due to the high polarization degree in the interarm regions with structures as large as 5 kpc in size, as seen in Fletcher et al. (2011). 3C295 and the relatively face-on spiral galaxy M51 were observed simultaneously for a 5 hour period in May 2011 during nighttime to minimize ionospheric distortions.

Figure 1, left image, shows M51 at 145.12 MHz calibrated by using the transfer of gain solutions method described in section 3. The rms for this image is approximately 7mJy/beam which can be improved for a single subband by the subtraction of nearby sources. As one can see from comparing the radio image to the optical image, an extended disk is very evident as well as the inner western spiral arm. The image also looks very similar to an image obtained by Segalovitz (1976) at 610 MHz. However greater resolution is achieved in the LOFAR image with a beamsize of $61 \times 30$ arcsecs. Robust weighting of 0.25 was used.

Figure 1: Left: M51 for a single subband at 145.12 MHz (contours) with a bandwidth of approximately 400 KHz overlayed onto an optical DSS image. (D.Mulcahy). Right: NGC4631 for a single subband at 157 MHz (bandwidth is approximately 400 KHz) (contours) calibrated from a single source in the field, overlayed onto an optical blue DSS image (R.Drzazga).
5 Dual observations of 3C286 & NGC4631

3C286 and the edge-on galaxy NGC4631 were also simultaneously observed in May 2011 during nighttime. The purpose of observing this galaxy was to detect the extended radio halo known to exist seen in Golla & Hummel (1994). The large thickness of the radio halo is due to the high star formation efficiency rate in the disk as well as gravitational interaction with NGC4656 which can be seen from Krause (this volume). Figure 1, right image, shows an image of NGC4631 that has been calibrated with BBS on a single source in the field itself (4C+32.40) with a total flux of 3.2 Jy (at 157 MHz), interpolated between NVSS and VLSS. This was then followed by two selfcal cycles. The rms noise is 20 mJy/beam which again can be improved within a subband. The beam is 165×118 arcsecs. A very extended synchrotron halo can be seen which is comparable to the image from Hummel & Dettmar (1990) at 327 MHz. Efforts are currently being made to create images using the transfer of gains solutions method.

6 Conclusions

From these two observations, it is clear that LOFAR has started to give reliable images of extended sources. The extended synchrotron disk and halo of M51 and NGC4631 are easily seen in our images which were expected from observations in other low wavelengths seen in for M51 at 610 MHz and for NGC4631 at 327 MHz. It is important to note that the presented images are from a single subband. When the whole bandwidth of 24 MHz (122 subbands) is combined, a significant increase in sensitivity is expected. This should reveal the very outer regions of these galaxies.

A search for polarization with RM Synthesis is planned in the coming months.

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