Modulation properties of radio-emitting neutron stars

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CHAPTER 1

Introduction

1.1 The discovery of pulsars

The discovery of pulsars, which started a new era of Radio Astronomy, was made on the 6th of August 1967 by the then graduate student, Jocelyn Bell. She studied, together with her Ph.D. advisor Dr. Antony Hewish, interplanetary scintillation by measuring the intensity fluctuations in the radio signals coming from distant radio sources. During these observations they detected a strange source of radio emission, which they at first considered to be unwanted radio interference (see Fig. 1.1). However, the appearance of the “scruff” at the same sidereal time in the following days led to the conclusion that the origin of the signal is extraterrestrial. The signal had strange characteristics; it consisted of pulses with a repetition rate of 1.34 seconds and was, somewhat in jest, given a designation Little Green Men 1. Soon afterwards, in December the same year, a second source (PSR B1133+16) was discovered and it became clear that a new class of radio astronomical objects, dubbed pulsars, became known to mankind. The serendipitous discovery of the first pulsar by Hewish et al. (1968) was soon followed by the discovery of more sources (Pilkington et al. 1968) and astronomers began to search for an explanation of their nature. In 1974, Antony Hewish and Martin Ryle were awarded the Nobel Prize in Physics, “for their pioneering research in radioastronomy”, with for Hewish the addition, “for his decisive role in the discovery of pulsars”.

1Pulsar is a contraction of pulsating star coined by a journalist from the Daily Telegraph.
2http://nobelprize.org/nobel_prizes/physics/laurates/1974
The work which laid the first foundations of the theory of these new objects was done much earlier by Baade & Zwicky (1934). They studied the properties of cosmic rays, which they proposed to originate in supernova explosions. In addition, they introduced a hypothesis that supernovae represented the transition stages between ordinary stars and \textit{neutron stars} consisting mainly of neutrons. This hypothesis was mentioned by Gamow (1939) who in his work on scenarios of stellar evolution, considered supernovae and neutron stars as one of the possible final stages following the collapse of a star, applicable to stars within a sharply defined mass range. In 1939, Oppenheimer & Volkoff derived an equation which constrained the structure of a spherically symmetric body of isotropic material which is in static gravitational equilibrium. This equation could be solved by using the Einstein equations for a general time-invariant, spherically symmetric metric. This resulted in the first upper limit to the mass and radius of neutron stars. The authors showed that these exotic objects would be very small, too small to be observed.

During 1968 more and more new pulsars were discovered. The discovery which finally proved the connection with supernovae, and showed that pulsars had to be rotating neutron stars was that of two pulsars in the centre of two supernova remnants. The first, the Crab Pulsar, as it is called today, was detected by Staelin & Reifenstein (1968) in the Crab Nebula, the remnant of the supernova explosion in 1054 A.D. (Biot 1841; Duyvendak 1942a,b). The second source, that resided in the Vela Supernova Remnant was discovered by Large et al. (1968). Both pulsars had very short periods of only 33 and 89 milliseconds, respectively, and the only objects which could rotate that rapidly and emit radio emission were \textit{highly magnetised rotating neutron stars} (Gold 1968).

### 1.2 Formation of neutron stars

Neutron stars are the result of the evolutionary path of stars with large masses ($\gtrsim 8 - 11 \, M_\odot$), which ends in a violent explosion which is called a Type II Supernova. During the lifetime of stars, their radiation is generated by the nuclear fusion happening in their interiors. Their large masses allow these stars to fuse the elements heavier than hydrogen and helium, something which cannot be done by the lighter stars like the Sun. The radiation pressure sustained by the fusion supports the star against gravitational collapse due to its own mass. The evolution of the star continues until the fusion of lighter to heavier elements reaches a limit in which a core of nickel and iron is formed. The star is now at a pre-supernova stage and has a shell-like structure composed of a nickel-iron core surrounded by layers of burning silicon, neon, oxygen, carbon, and helium, and a vast mantle of hydrogen. Due to convection, these shells tend to mix up. The nickel and iron are elements which cannot fuse further and the core builds up its mass until it reaches the limit of $1.44 \, M_\odot$ which is well known as the “Chandrasekhar mass”. At this point the fusion process starts absorbing energy from the core altering the pressure and temperature conditions. Eventually fusion halts and the lack of radiation pressure from the burning of elements allows the gravitational forces to take over. The degeneracy pressure of electrons present in the core is exceeded and the core collapses until it is halted by neutron degeneracy pressure, causing the implosion to bounce outward. The energy of the bounced shock wave has a catastrophic effect on the surrounding stellar
material, detaching it from the core and forming a supernova explosion. The neutron degeneracy pressure stops the core from further collapse. During the collapse of the progenitor star, its magnetic flux and angular momentum are conserved. When a neutron star is formed, it retains only a percentage of its predecessor’s mass (about $1.4 M_\odot$) and radius (about 10 km), which results in a greatly amplified surface magnetic field and rotation rate. The presented scenario illustrates the basic aspects of the formation of a typical neutron star. However in the process of formation there is in addition also a dynamo effect which can play a role by greatly enhancing the magnetic field strength and thereby forming another type of neutron star.

