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Search and detection of low frequency radio transients

Spreeuw, J.N.

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Introduction

1.1 Preparing for LOFAR

Although radio astronomy started at low frequencies (20.5 MHz), with the pioneering work of Karl Jansky (Kraus 1986), in the decades after the war the focus of radio astronomy shifted to higher frequencies, with higher angular resolution per unit of projected baseline and little ionospheric disturbance. Low-frequency radio astronomy in the US languished in the '80s when Clarke Lake Radio Observatory was closed down (White et al. 2003). Technical developments, such as optical fibre, have opened the opportunity of achieving high angular resolution at low frequencies, by correlating data from very long baselines. In this way, the sensitivity limitation from noise by confusion of sources can be avoided. Another aspect that has influenced the design of low frequency arrays is the difficulty of designing dishes that are large and sufficiently stiff at the same time and can be built at reasonable cost. Collecting area and other considerations led to the first design concepts of LOFAR (Bregman 2000) in the late '90s: an aperture synthesis instrument without steerable parts for the frequency range 10-300 MHz, comprised of 30 stations spanning baselines up to 300 km. Each station would consist of a few hundred dipoles. Over the years, the design for the Low Band Antenna (LBA) and High Band Antenna (HBA) has changed. The most recent images of both antenna types are shown in figures 1.1 and 1.2. Also the station layout and the array configuration was altered, particularly after a significant descop. Figure 1.3 shows an aerial photograph of the location of the inner core stations in the very heart of LOFAR on top of a large terp, i.e., an artificial hill. The LOFAR core, near Exloo in the province of Drenthe, The



Figure 1.1: Low Band Antennas as they are presently deployed.

Netherlands, is presently (2010) being completed. There will be at least 18 core stations, 18 remote stations (in the Netherlands) and 8 international stations. These and other planned but yet not (fully) funded international stations are depicted in figure 1.4.

The research plan for my Ph.D. position was written down in 2004 when only prototype stations, such as ITS (Wijnholds et al. 2004) and THEA, the Thousand Element Array (Bij de Vaate et al. 2003), were deployed. At that time it was anticipated that the roll-out of LOFAR would be completed by the end of 2006. Originally, I would spend the first two years of my thesis (2005, 2006) on the development of code for the detection of transient sources and apply this code in the last two years (2007, 2008) to actual LOFAR data. The LOFAR science case (De Bruyn et al. 2002) mentioned the search for variable sources and "LOFAR as an All-Sky Monitor". Fast radio transients were to be discovered by processing visibilities and/or maps from short integrations in real time. Those maps would together cover a large patch of the sky. They could, in fact, be image cubes, with frequency as a third dimension. All data were to be recorded in full Stokes, so in principle four maps could be made from any integration. The message was clear: the datastream was huge and only compressed forms of data could be stored indefinitely. Any code written to find transient sources in the LOFAR datastream would have to be fast, efficient and fully automated, performing only tasks that were obviously necessary.

Although these requirements were well understood, essential directions were unclear at the



Figure 1.2: A close-up of two High Band Antennas.

beginning of this project. For instance, the optimum way of finding transients was not obvious. The "classic" way has always been to compare the fluxes of all sources in a number of maps. If there were only one source that was substantially brighter or fainter in one map than in all other maps while all the other sources had similar flux, one could be pretty confident of having found a transient source. However, in radio astronomy the maps come from (u, v) data and it was not yet investigated if there were certain techniques that could find transient sources directly in the visibilities. In particular, it was anticipated that the ionosphere would leave phase errors in the data and that perhaps after subtraction of consecutive datasets these errors would cancel out. Generally, there is no straightforward manner of subtracting consecutive sets of visibilities because the (u, v) coverage changes with time, so subtraction cannot be done without interpolation, unless the (u, v) coverage is complete. On the other hand, on very short timescales, on the order of seconds, one may argue that the (u, v) coverage does not change significantly and visibilities may be subtracted baseline by baseline. It turned out that this could yield acceptable results in a quiet ionosphere if "second-order-differencing" is applied, but subtracting maps pixel by pixel may still work well (Miller-Jones 2006). Still desperately needed are tests in an unstable ionosphere. Things are much simpler if a proper model of the field is available. That model can be used to calibrate a time sequence of (u, v) datasets and also to subtract it from those datasets after calibration. The time sequence



Figure 1.3: A 2009 photograph of the location of the inner core stations in the very heart of LOFAR. The inner core stations will be built on top of a large "terp", i.e. an artificial hill. This "super terp" is surrounded by a large ditch.

of dirty images from the residual (u, v) data will show any transient source well above the noise. In any case, it was obvious for the detection of transients, that routines for extraction and measurement of sources in images, dirty or cleaned, were needed.

