Searching for pulsars with LOFAR

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ENGLISH SUMMARY

DISCOVERY OF RADIO PULSARS: ROTATING NEUTRON STARS

Radio pulsars, the subject of this thesis, were discovered in 1967 by Jocelyn Bell Burnell. At that time she was working on her PhD thesis research on so-called interplanetary scintillation (IPS) using the, for that time, large radio telescope, the Cambridge IPS array. On inspection of the recorded data she repeatedly came across interference-like signals. When one of these was repeatedly observed at the same spot on the sky, and after interference by man-made radio signals or even those from some intelligent aliens were excluded it became clear that a new type of astrophysical object had been discovered. The very stably pulsing signal that was observed, a “radio pulsar”, could in the end only be explained as the emission from a very compact source that was rotating much as a lighthouse. Radio pulsars turned out to be a type of compact astrophysical source not seen before, a so-called neutron star.

Neutron stars are the stellar remnants of quite heavy stars, those with masses between 8 and 25 solar masses as measured at the start of their lives as stars. These stars burn through their fusion fuel relatively quickly and end their lives in spectacular explosions, at which point the neutron star is formed. These explosions, so-called supernovae, are initiated when the star runs out of fuel and can no longer withstand its own gravity. The core of the star implodes to a neutron star and the outer layers of the star are ejected into space. Because stars always possess some amount of rotation the neutron star will also rotate; in more physical terms the angular momentum is a conserved quantity. Because a neutron star shrinks during its formation it must start rotating faster to conserve angular momentum. This can be further amplified by an asymmetric supernova or the accretion of material at later points in the neutron star’s life. The fastest neutron star rotates at 716 rotations per second. This fast rotation combined with the immense magnetic field of neutron stars causes the acceleration of charged particles at the magnetic poles of the neutron star (much like particles accelerated in laboratories like CERN, but to much higher energies). Those particles then create a bright, narrow beam of radio emission over the magnetic poles. As this beam sweeps Earth, several hundreds of light years away, it is observed as a pulse of radio emission. The rotation of the neutron star causes a regular series of these pulses.

1While several types of supernovae exist, I am only mentioning the type involved with the formation of a neutron star.
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that persists for millions of years: a radio pulsar.

Shortly after the discovery of the neutron by Chadwick in 1932, it was already suggested that supernovae could form neutron stars. In a neutron star gravity is counteracted by the repulsion of neutrons, this repulsion is the last barrier to a full collapse of the star a black hole. Neutron stars are exotic celestial bodies where exotic circumstances can be found — circumstances that cannot be replicated in Earth based laboratories. This fact makes neutron stars interesting physics laboratories in and of themselves. As an illustration the mass of a neutron star is typically estimated to be 1.4 solar masses while its radius is only about 10 kilometers! One of the current questions in the research of neutron stars is: how heavy and compact can a neutron star become before it collapses under its own gravity? The answer to that question depends on the detailed properties of particles much smaller than the atom. But how is it we can measure these properties for a star that is many light years removed from Earth? The fact that a neutron star has such a large mass is of assistance: just like a flywheel its rotation speed is very constant. Because of this the arrival of the pulse can be predicted with extreme accuracy and any deviations thereof can thus be measured very precisely. The pulsar’s rotation slows down over time as the magnetic field it drags around radiates away some of the rotational energy (measuring this slow down allows estimates for the age and the strength of the magnetic field to be made). Sudden changes in the pulsar’s rotational velocity (so-called glitches) betray information about the pulsar’s interior. For pulsars in binary systems the arrival time of the pulses is affected by the presence of a binary companion. The deviations in arrival time can then be used to measure the weight of the companion object, and in some systems allow extremely accurate tests of our theories of gravity (especially in the one double pulsar system known to date).

Pulsars orbiting dwarf stars

In Chapter 2 we describe a search for radio pulsars orbiting so-called sdB (subdwarf-B) stars. These dwarf stars with typical masses of half a solar mass derive their name from the fact that their spectrum looks like that of a B stars (large, heavy stars). From optical observations it is known that the majority of sdBs are in binary systems. Because the sdB star masses are known and their orbital velocity can be measured from their spectrum, an indirect measurement can be made of their companion's mass. In many cases it is also possible to observe this companion directly. There are cases, though, where that is impossible as the sdB star is much brighter than its companion (and thereby masking its signature). There are a number of companion types for which this true, such as planets, small light stars and so-called compact objects. Compact objects in this context are white dwarfs (the slowly cooling remains of sun like stars), neutron stars and black holes. Several sdB + white dwarf systems are known, one with a black hole but so far none with a neutron star companion. The discovery of a neutron star as a binary companion to an sdB star would provide extra information about the evolution of sdB binaries.

