High precision radio pulsar timing

Janssen, G.H.

CHAPTER 1

Introduction

1.1 Radio pulsars

The first radio pulsar, now known as PSR B1919+21, was discovered in July 1967 by Jocelyn Bell and Antony Hewish (Hewish et al. 1968). Their original project was set up to scan the sky once every four days in order to measure the angular diameters of quasars. Surprisingly, once in a while, a tiny piece of “scruff” showed up at the same sidereal time on the chart paper

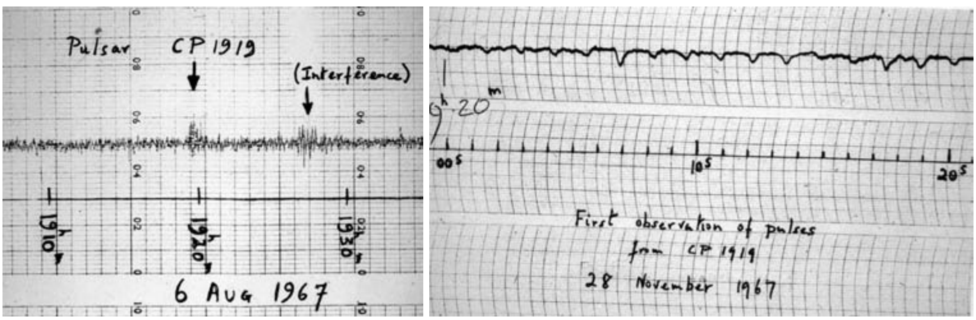

Figure 1.1: (a) Paper chart showing the discovery of PSR B1919+21, originally called CP 1919 (Cambridge Pulsar, the 1919 was based on its right ascension position). (b) An observation using higher time resolution showing the individual pulses of this 1.34 s pulsar.

that was used for recording the observations (Fig 1.1a). By switching their chart recorder to higher speed, thereby increasing the time resolution of their observations, they detected the very stable pulses with a period of 1.3 s that made the “scruff” appear as seen on their first paper charts (Fig 1.1b). It took about a month before they realised, and confirmed, that the signal originated from a source outside our Solar system. Because the signal repeated on such short timescales, and was very stable in its periodicity, at first the explanation of the signal being generated by “Little Green Men” could not be ignored. When the second source (PSR B1133+16) was found in December 1967, it became clear that they had found a new class of astronomical objects. The discovery papers of the first four pulsars were published in 1968 (Hewish et al. 1968; Pilkington et al. 1968), and the explanation of pulsars being rotating neutron stars was presented first by Pacini (1968) and Gold (1968). Antony Hewish was awarded the Nobel Prize in Physics[1] in 1974 (together with Martin Ryle) “for their pioneering research in radioastrophysics, and Hewish for his decisive role in the discovery of pulsars”.

Pulsars are highly magnetised, rapidly rotating neutron stars. They emit a radio beam along their magnetic axis, acting like cosmic lighthouses. Neutron stars are the end products of massive stars, and are formed during the supernova explosion that marks the end of the normal nuclear fusion life of the progenitor star. Presently, about 1800 pulsars are known, and they exist in all sorts and variations. Most of them are like the first four pulsars found, having spin periods of about 1 s and magnetic field strengths of roughly 10^{11} to 10^{12} G. A neutron star is about 20 km in diameter, but has a typical mass of about 1.4 $M_\odot$. Also even more extreme cases of pulsars exist, having millisecond spin periods, extremely high magnetic field strengths, or showing irregularities in their rotational or pulse emission properties.

Since the first pulsar was discovered more than 40 years ago, the physics of pulsars has become better understood (see e.g. Lorimer (2008) for a review). However, there are still a lot of mysteries to be solved; the generation and mechanism of emission in the different wavelength regimes is not understood in great detail, and even today completely new classes of pulsars are found (RRATs, radio-emitting magnetars). Over the last 40 years some exciting discoveries have been made where pulsars have played a key role: the discovery of a pulsar in a (relativistic) binary system (Hulse & Taylor 1975), the first millisecond pulsar (MSP; Backer et al. 1982) and the double pulsar system J0737−3039 (Burgay et al. 2003).