1.2 Source extraction in maps

Another issue that was unclear at the start of my Ph.D. project was the necessity of writing new software for source extraction. Source extraction generally means the identification of sources in images by segmentation and labeling contiguous pixels (islands). Naturally, source measurement was also needed. By this we mean the calculation, for each island of pixels, of the flux (peak and integrated), position, size and shape.

I soon found out that SExtractor (Bertin & Arnouts 1996) could process most FITS images in a second, meeting the required speed for LOFAR. An interesting aspect that needed to be investigated was the accuracy of its source measurements and error bars, since no fitting was done, all source parameters were derived from moments. In the end, SExtractor failed to meet our requirements with respect to optimum accuracy. The (barycenter) positions were

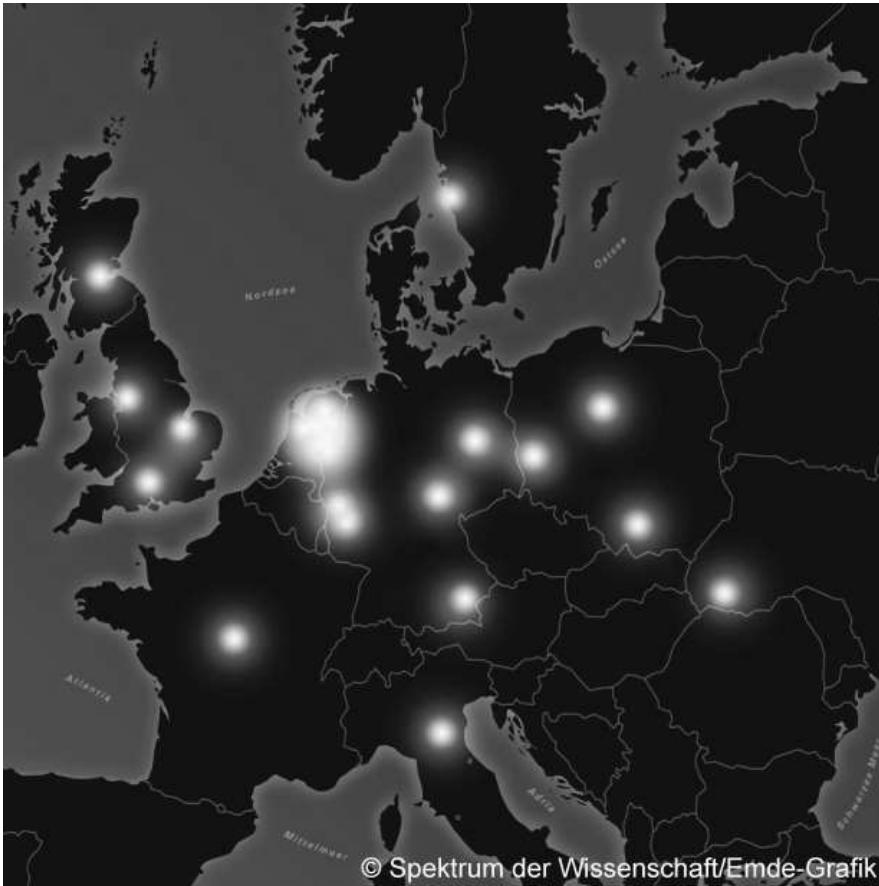


Figure 1.4: The bright spots indicate all LOFAR stations that are currently deployed or being deployed, funded and/or planned. Only 8 international stations are presently (2010) funded, 5 in Germany, 1 in France, 1 in the UK and 1 in Sweden.

less accurate than from fitting and there were systematic underestimates of the peak flux density. Both of these problems become prominent at high signal-to-noise levels, as shown in figures 1.5 and 1.6.

At that point it became clear that new software needed to be developed, software that would meet the requirements with regard to speed and accuracy. Python was well on its way of becoming a popular programming language for scientific applications when Space Telescope Science Institute (STScI) adopted it for their processing routines. They developed fast routines for segmentation and labeling¹, the very basis of source extraction in images. I