This type of neutron star is called a magnetar. Its formation proceeds in a similar way as in the case of a canonical pulsar, up to a certain point. Unlike normal neutron stars where we think that the field originates simply due to the conservation of magnetic flux, in magnetars the field is amplified by a dynamo process in the core. This is closely connected with the idea of the convection of gas. It is known that gas can circulate by convection within a star. That is, the warm bundles of ionised gas rise up into the higher parts of the star while the cold ones sink. The ionised gas is a very good conductor which result in a dragging of the magnetic field lines by the moving gas. This means that in favourable conditions the magnetic field can be amplified. The dynamo effect is considered to be responsible for generating the magnetic fields of stars and planets. Duncan & Thompson (1992) put forward the magnetar theory, using the finding of Burrows (1987), that the same convection takes place in a newly formed neutron star, which coupled with its fast rotation can increase the strength of the magnetic field of newborn neutron stars by three orders of magnitude when compared to normal pulsars. Subsequently, the fast rotation rate rapidly decreases significantly, as a result of the large electromagnetic torque exerted by the rotating magnetic field, and the neutron star becomes a magnetar. During the following years the magnetar theory has been accepted as a likely explanation for Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars.
Figure 1.2: A plot depicting the main features in the radio emitting neutron star. The plot presents the major terms and regions used in the discussion in this chapter. Figure is taken from Rubio-Herrera (2010).

1.3 Properties of radio emission

The radio emission from neutron stars is believed to originate from above their magnetic poles. The emission is directed towards the Earth in beams which are aligned with the pulsar magnetic axis as shown in Fig. 1.2. The pulsed nature of the emission from a pulsar comes from the fact that the spin and magnetic axes are in general non-aligned. Once per stellar rotation the beam of radiation sweeps across the Earth and a pulse of radio emission is seen. This is called the *lighthouse effect* and the time which passes between the consecutive sweeps of the beam is called the *pulse period*. If a sufficient number of pulses is added together then an *integrated* or *average pulse profile* is formed. Average pulse profiles have different shapes for each pulsar and are very stable for any observation at the same radio frequency (Helfand...
et al. 1975). These profiles bear the information about the structure of the emission beam and can be thought of as a characteristic “fingerprint” of a pulsar. The average pulse profiles show various levels of complication and can assume the simplest forms resembling a Gaussian up to very complicated profiles composed of many peaks, so-called components. However, the majority of the information about the radio emission of pulsars is revealed through the study of their individual pulses which vary in shape and intensity on a pulse-to-pulse basis.

In order to visualise and investigate these variations it is best to use a so-called pulse stack which is formed by taking consecutive pulse profiles and plotting them one above the other. The vertical and horizontal axes of this two-dimensional representation of a pulsar signal are now described by pulse number and pulse longitude, respectively. An example of a pulse stack is presented in Fig. 4.1 in Chapter 4. It can be seen from the plot that the successively appearing pulses are composed of subpulses which form an extraordinary pattern. This pattern was first spotted in the observations of pulsars B2016+28 and B1919+21 made by Drake & Craft (1968). Soon the phenomena of marching (Sutton et al. 1970) or drifting subpulses (Huguenin et al. 1970) was found to be quite common among pulsars and could be described as a constant change of the phase of successively appearing subpulses within a fixed longitude range. The drifting subpulse phenomenon can be best seen in Fig. 4.1 in Chapter 4, where the subpulses form drift bands quantified by two values, $P_3$ and $P_2$, which describe the vertical and horizontal separation of the drift bands, respectively. The drifting subpulse phenomenon is also known to be closely connected with two other phenomena. The first is called a drift mode change in which two (or more) drift rates are exhibited by the pulsar. In Fig. 4.1 in Chapter 4, two drift modes are seen clearly and they are separated by the manifestation of another phenomenon which is known as nulling. Nulling is observed as a cessation of pulsar emission for a certain number of pulse periods. Just from this example it is clearly seen that the pulsar radio emission is very complicated and requires a very sophisticated theory in order to explain it.