Pulsars are very interesting objects; they are unique tools to study the properties of matter at extreme densities as their densities are so extreme that they are not reproduceable on Earth. Not only are pulsars very exciting objects in their own right, one of their most important features is their very stable clock-like emission. Already in the discovery paper by Hewish and Bell, the long-term stability of the signal was recognised and used to exclude a companion to the pulsar. Nowadays it can be shown that some pulsars can reach stabilities equalling the best atomic clocks on Earth, on timescales longer than a year (Matsakis et al. 1997; Lorimer 2008). Using pulsars as distant clocks provides the basis of high precision timing measurements.

[1] http://nobelprize.org/nobel_prizes/physics/laureates

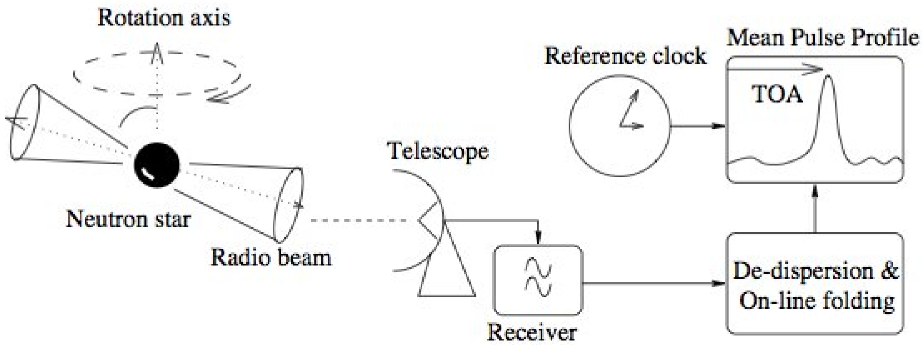

Figure 1.2: Schematic overview of a time of arrival calculation. Figure taken from The Handbook of Pulsar Astronomy (Lorimer & Kramer 2005).

1.2 Pulsar timing

Radio pulsar timing provides a unique tool to probe various astrophysical processes. Besides monitoring the intrinsic spindown behaviour of pulsars, it is used to probe the interstellar medium and its possible changes. Interactions of the superfluid interior of the star with the solid crust have measurable effects on the rotation rate of the neutron star. By measuring the pulse arrival times, the size of the glitches (Chapter 2) can be determined, and will ultimately lead to better constraints on the equation of state for matter at extremely high densities. When a pulsar is in a binary system with another star, Doppler effects in the pulsed signal can be measured, leading to the orbital parameters being derived and monitored. Pulsars in narrow orbits around another compact object, such as a white dwarf or another neutron star may need relativistic corrections to their orbital parameters (e.g. Weisberg & Taylor 2005, Chapter 3). In fact, the relativistic orbital decay of PSR B1913+16 was measured using pulsar timing (Fig. 1.4), and this was the first indirect proof of the existence of gravitational waves. For this measurement, Hulse & Taylor were awarded the Nobel Prize in Physics[1] in 1993. Furthermore, in a few cases, the measurements of two relativistic corrections can lead to the determination of the individual masses of the system, and when more than two are available, the measured parameters can be usable to test theories of gravity (e.g. Stairs et al. 2002; Kramer et al. 2006). Ultimately, it is predicted that when about 20 stable millisecond pulsars can be measured for a time span of 5 to 10 years with accuracies of about 100 ns, a pulsar timing array can be formed and used to directly detect the signal of a gravitational wave background (e.g. Jenet et al. 2006).

Pulsars as clocks

Fig. 1.2 shows a schematic overview of how a pulse time of arrival is calculated. A pulsar is observed for a few minutes to an hour, depending on its brightness. As single pulses are