¹See <http://stdas.stsci.edu/numarray/numarray-1.5.html/index.html>

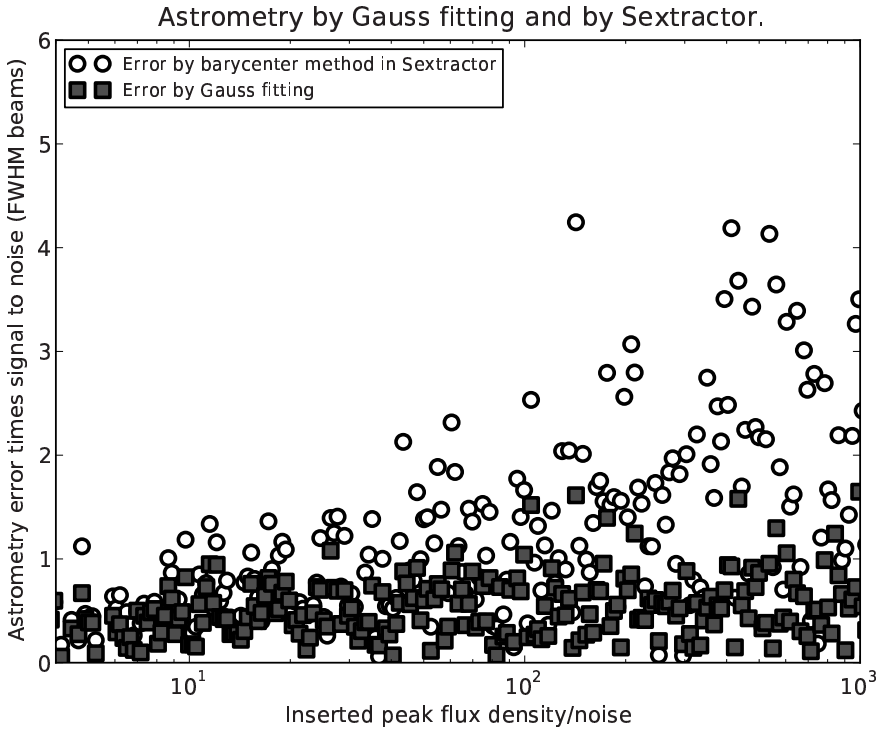


Figure 1.5: The barycenter method for calculating the position of a source does not reach the theoretical limit of accuracy and high s/n . If the beam is oversampled this effect is lessened. For this test we pixellized a fixed Gaussian and added correlated noise from random locations in a source free radio image after we scaled it in order to create a range of s/n ratios.

accidentally run into the simplest possible source extraction code, based on those routines, in a tutorial by two people from STScI (Greenfield & Jedrzejewski 2007, paragraph 3.7.9). The most essential commands are listed here:

$$\text{clipped} = \text{where}(\text{sci} > \text{threshold}, 1, 0) \quad (1.1)$$

$$\text{labels, num} = \text{nd_image.label}(\text{clipped}) \quad (1.2)$$

$$f = \text{nd_image.find_objects}(\text{labels}) \quad (1.3)$$

`nd_image` is the extension module to `numarray` written at STScI. The first command selects all pixels above the threshold and gives them the value 1. The second labels groups of pixels based on connectivity. By connectivity we mean the level of contiguity. By default we use 4-connectivity which means that groups of pixels only connected at corners are considered separate. This is not the case when one uses 8-connectivity. The last command uses

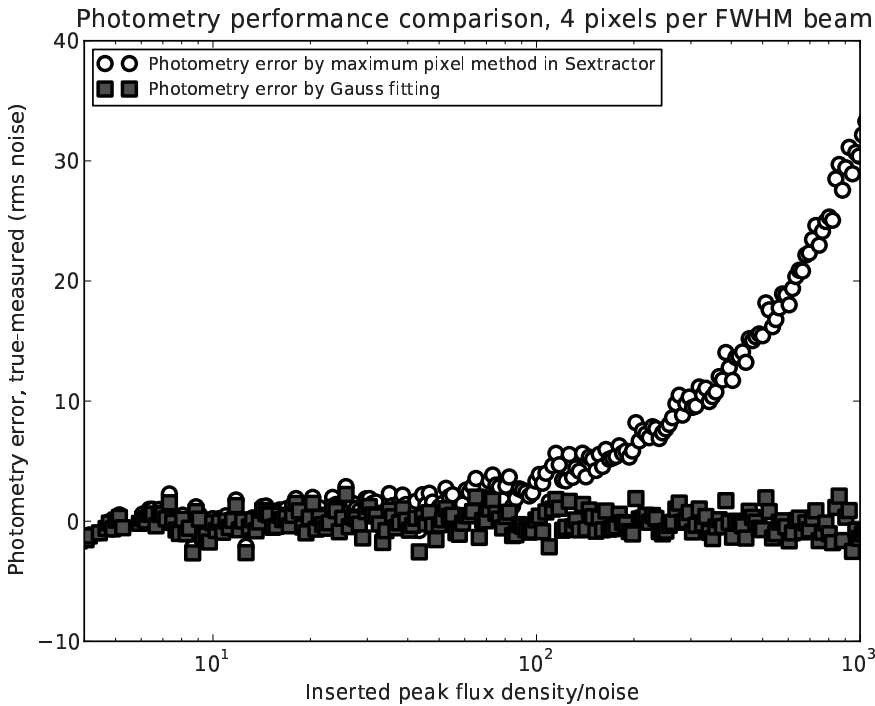


Figure 1.6: The peak pixel method for photometry on point sources does not reach the theoretical limit of accuracy and high s/n. If the beam is oversampled this effect is lessened. This plot was constructed from the same data as figure 2.4.