1.4 Physics of radio emission

The first approach to explain the radio emission mechanism of neutron stars was made by Sturrock (1971), who has shown that electron-positron pairs are formed in the strong magnetic fields of pulsars due to curvature radiation and these pairs are responsible for the observed radio emission. This interpretation, however, was incomplete as it did not consider a magnetosphere comprised of charged particles corotating with the neutron star as first described by Goldreich & Julian (1969). The model of Ruderman & Sutherland (1975) used the previous works and proposed the first explanation of the phenomenon of drifting subpulses. Their model assumed the presence of a magnetospheric quasi-steady vacuum gap above the surface of the neutron star in which sudden and momentary discrete discharges of particles take place. These so-called spark discharges, or sparks generate electron-positron pairs which flow out in bunches along the curved magnetic field lines, where, at a height which is estimated to be tens of stellar radii (Cordes 1978), they produce a secondary pair plasma which is believed to produce the radio emission. Additionally, the sparks circulate together in an organised manner in what is called the carousel of sparks, around the magnetic
Figure 1.3: The $P - \dot{P}$ diagram showing the different types of neutron stars as depicted in the lower right corner. The lines showing constant magnetic field $B$, characteristic age $\tau_c$ and spin down energy loss rate $\dot{E}$ are shown. The hashed region is occupied by “Vela-like” pulsars and the double hashed, by “Crab-like” pulsars. The regions in gray denote the areas where the radio pulsars are not predicted to exist by the present theoretical models. Figure is taken from Lorimer & Kramer (2005).

axis due to $\mathbf{E} \times \mathbf{B}$ drift. Each of the sparks gives rise to a drift band, since they rotate slower in the carousel than the pulsar rotation rate. This is now considered to be the most developed model describing the pulsar emission mechanism. An excellent example of a study of pulsar emission using the carousel model as being responsible for drifting subpulses is a series of papers on PSR B0943+10 (Deshpande & Rankin 2001; Asgekar & Deshpande 2001; Rankin et al. 2003). Extensive observational studies on subpulse modulation and polarisation properties are well explained in the light of the aforementioned model. However, it is important to note, that the curvature radiation proposed to be responsible for the radio emission is an inefficient process (Lesch et al. 1998) and emission by bunches of particles has been completely dismissed by Melrose (1981) as being too slow and too unstable to occur. Moreover, the Ru-
derman and Sutherland model cannot explain certain phenomena observed in the emission of pulsars, i.e. non-linear drift bands or very long carousel circulation times (van Leeuwen et al. 2003). Over the years, further developments have been proposed which could account for those phenomena (e.g. Gil & Sendyk 2000; Gil et al. 2003). Other models propose the maser emission mechanism as responsible for pulsar radiation. This emission is generated by particles which undergo linear acceleration resulting in coherent radiation (Rowe 1995).

For a long time pulsars were thought to be the only class of neutron stars which could emit pulsed radio emission. However, Camilo et al. (2006) detected emission from XTE J1810−197, the first magnetar to emit pulsed radio emission. This discovery, soon followed by two more: 1E 1547.0-5408 (Camilo et al. 2007b) and PSR J1622-4950 (Levin et al. 2010), gave rise to a whole new class of radio emitting neutron stars. Magnetars are a class of X-ray and gamma-ray emitting slowly rotating neutron stars which are thought to be powered by the energy stored in their extremely intense magnetic fields (higher than $10^{14}$ G, two orders of magnitude greater than for an average radio pulsar). The peculiar radio emission properties of these sources defied a theoretical explanation until Thompson (2008a,b) gave an extensive explanation of the pair creation processes and proposed the model of a dynamic outer magnetosphere as an explanation for the radio emission from magnetars.