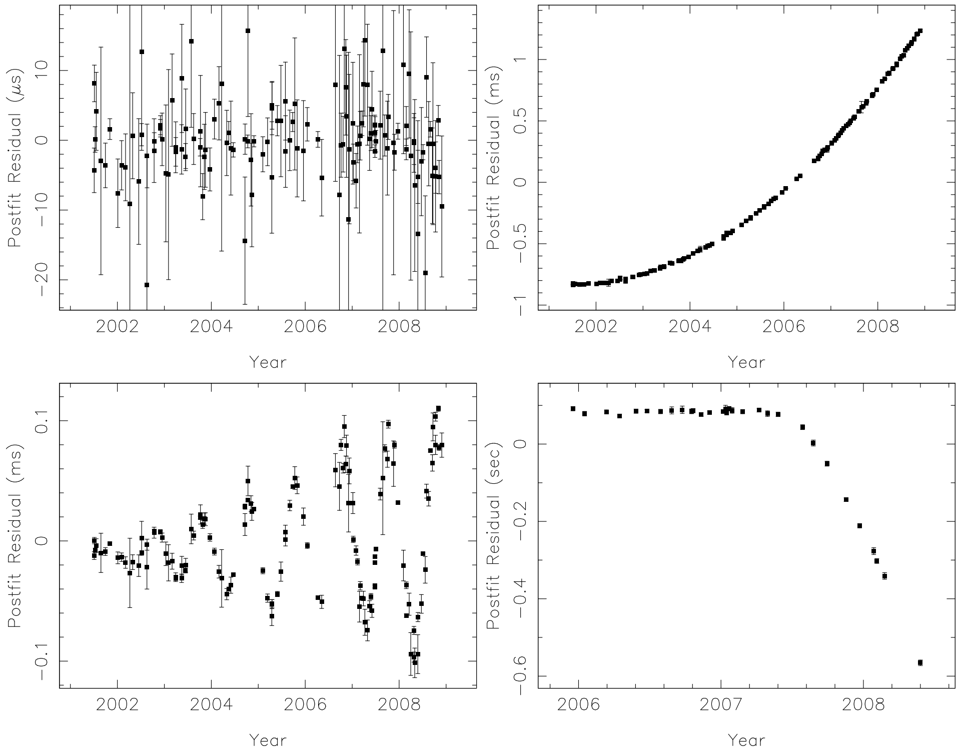

Figure 1.3: Timing residuals and the effects of different errors in the timing model. *Top left:* Best-fit residuals for PSR J1918−0642, a 7.6 ms pulsar in an orbit around a white dwarf. *Top right:* Timing residuals for PSR J1918−0642 with a 2% error in the spin period derivative, resulting in a parabolic increase in the error in the residuals. *Bottom left:* Timing residuals for PSR J1918−0642 with a 50% error in the proper motion. This leads to a sinusoidal effect with a period of one year, increasing with time. *Bottom right:* Residuals for PSR J1847−0130, a 6.7 s pulsar affected by a glitch in mid-2007.

usually too weak to be detected individually, and also because the profile of pulsars is varying from pulse to pulse, for pulsar timing an integration over the whole observation length is used. Optimally, a wide bandwidth is used for observing, and as the interstellar medium slows down the signal dependent on observing frequency, the signal has to be corrected for the time delay across the bandwidth (dedispersion). The combined result is a summation over frequency and time, leaving one single profile per observation. This profile is cross-correlated with a high signal-to-noise template that is representative for that pulsar, to find the phase offset that has to be added to the midpoint of the observation to calculate the time of arrival (TOA) for that particular observation. This TOA gets a time stamp from a local clock at the observatory. The Global Positioning Satellite (GPS) system is used to correct the local time to the best available worldwide timestandard, TT (terrestrial time). Finally, the arrival time as measured at the telescope is transferred to the corresponding arrival time at the Solar system barycentre.