Through prior optical observations four sdB binaries containing compact objects with masses close to that of a neutron star had been identified, but it could not be
proven that a neutron star was in fact present. The detection of a neutron star would prove that sdBs can form around neutron stars. Using the Green Bank Telescope (GBT), a large radio telescope in the USA with the largest fully steerable dish in the world of about 100 m, we observed the four sdB binaries possibly hosting neutron stars. I then searched these observations for radio pulsations. Despite the sensitivity of our observations we did not find pulsating radio signals: these non-detections allowed us to put an upper limit on the maximum brightness of such a signal. That upper limits are so strict that if any pulsars were present in these systems they must either be very weak emitters of pointed away from Earth.

**Pulsars with LOFAR**

In the past decade a very large radio telescope was built in the Netherlands. This observatory, the Low Frequency Array (LOFAR), derives its name from the low radio frequencies at which it observes. LOFAR observations are performed in two frequency bands, 10-90 MHz and 110-240 MHz. LOFAR consists of a network of relatively simple, so-called dipole antennas, unlike telescopes such as the Dwingeloo telescope or the Westerbork Radio Synthesis Array or the aforementioned GBT that consist of one or more radio dishes. The signals received all LOFAR antennas are digitized and sent to central computer via a fast glass fiber network. This central computer, at the time of writing a IBM Blue Gene/P super computer, combines all dipole signals such that LOFAR functions as one very large radio telescope. Because most of LOFAR’s signal processing is performed in software it is a very flexible telescope — LOFAR is also called the first software telescope.

Because LOFAR is both very sensitive and very flexible it is useful for several kinds of astronomical research. As this thesis is about radio observations of radio pulsars, I will limit myself to a description of LOFAR’s possibilities for pulsar observations. One of the research Key Science Projects of the LOFAR collaboration is the Transients Key-science Project (TKP). This group is researches any variable or transient radio sources visible to LOFAR. Pulsars are variable radio sources, both on short timescales because of their radio pulsations and on longer timescales where pulsars show overall brightness variations, some pulsars are even known to turn on and off on various timescales. Within the TKP there is one group specialized on radio pulsars, the so-called Pulsar Working Group (PWG). Pulsar research using LOFAR can quantify the as yet not well known properties of pulsars at low radio frequencies and possibly identify all nearby dim pulsars. Along with the other researchers of the PWG I undertook the first pulsar searches with LOFAR.

Pulsars are discovered in one of two ways, either in observations of systems where their presence is suspected, or in blind observations of the sky. The search for pulsars in sdB binaries mentioned above is an example of a targeted survey. When no prior knowledge of the presences of pulsars is used to target a specific locations of sky the observations are called blind. In the so-called commissioning period of LOFAR, the period in which LOFAR was built and tested, I worked on the first, blind, test surveys for new pulsars using LOFAR. Whilst the telescopes capabilities were still being extended and the calibration improved, we performed two large sets of
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blind observations, whose data were searched for the presence of pulsar signals. We conducted these two surveys using two different beam-forming (a process I describe below) techniques to test different aspects of LOFAR.

For every radio telescope that uses a dish type receiver the field-of-view (FoV) is set by the shape of the dish and receiver and its observing frequency. The FoV of a radio telescope is also called its primary beam. When the telescope needs to observe a certain object on the sky it is rotated such that that source falls inside of the primary beam. For LOFAR it is not possible to rotate the telescope as the telescope contains no moving parts. The individual LOFAR antennas always see the entire sky, but by processing the observed signals it becomes possible to observe only a specific patch of sky at high sensitivity. The FoV, the beam, of LOFAR is formed after the fact and mostly in software. Because the central computer of LOFAR is very powerful and because the digitized antenna signals can easily be copied it is easily possible to form several beams simultaneously (and hence to observe several patches of sky simultaneously). For pulsar observations there are two ways of forming beams, either through so-called incoherent beam-forming, or through so-called coherent beam-forming. Which mode is used depends on the specific goals of an observation. Incoherent beam-forming allows a large FoV to be formed at the expense of some of LOFAR’s total sensitivity. Coherent beam-forming allows LOFAR’s full sensitivity to be used whilst allowing a significantly smaller patch of sky to be observed.

PULSAR SEARCHES WITH LOFAR

The first large, blind, radio pulsar surveys using LOFAR is the LOFAR Pilot Pulsar Survey (LPPS). The goal of LPPS was to test LOFAR’s incoherent beam-forming. For each LPPS observation seven simultaneous beams were observed. Because these beams covered such a large patch of the sky, we were able to observe a large fraction of the northern sky without using excessively large amounts of observing time. Searching the LPPS data allowed the re-detection of 65 previously known pulsars. One of these pulsars had only been discovered several months prior in another sensitive pulsar survey (the so-called Greenbank Northern Celestial Cap survey that uses the aforementioned GBT telescope), this directly showed that a software telescope like LOFAR is capable of conducting pulsar surveys. We further were able to put an upper limit on the occurrence of short, bright radio bursts observable at low radio frequencies because of the large area of sky observed for LPPS. Such bright bursts, whose origin seems to lie far outside our Milky Way, have recently be discovered at higher observing frequencies. Their origin remains completely unclear and is one of the mysteries of radio astronomy. We present LPPS in detail in Chapter 3.