The third class of sources which joined the radio emitting neutron stars are Rotating Radio Transients (RRATs) which sporadically emit very bright radio pulses. Apart from their very sporadic emission they share most of their properties with radio pulsars (Kramer 2008) and the idea was put forward by Weltevrede et al. (2006) that RRATs can be explained as distant normal radio pulsars which are seen thanks to their strongest pulses. The observations and studies of radio emitting neutron stars illustrate the diversity of their properties. It is important to study all the different manifestations in order to understand their nature and find the common origin of their radio emission.

### 1.5 Characteristic quantities

The characteristic features of a radio pulsar, that is large mass, small diameter, strong magnetic field and high spin frequency reveals their extreme physical properties. The observations of the Crab pulsar by Richards & Comella (1969) showed for the first time that the star was spinning down, increasing its period with time. The rate at which the pulsar is increasing its period is given by the period derivative $\dot{P}$. The rotating magnetised neutron star looses its angular momentum by the emission of magnetic dipole radiation. This braking effect is evident from the increase of the pulse period. The magnetic dipole radiation of a rotating magnet with dipole moment $\vec{m}$ leads to a loss of rotational kinetic energy of:

$$\dot{E} = -\frac{d(I\Omega^2)/2}{dt} = \frac{2}{3c^3} |\vec{m}|^2 \Omega^4 \sin^2 \alpha \text{ erg s}^{-1},$$

where $\Omega$ is the angular frequency, $c$ is the velocity of light, $I$ is the moment of inertia and $\alpha$ is the angle between the magnetic and rotation axis. Calculating the time derivatives and rearranging Eq. 1.1, an expression that relates $\Omega$ and $\dot{\Omega}$ is obtained:
\[ \dot{\Omega} = - \left( \frac{2 |\vec{m}|^2 \sin^2 \alpha}{I} \right) \Omega^3. \]  

(1.2)

The relation between \( \Omega \) and \( \dot{\Omega} \) can be expressed more generally as a power law, with \( \Omega \) given in terms of spin frequency, \( \nu \):

\[ \dot{\nu} = -K \nu^n. \]  

(1.3)

The value of the braking index \( n \) is usually assumed to be 3, as expected for magnetic dipole braking, but its measured value can be lower (e.g. Lyne et al. 1996). Integrating Eq. 1.3 will yield the formula to obtain the age of pulsar:

\[ T = \frac{P}{(n-1)\dot{P}} \left[ 1 - \left( \frac{P_B}{P} \right)^{n-1} \right], \]  

(1.4)

where \( P_B \) is the spin of a neutron star at birth. If the spin down of the pulsar is assumed to be entirely due to magnetic dipole radiation \( (n = 3) \) and the rotation period at birth is significantly smaller than the present value \( (P_B \ll P) \) then Eq. 1.4, can be written in a simplified form and the characteristic age, \( \tau_c \), of a pulsar can be calculated as:

\[ \tau_c = \frac{P^2 \dot{P}}{2P} \approx 15.8 \text{ Myr} \left( \frac{P}{10^{-15}} \right)^{-1}. \]  

(1.5)

From Eq. 1.2 it is possible to estimate the strength of the surface magnetic field \( (B_{\text{surf}}) \) of the neutron star. Remembering that at a distance \( r \) the magnetic field strength is: \( B = 2|\vec{m}|/r^3 \), Eq. 1.2 gives:

\[ B_{\text{surf}} = \sqrt{\frac{3c^3}{8\pi^2} \frac{I}{R^6 \sin^2 \alpha}} PP. \]  

(1.6)

For typical values of a neutron star with substituted; moment of inertia \( I = 10^{45} \text{ g cm}^2 \), radius \( R = 10 \text{ km} \) and \( \alpha = 90^\circ \) Eq. 1.6 can be written in a simpler form:

\[ B_{\text{surf}} \approx 10^{12} \left( \frac{P}{10^{-15}} \right)^{1/2} \left( \frac{\dot{P}}{\tau} \right)^{1/2} \text{ G}. \]  

(1.7)

The \( P - \dot{P} \) diagram (Fig. 1.3) is used to compare pulsars. We can see that the pulsar population splits into different groups defined by ages and magnetic field strengths. The evolution of a canonical isolated pulsar starts with its birth in a supernova explosion. Once it turns on as a radio pulsar its rapid rotation and slow-down rate mean that it is located in the upper left corner of the \( P - P \) diagram. As the pulsar ages according to Eq. 1.5 it moves towards the right and down crossing the lines of constant characteristic age along the way. The hatched and cross-hatched regions in the diagram denote the pulsars which are often found to be associated with supernova remnants. Eventually, after about \( 10^{5-6} \text{ years} \) the pulsar will reach the main pulsar population located in the middle of the diagram. As the
pulsar ages further, the slow down results in a decay of its emission and the pulsar moves toward the “graveyard” area where after $10^{7}$−$10^{9}$ years its radio emission shuts off.