those labels to select 2D arrays, i.e., groups of pixels. These are the islands that can then be "measured", i.e. the peak, total flux, position and shape parameters are determined. In fact, some of the measurement tasks were also included in `nd_image`:

$$\text{positions} = \text{nd_image.center_of_mass}(\text{sci}, \text{labels}, \text{range}(\text{num})) \quad (1.4)$$

This gives the barycenter positions of the islands. Of course, this is not the final word on the positions of the sources, or we would run into the same accuracy problems as SExtractor. However, the barycenter positions are good initial values for Gauss fitting. Moreover, it became clear that I had found an excellent framework for the extension of these algorithms and that the complete source extraction process could be written in Python. It was reassuring that Python as a programming language continued to develop. The `nd_image` routines were incorporated in Scipy and Numarray was further developed as Numpy. A complete, but not very detailed, overview of the source extraction process is depicted in figure 1.7. The first part of this thesis comprises a chapter on the description of all subprocesses in this scheme

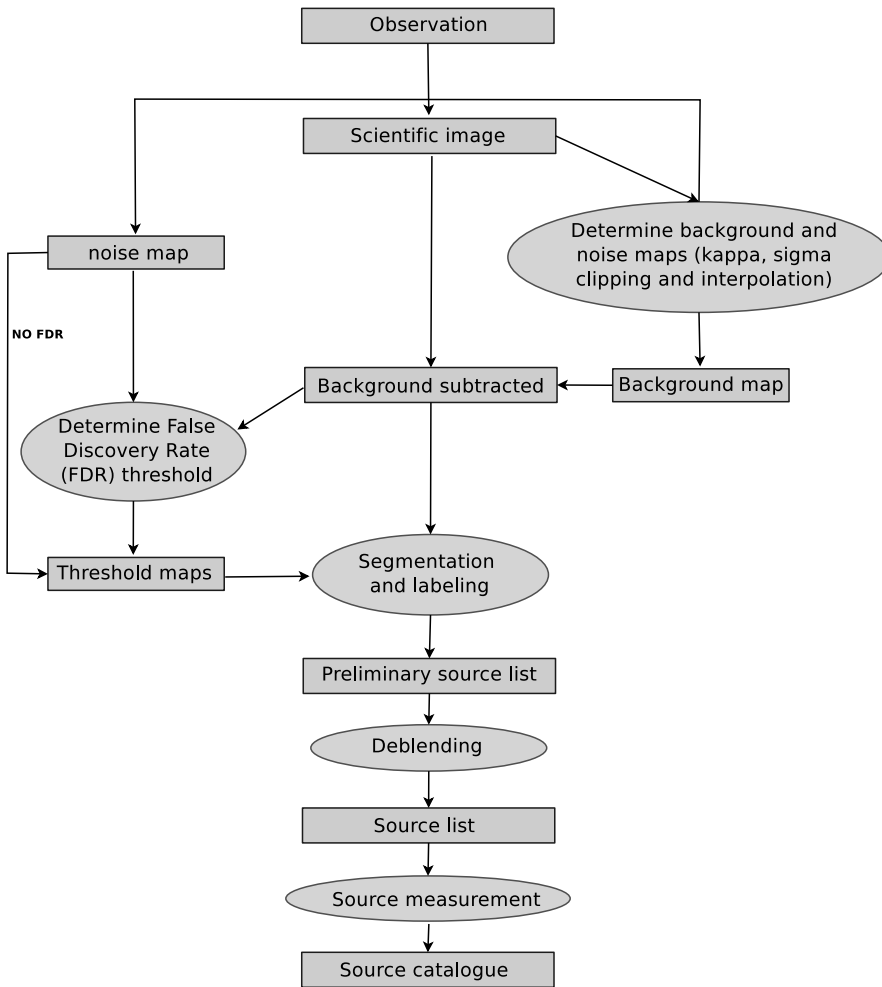


Figure 1.7: An overview of the source extraction process in the TKP pipeline

and another chapter on their validation, i.e., the actual checks that the output from the TKP software is correct.

1.3 Scientific expertise from studying transients with "classical" radio telescopes at low frequencies

Evidently, there was more we could do to prepare for transient searches with LOFAR besides the development of robust and efficient software for source extraction. Perhaps observations of transient sources with "classical" radio frequencies could reveal new techniques for detecting these sources. Luckily, two of those opportunities arose in the first few months after the start of my appointment!