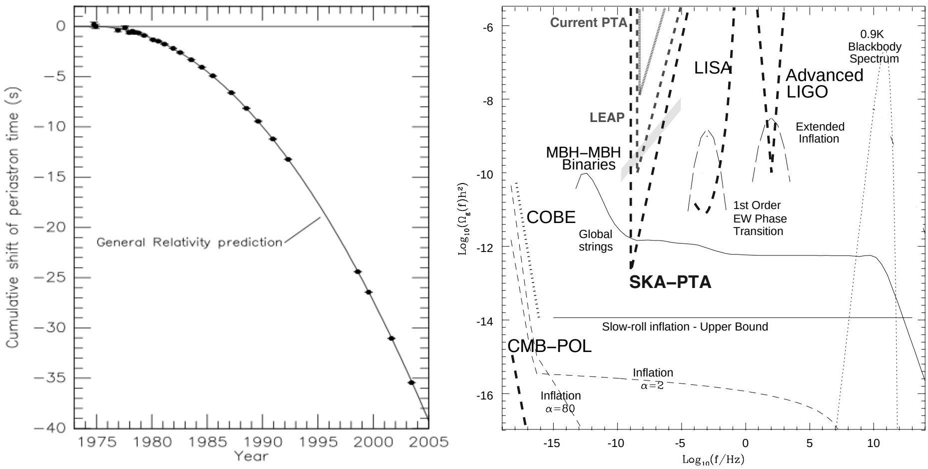

Figure 1.4: (a) Orbital decay of PSR B1913+16, the periastron position changes due to energy loss of the orbit due to the emission of gravitational radiation (Weisberg & Taylor 2005). The line represents the prediction of General Relativity. (b) Current detection limits for gravitational wave instruments (Figure from Kramer et al. 2004). Pulsar timing arrays will be most sensitive in the nanoHertz regime, and depending on the properties of the GW spectrum, will probe some of the expected ranges of GW emission.

Using this procedure, arrival times can be measured to accuracies on the microsecond level, and for some pulsars, even accuracies of tens of nanoseconds can be reached.

The arrival times are compared to a model for the pulsar's rotational behaviour, and the residuals to that model are examined. Any feature intrinsic to the pulsar, or affecting the signal while travelling towards the Earth that is not included in the model, will have its effect on the measured times of arrival for that pulsar. When the effect is large enough, the residuals to the timing model will show a systematic offset that grows with time, dependent on its cause (Fig. 1.3).

Usually, millisecond pulsars provide the best timing precision. Those pulsars are the most stable rotators due to their extreme spin rates, and as their profiles are correspondingly narrow, the TOAs are measurable with the highest accuracy and timing parameters best determined. Furthermore, the best timing solutions are obtained when using data sets that consist of large numbers of TOAs, and covering large time spans. In practice, this requires combining data sets from multiple telescopes or observing systems.

1.3 The European Pulsar Timing Array

In 2006, the European Pulsar Timing Array[2] (EPTA) collaboration was established, in which the five 100 m class radio telescopes are used, operated by their host institutes in Europe: The 96-m equivalent Westerbork Synthesis Radio Telescope (WSRT) operated by ASTRON in the Netherlands, the 76-m Lovell Telescope at Jodrell Bank in the UK, the 100-m Effelsberg Telescope run by the Max-Planck Institut für Radioastronomie in Germany, the 94-m equivalent Nançay Radio Telescope in France, and the 64-m Sardinia Radio Telescope (under construction) in Italy. Each observatory has a long history of pulsar timing observations, and its own strengths and capabilities in observing instrumentation. See Table 1.1 for an overview of the instrumentation currently in use by the EPTA. As a group, the EPTA observes a large set of pulsars, and for optimal results, systematically organises the observing capabilities to have a better coverage in time, orbital phase, and observing frequency for each pulsar. Combining the data sets from all EPTA telescopes has resulted in the biggest data sets ever used for timing (Chapters 3,5,6), leading to a huge improvement of the timing solutions for individual pulsars.

The main goal of the EPTA however, like other pulsar timing array collaborations around the world, is to work towards proving the existence of gravitational waves by a direct measurement. Gravitational waves are small disturbances in space-time that are caused by the movement of masses in space-time itself. They originate from a wide variety of sources, and are expected to occur over a wide range of frequencies. So far, the existence of gravitational waves has only been proven indirectly by measuring the orbital decay of relativistic pulsar binary systems using timing observations (Fig. 1.4, taken from Weisberg & Taylor 2005). Apart from interferometric ground-based gravitational wave detectors like LIGO[3], VIRGO[4] and GEO600[5], and the planned space antenna mission LISA[6], a different method exists: the pulsar timing array (Foster & Backer 1990). An instrument like this will use an array of millisecond pulsars as the endpoints of a galaxy-scale GW detector. It will be sensitive to GWs having frequencies in the nanoHertz regime, being complementary to the frequency bands addressed by other detectors (Fig. 1.4b). The aim of a PTA is to detect a stochastic GW background, by measuring correlations in the timing residuals of pulsars that are distributed across the sky (Jenet et al. 2005; van Haasteren et al. 2008). In general, a random superposition of GW emission is expected from a large number of independent sources, leading to a stochastic GW background. The most significant contributors to this background are GWs originating from supermassive binary black hole mergers during the evolution of galaxies in the early universe. Also, more exotic sources can contribute, like inflation, phase transitions in the early universe, or the effects of cosmic strings that are predicted by gravitational string theories (e.g. Kramer et al. 2004).