In the case of the magnetars, the evolution is still a mystery. It is thought that their evolutionary paths start in the top left corner of the plot with small pulse periods which are quickly reduced from initial values due to the strong magnetic braking, also their spin-down rates are so high that they evolve very quickly across the $P$−$P$ diagram. In this scenario presented the active life of a magnetar is short. Their strong magnetic fields are thought to decay after about $10^{4}$ years, after which their magnetar activity ceases.

1.6 Summary: a guide to this thesis

In this thesis I present the results of studies of the modulation properties of radio emitting neutron stars. The first chapter is devoted to the study of the radio emitting magnetar AXP XTE J1810−197. Using the 76-m Lovell, the 94-m equivalent Westerbork Synthesis Radio Telescope and the 100-m Effelsberg radio telescopes in May and July 2006 I performed the only simultaneous single-pulse observations so far of XTE J1810−197 at frequencies of 1.4, 4.9 and 8.35 GHz. Then I applied a number of techniques in order to study the properties of this radio emitting magnetar and compare them to those of ordinary radio pulsars. The simultaneous observations of the magnetar at three different frequencies proved to be very useful for characterising the properties and understanding the radio emitting magnetars in the light of the present knowledge of neutron stars. Its modulation properties show multiple spiky subpulses equally separated in the pulse profile and a lack of drifting, which shows that the radio emission mechanism of magnetars must be of different origin than that of pulsars. These observations further reveal that the radio emission from the magnetar, at least in its very bright phase, is unlike that of the radio pulsars.

The rest of this work is focused on radio emitting pulsars. The next two chapters of the thesis (Chapters 3 and 4) are dedicated to the study of the temporal properties of drifting subpulses from radio pulsars. In Chapter 3, I introduce a new technique, called the Sliding Two-Dimensional Fluctuation Spectrum, used for detecting and characterising the temporal changes of drifting subpulses from radio pulsars. In order to test this method I used simulated data and the archival data of three pulsars, B0031−07, B1819−22 and B1944+17. The results from the analysis of these data sets show, that the S2DFS method is robust and complementary to the other fluctuation spectral methods in detecting and characterising the temporal changes in drifting subpulses from radio pulsars.

In the fourth chapter I present the results from the largest study so far of temporal modulation properties of radio pulsars using a large number of archival observations of pulsars made, with the WSRT at two frequencies. Using the novel S2DFS technique introduced, in Chapter 3, I was able to perform a detailed investigation of the temporal properties of phenomena like aliasing, null-induced mode changing and the behaviour of multicomponent pulse profiles.

I also investigated the results, from the high-quality simultaneous dual-frequency full-polarisation observations of the highly peculiar pulsar B0826−34, with the 64-m Parkes radio telescope at 685 and 3094 MHz (Chapter 5). This pulsar shows the phenomenon of drifting
across its extremely wide average pulse profile. I confirm the presence of weak emission during what was previously thought to be nulling, at the higher frequency. The average pulse profile produced in the weak stage at the higher frequency is very similar in shape to that of the lower frequency.

To summarise, the work done in this thesis focuses on the rich manifestation of the phenomenon of subpulse modulation. By studying the magnetar I have shown that despite the extremely strong $S/N$ and pulsed radio emission, the source is unlike normal radio pulsars. The observations of the unusual pulsar B0826−34 shows that simultaneous dual-frequency observations improve the interpretation of its unusual weak-mode emission and the results from the polarisation studies suggest that the current models aiming to explain polarisation of the pulsar signals require further work. The work I have done on the properties of subpulse modulation of a large sample of pulsars shows this type of the temporal changes is common among pulsars. The method used to characterise the temporal modulation properties is shown to work efficiently. However, in order to explore the temporal modulation in even greater detail, a new improved method of analysis is required.