1.3.1 SGR 1806-20

On 2004 December 27 a Giant Flare (GF) of γ -rays from the soft- γ -ray repeater (SGR) 1806-20 was detected by INTEGRAL, Swift and three other space missions in the third interplanetary network of GRB detectors (Hurley et al. 2005). It caught the attention of the general public as the brightest flash of radiation from beyond the solar system ever recorded. Astronomers studied the afterglow of the explosion from this magnetar by follow-up observations at various wavelengths (Rea et al. 2005; Israel et al. 2005; Palmer et al. 2005; Schwartz et al. 2005; Fender et al. 2006). In particular, the flux from the radio nebula produced by the explosion (Gaensler et al. 2005a; Cameron et al. 2005; Taylor et al. 2005) was measured very frequently in 2005 January. These observations focused on total intensity measurements at various radio wavelengths between 0.24 and 8.5 GHz and on polarimetry at 8.5 GHz. Some polarimetry was done at lower frequencies, but without the proper correction for the leakages (Gaensler et al. 2005b).

One chapter of this thesis describes a set of 19 WSRT observations pointed at SGR 1806-20. It involves polarimetry at 350, 850 and 1300 MHz. Also, the Stokes I flux from the radio nebula at 350 and 850 MHz was measured more accurately by observing the same field again in 2005 April/May. In this way, the background sources could be subtracted from the visibilities of the 2005 January observations. One of the main conclusions from these observations is that we do not see any compelling evidence for significant depolarization at low frequencies, but strong evidence for different polarization angles as shown in figure 1.8, indicating that we are probing substructure that is not appearing at high frequencies. This is actually a quite encouraging result for LOFAR. Imagine that LOFAR would have been fully deployed at the time of the GF: we would have known a great deal more about the evolution of the radio nebula and its magnetic fields, until a few weeks after the explosion.

1.3.2 GCRT J1745-3009

Another opportunity for studying a transient source at low frequencies arose in 2005 March when a paper about a peculiar transient source appeared in *Nature* (Hyman et al. 2005). This truly amazing source showed five bursts at the Jy level each lasting about 10 minutes with a 77 minute recurrence during a 6h observation at 325 MHz on 2002 September 30/October 1. The source is located 1.25° south of the Galactic Center and just outside a supernova remnant. Theorists immediately started to investigate if the recurrence time could be attributed to a pe-

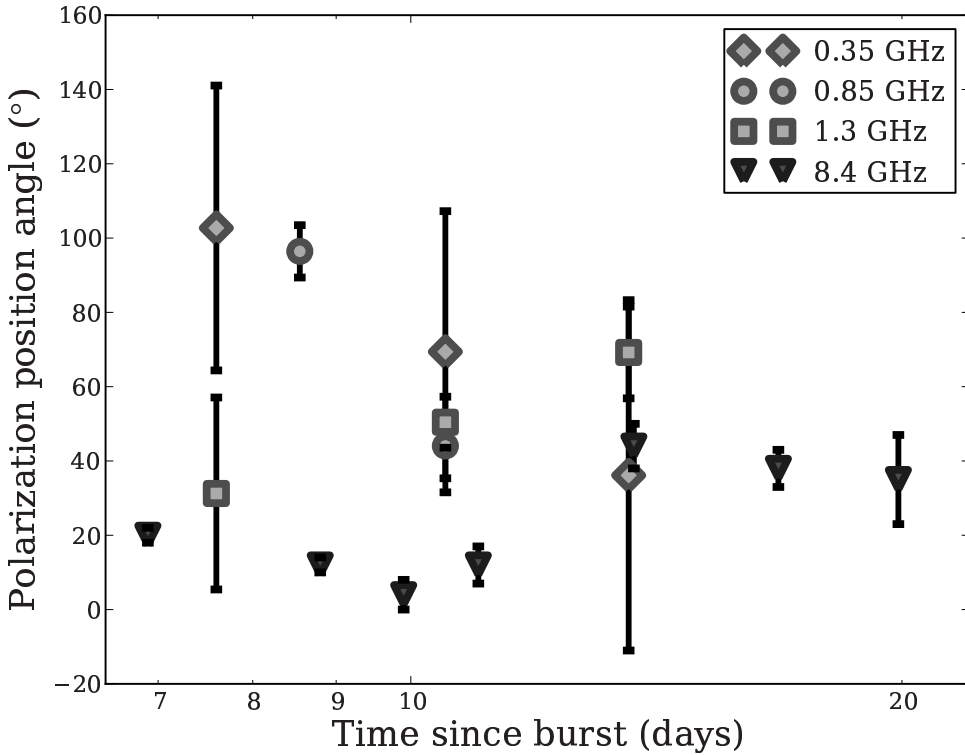


Figure 1.8: The polarization angles of the radio nebula produced by the Giant Flare from SGR 1806-20 at 350, 850, 1300 and 8400 MHz