The large existing data set, combined with an excellent outlook for the future, makes the EPTA a very competitive candidate for being the first to prove the existence of GWs by a direct measurement.

[2] http://www.astron.nl/~stappers/epta/ [3] http://www.ligo.caltech.edu [4] http://www.virgo.infn.it/
[5] http://geo600.aei.mpg.de/ [6] http://lisa.nasa.gov/

Table 1.1: The instrumentation used by the EPTA.

Telescope	Freq (MHz)	BW (MHz)	T_{sys} (K)	Occurence
Effelsberg	860	40	60	rarely
	1400	100	20-25	often
	2700	80	20-25	rarely
	4900	500	30	rarely
	8400	1200	30	rarely
Jodrell Bank	1400	100	25	often
	6000	500	25	eventually
Nançay	1000-3500	128	35	often
WSRT	328	60	120	often
	840	80	75	rarely
	1100-1800	160	27	often
	2300	160	30	rarely
	4900	160	30	rarely
Sardinia	300/1400	100/500	25	eventually
	6700	500	25	eventually

1.4 This thesis

This thesis presents five projects that together highlight the wide range of possibilities of radio pulsar timing, and nicely shows the advantages of having data sets originating from the four large radio telescopes now available within the EPTA collaboration.

In Chapter 2, timing measurements of seven pulsars were used to detect *glitches* in the rotation rates of those pulsars. Glitches are indicative of processes in the interior of the neutron star, and are a unique tool to probe matter at extremely high densities. We have detected a significant set of small glitches, showing that the number of glitches at the small end of the distribution has been underestimated so far. This indicates that when sensitivity of detectors, and timing accuracy of TOAs is improved, it will be possible in the future to detect even smaller glitches which may alltogether lead to better insight in the interior properties of the neutron star.

For Chapter 3, data sets from five telescopes around the world were combined to find the best possible timing solution for a double neutron star binary, PSR J1518+4904. This is considered a mildly relativistic binary system, and because the orbit of this pulsar is quite wide, the relativistic effects are not easily measurable. However, by combining all TOAs that were measured of this pulsar since its discovery into one timing solution, it was possible to set constraints on the individual masses of the system, and the inclination of its orbit.

In Chapter 4, a new survey is presented that has been undertaken at the WSRT since 2004. This survey has used a unique beam-forming method making full use of the capabilities of the telescope. The small single dishes provide a large field of view to be covered in a single observation, however the array-like configuration of the telescope allows monitoring the sky with high resolution. We have surveyed the Cygnus region with this new method, called 8gr8 , and we present the first pulsars ever discovered with the WSRT. We have used a follow-up timing program to probe their spindown behaviour.

Chapter 5 gives a good example of the advantages of the ongoing long-term timing program at the WSRT. Since 1999, several pulsars have been observed on a monthly basis. Using observing time baselines up to 10 years we were able to measure long-term effects in the timing of four millisecond pulsars. From this, we were able to constrain the radial velocities from proper motion measurements of these pulsars.

In general, the rotational, astrometric and binary parameters are best measured when using as many TOAs as possible. Although most European observatories have a long-term timing program in place, combining the data sets has resulted in better timing solutions for various pulsars. However, combining data sets originating from different telescopes is not trivial, and combining several data sets from multiple EPTA telescopes is only useful when all possible differences between the observing and analysis procedures are accounted for. Chapter 6 provides the basis of an extensive study to the effects that give rise to certain errors in the TOA calculations. We present a few examples of pulsars that are measured by multiple telescopes within the EPTA, that are affected by different causes of errors in their TOA measurements. We have provided guidelines for the EPTA collaboration to optimally align and combine data sets for pulsars affected by various types of TOA measurement influences.