In Chapter 4 I describe the second blind pulsar search with LOFAR. This follow-up of LPPS is called the LOFAR Tied-Array Survey (LOTAS). This survey was used to test the “tied-array” mode (i.e. coherent beam-forming). During each observation 19 beams were formed, that together covered less sky than a single seven beam LPPS observation, whilst being more sensitive. In LOTAS we observed 27 previously known pulsars, of which four were very recent discoveries. Because of its higher sensitivity we were also able to discover a few new pulsars. These two previously
unknown pulsars, known as PSR J0140+5621 and PSR J0613+3731 (it is convention to name pulsars after their sky coordinates), are the first LOFAR pulsar discoveries. For these pulsars we undertook follow-up observations to better determine their positions. For this type of observations we formed a large number of simultaneous beams (217) around the preliminary position derived from the discovery observation. LOFAR is currently the only telescope that has the capability that can produce these type of confirmations directly. The position of pulsar PSR J0140+5621 was determined precisely very quickly in this way, while for PSR J0613+3731 several observations were necessary to determine its position (but fewer than would normally be the case using another telescope). To determine some of the pulsars’ parameters we performed so-called timing observations on both LOFAR discoveries. By repeatedly observing the exact arrival time of the pulse we determined the exact rotational period and its evolution. We were then able to estimate the ages and pulsar magnetic fields. One of the discovered pulsars, PSR J0140+5621, has a relatively strong magnetic field of \(10^{13.09}\) Gauss, or about 24,600,000,000,000 times stronger than Earth’s magnetic field.

Most pulsars can only be discovered through their periodic emission. Periodic in this context means pulsations recurring very stably and regularly during the whole observation. Other pulsars, however, can also be detected through their individual bright pulses. This decade it became clear that a certain class of neutron stars, so-called Rotating Radio Transients (RRATs), can only be discovered through their single-pulse emission. Furthermore, the discovery of short and bright radio flashes from outside our Milky Way was also the by-product of pulsar surveys conducted with the Australian Parkes telescope. For both LPPS and LOTAS we searched the data for the occurrence of this type of bursts. I tried to further automate the process of searching for this type of bursts. In chapter 5 I describe an extension to the current search procedures that can help the selection of interesting signals.

**THE NON-DETECTION OF GEMINGA**

**GEMINGA** is a famous pulsar first observed using gamma-rays. In the early 1970s the Small Astronomy Satellite 2 (SAS-2) was launched that conducted observations of gamma-rays, a type of radiation with more energy per light particle than x-rays. Because of limitations to its sensitivity and its modest spatial resolution, SAS-2 was able to observe only a few sources; two previously known supernova remnants containing pulsars (the Crab and Vela) and an unidentified, bright source now known as Geminga. The COS-B satellite that was active in the late 1970s and early 1980s, observed 25 gamma-ray sources, but their identification remained difficult. A problem in identifying Geminga was that its position could not be determined accurately based on its gamma-ray detection. The discovery of a possible x-ray and subsequent to that a possibly optical counterpart strongly suggested that Geminga was in fact a neutron star. In 1992 pulsations in soft x-rays (x-rays with relatively little energy per light particle) were discovered that were later also found in archival SAS-2 and COS-B data. This discovery showed that Geminga was in fact a pulsar (and therefore a neutron star). Whether Geminga was detectable using a radio telescope remained in question, especially as earlier attempts to detect it in radio had failed. In 1997 Russian astronomers published radio observations of Geminga. For these observations
they used both the Large Phased Array (LPA) and DKR-1000 telescopes in Puschino. Both these telescopes operate, much like LOFAR, at low radio frequencies (the LPA around 102 MHz for example). No other telescope had the sensitivity of the Puschino observatory at low radio frequencies. LOFAR can match the LPA in sensitivity and an attempt to replicate the controversial result was obvious. We therefore, using the LOFAR high band (or more precisely 110-188 MHz) we observed the known position of Geminga and searched the data for radio pulsations. While our LOFAR observation was more than an order of magnitude more sensitive than the earlier LPA observations we have not been able to detect such emission. From this we concluded that earlier detection were likely spurious; although we leave open the possibility that Geminga, like some pulsars are known to do, turned off its radio emission and is therefore no longer observable using LOFAR.

CONCLUSIONS

In this thesis I show that LOFAR is a very capable observatory with which to conduct pulsar surveys. This follows from the fact using data from LOFAR’s commissioning period, a period when problems with the telescope are to be expected, we were able to discover two pulsars.