riod of rotation (Zhang & Gil 2005), revolution (Turolla et al. 2005) or precession (Zhu & Xu 2006). A nulling pulsar and an 'X-ray quiet, radio-loud' X-ray binary were also suggested (Kulkarni & Phinney 2005) as well as an exoplanet and a flaring brown dwarf (Hyman et al. 2005). The discovery led to follow-up observations and re-examination of archival data at both 325 MHz and other bands. Those did not reveal a source (Zhu & Xu 2006; Hyman et al. 2005, 2006), with two exceptions (Hyman et al. 2006, 2007). Both of the redetections were single bursts, possibly due to the sparse sampling of these observations. The first redetection was possibly the decaying part of a bright (0.5 Jy level) burst that was detected in the first two minutes of a ten minute scan. The second redetection was a faint short (≈ 2 minute) burst that was completely covered by the observation. The average flux density during that burst was only 57.9 ± 6.6 mJy/beam. This redetection also showed evidence for a very steep spectral index ($\alpha = -13.5 \pm 3.0$). In summary, the source was only detected at three epochs, separated by less than 18 months, all at 325 MHz, while the source was not detected in this band at 33 epochs over a period of more than 16 years (see Hyman et al. 2006, table 1) nor in any other

band, ever.

We observed the field containing GCRT J1745-3009 with the WSRT at 325 MHz (2005 March) and at 1350 MHz (2005 May), but did not detect the source. My attention was drawn to a source on the opposite side of the supernova remnant that did not appear in a map that was made by concatenating four datasets from the late '80s (see LaRosa et al. 2000, figure 11). The noise levels in this map were such that it should have been detected at the $10 - 20\sigma$ level, so a clear detection was expected. We investigated possibly transient behaviour of this source by reducing these and other observations from the '80s in the VLA archive. We found that the source was actually clearly present in one of our maps with a sufficiently low noise level and good (u, v) coverage. We concluded that, most likely, the source was in fact concealed by a negative background peak and that the fidelity of the LaRosa et al. (2000) maps is questionable. This can be seen more clearly if one has a look at the larger $4^\circ \times 2.5^\circ$ and $4^\circ \times 5^\circ$ images (see LaRosa et al. 2000, figures 1 and 5).

A large but unsuccessful effort was put into establishing the transient nature of this source. However, it is actually an important lesson for transient searches with LOFAR, in the sense that the fidelity of maps has to be judged by considering not only noise levels but also a few other criteria, like the presence of many contiguous pixels with negative values.

As an exercise, I also re-reduced the discovery dataset of GCRT J1745-3009. After many iterations of self-calibration I attained noise levels in my maps substantially lower than mentioned in the discovery paper (Hyman et al. 2005) and I included those results in a paper on this source. The referee then encouraged me to also re-extract the lightcurve which led to a wealth of new information on the source. For instance, it turned out that all five bursts have the same shape, with a steep rise, a gradual brightening and a steep decay as shown in figure 1.9. We improved the accuracy of the recurrence period by an order of magnitude and we found no evidence for aperiodicity. This means that, in terms of possible models for this source, rotating systems are favoured and that models that predict symmetric bursts can be ruled out.

1.4 Theoretical predictions for the detection of radio emission from extrasolar planets with LOFAR

Another aspect of successful transient searches with LOFAR, besides the development of software and scientific expertise is the devising of an observational strategy. A priori, this is a pretty complicated matter. First of all, there are known and unknown transients. For the latter group, an observational strategy can be devised if they belong to a class of known transient radio sources, by interpolating and extrapolating the observational characteristics of their class. For the former group, things could be simpler. However, since the sky is relatively unexplored at LOFAR frequencies, we are not sure what to expect from targeted LOFAR observations of known sources with established transient behaviour at **higher** frequencies and we still have to do quite a bit of uncertain (frequency) extrapolation.

The known extrasolar planets ("exoplanets") are targets for LOFAR although their transience

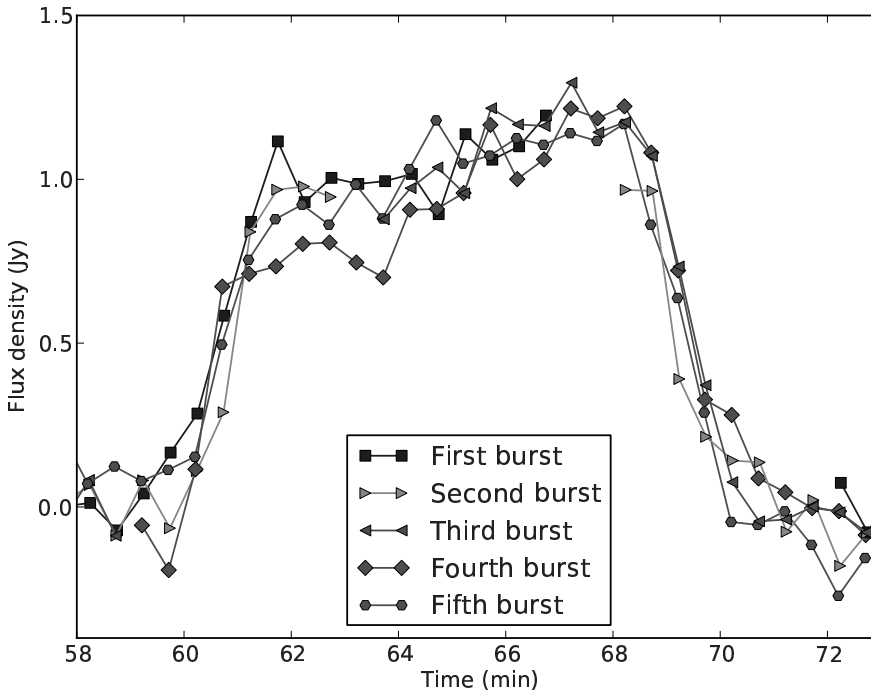


Figure 1.9: The plot above shows the five bursts from the discovery dataset of GCRT J1745-3009 with 30s sampling folded at intervals of 77.012 minutes. Time is relative to 20h50m00s on 2002 September 30 (IAT) (plus multiples of 77.012 minutes).

has never been observed at **any** frequency. Only in the case of eclipsing exoplanets, was the optical flux from the star slightly variable, i.e., the exoplanet would block a small fraction of the starlight. However, variability of this kind cannot be extrapolated to radio frequencies. In fact, the emission process that may result in the first detection by LOFAR of radio emission from an extrasolar planet is of a completely different origin and similar to Jupiter's radio storms: cyclotron emission from charged particles from a stellar wind that get trapped in the planet's magnetosphere. In the case of Jupiter and, more generally, in the solar system beyond 1 AU, the kinetic flow power is much larger than the Poynting flux from the interplanetary magnetic field, but the latter is converted much more efficiently into radio power. In fact, it turned out, when we considered the parameters of all 197 known exoplanets (2007 January), that the conversion of magnetic Poynting flux into radio waves was the most promising mechanism for producing detectable low frequency emission. The results for this mechanism, called the **magnetic energy** model, are shown in figure 1.10. The equivalent of the Jupiter-Io interaction, called the **unipolar** model, did not yield any observable emission for this set of exoplanets. We conclude that radio emission from a few of the exoplanets that were known early 2007 could be detected by LOFAR.

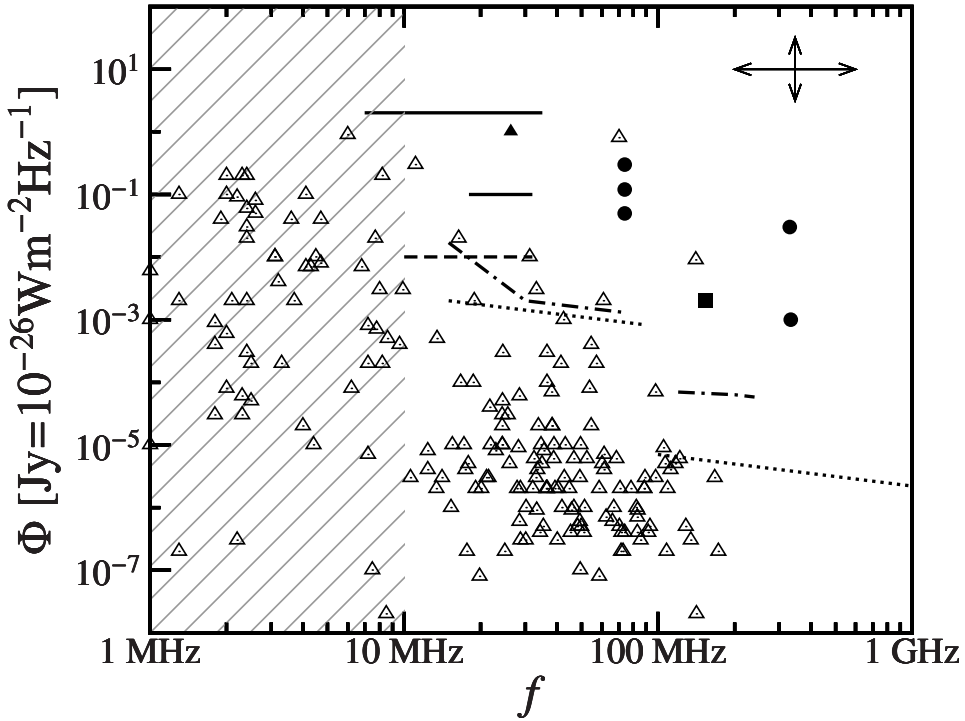


Figure 1.10: Maximum emission frequency and expected radio flux for known extrasolar planets according to the **magnetic energy** model, compared to the limits of past and planned observation attempts. Open triangles: Predictions for planets. Solid lines and filled circles: Previous observation attempts at the UTR-2 (solid lines), at Clark Lake (filled triangle), at the VLA (filled circles), and at the GMRT (filled rectangle). For comparison, the expected sensitivity of new detectors is shown: upgraded UTR-2 (dashed line), LOFAR (dash-dotted lines, one for the low band and one for the high band antenna), LWA (left dotted line) and SKA (right dotted line). Frequencies below 10 MHz are not observable from the ground (ionospheric cutoff). Typical uncertainties are indicated by the arrows in the upper right corner.

Bibliography

- Bertin, E. & Arnouts, S. 1996, *A&AS*, 117, 393
- Bij de Vaate, J., Wijnholds, S., & Bregman, J. 2003, in *Phased Array Systems and Technology*, 2003. IEEE International Symposium on, 359–364
- Bregman, J. D. 2000, in *Perspectives on Radio Astronomy: Technologies for Large Antenna Arrays*, ed. A. B. Smolders & M. P. van Haarlem, 23
- Cameron, P. B., Chandra, P., Ray, A., et al. 2005, *Nature*, 434, 1112
- De Bruyn, A. G., Fender, R. P., Kuijpers, J., et al. 2002, *Exploring the Universe with the Low Frequency Array - A scientific case*
- Fender, R. P., Muxlow, T. W. B., Garrett, M. A., et al. 2006, *MNRAS*, 367, L6
- Gaensler, B. M., Kouveliotou, C., Gelfand, J. D., et al. 2005a, *Nature*, 434, 1104
- Gaensler, B. M., Kouveliotou, C., Wijers, R., et al. 2005b, *GRB Coordinates Network*, 2931, 1
- Greenfield, P. & Jędrzejewski, R. 2007, *Using Python for Interactive Data Analysis*
- Hurley, K., Boggs, S. E., Smith, D. M., et al. 2005, *Nature*, 434, 1098
- Hyman, S. D., Lazio, T. J. W., Kassim, N. E., et al. 2005, *Nature*, 434, 50
- Hyman, S. D., Lazio, T. J. W., Roy, S., et al. 2006, *ApJ*, 639, 348
- Hyman, S. D., Roy, S., Pal, S., et al. 2007, *ApJL*, 660, L121
- Israel, G. L., Belloni, T., Stella, L., et al. 2005, *ApJL*, 628, L53
- Kraus, J. D. 1986, *Radio astronomy* (Powell, Ohio: Cygnus-Quasar Books)
- Kulkarni, S. R. & Phinney, E. S. 2005, *Nature*, 434, 28
- LaRosa, T. N., Kassim, N. E., Lazio, T. J. W., & Hyman, S. D. 2000, *AJ*, 119, 207
- Miller-Jones, J. C. A. 2006, *Another method of differencing in the uv -plane*, Tech. rep., University of Amsterdam
- Palmer, D. M., Barthelmy, S., Gehrels, N., et al. 2005, *Nature*, 434, 1107
- Rea, N., Israel, G., Covino, S., et al. 2005, *The Astronomer's Telegram*, 645, 1

- Schwartz, S. J., Zane, S., Wilson, R. J., et al. 2005, *ApJL*, 627, L129
- Taylor, G. B., Gelfand, J. D., Gaensler, B. M., et al. 2005, *ApJL*, 634, L93
- Turolla, R., Possenti, A., & Treves, A. 2005, *ApJL*, 628, L49
- White, S., Kassim, N. E., & Erickson, W. C. 2003, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 4853, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, ed. S. L. Keil & S. V. Avakyan, 111–120
- Wijnholds, S. J., Bregman, J. D., & Boonstra, A. J. 2004, *Experimental Astronomy*, 17, 35
- Zhang, B. & Gil, J. 2005, *ApJL*, 631, L143
- Zhu, W. W. & Xu, R. X. 2006, *MNRAS*, 365, L16