Chapter 1

Introduction

1.1 Overview

The discovery of pulsating radio sources (Hewish et al. 1968) named as **Pulsars** has turned out to be one of the great discoveries in astronomy. As we understand now, pulsars are highly magnetised, rapidly rotating neutron stars. The existence of such stellar objects was discussed well before the discovery of pulsars. For example, soon after the discovery of neutrons, Baade & Zwicky (1934) had suggested a possible connection between the supernova phenomena and the formation of neutron stars.

The most striking property of these pulsating radio sources was that their pulse repetition periods were found to be stable to better than 1 part in 10^7 over intervals of a few months. This, along with the short duration of pulses, implied that these astronomical objects must be very compact and sufficiently massive. White dwarfs and the theoretically predicted neutron stars were the natural candidates for such compact objects. The subsequent discoveries of two short period pulsars, the Crab and the Vela pulsars (Staelin & Reifenstein 1968, Large et al. 1968), with periods of $\sim$ 33 ms and $\sim$ 89 ms respectively, ruled out the possibility of white dwarfs being the source of the observed pulsed radiation. In the initial attempts to explain the periodicity, three distinct mechanisms were considered: radial pulsations, orbital motion and rotation. When radial pulsation was considered, the observed range of two orders of magnitude in period implied a density range too large to be possible for a single class of objects (radial pulsation period is proportional to $\rho^{-\frac{1}{2}}$, where p is the mean stellar density). The models with orbital motion also had serious difficulties and they were ruled out conclusively when the pulsation period was observed to increase with time; contrary to the trend expected in these models. Thus rotation of the neutron star alone remained as a viable explanation for the pulsar clock mechanism (Gold 1968). The Crab and the Vela pulsars being associated with supernova remnants gave a strong support to this conclusion.

Neutron stars are extremely dense objects with masses comparable to the mass of the sun, but with radii of only about 10 km. Strong self gravitation enables them to withstand rotation rates as high as several hundred times a second. These objects are believed to have a solid crust made up of iron nuclei forming a strong lattice structure embedded in a sea of fermi electrons in the outermost regions, and a superfluid interior made up of degenerate neutrons along with superconducting protons and degenerate electrons. Density of these objects vary from 10^4 g cm^{-3} close to the surface to $4-5 \times 10^{14}$ g cm^{-3} at the core and they are also found to possess very strong magnetic fields of the order of $10^8 - 10^{12}$ gauss. These fields are frozen into the neutron star matter and hence rotate with the star, generating intense electric fields which in turn are responsible for accelerating charged particles to ultra-relativistic speeds. These charged particles, in turn, emit curvature radiation as they move along the open magnetic field lines. As a result we see pulses whenever the cone of open field lines crosses our line-of-sight. Despite the high intensity observed, the radio emission represents only a small fraction of the total energy loss rate. Most of the energy lost from the system is carried away by the low-frequency electromagnetic waves.

Most of the rotation powered pulsars emit radiation at radio frequency while the accreting binary pulsars emit X-rays where the source of energy is accretion rather than rotation. A number of radio pulsars have also been observed at optical, X-ray and γ-ray frequencies. Multifrequency as well as long-term observations have given a wealth of information about the interior structure of neutron stars and their emission mechanism. Yet there exist a lot of unanswered questions. Pulsars also act as a useful probe of the interstellar medium, and help to study the distribution of the free-electron density and the structure of the magnetic field in our galaxy. They also provide rare opportunities to test many important theories under physical conditions which are not reproducible in the laboratory. The physics involved in the pulsar studies ranges from classical dynamics and electromagnetism to quantum mechanics and general relativity (for a detailed review, see Pulsars as Physics Laboratories, eds Blandford et al. 1992). The study of pulsars presents challenges to both, the observers to develop new observing techniques as well as the theorists to come up with better models for the internal structure and the emission mechanism of the neutron stars to match with the observations.

Although 700 pulsars are known so far, period derivative measurements (required for the estimation of age and the magnetic field strength of pulsars) are not available for a significant fraction of the sample. Rotational parameters of pulsars can be determined by carrying out ***timing observations*** systematically over a long time scale. In addition to the secular slow-down, sudden jumps in the period ***(glitches)*** as well as slow variations known as ***timing noise*** are observed in some relatively young pulsars. Study of these phenomena provides valuable clues to our understanding of the interior structure of the neutron stars. With a long term goal of extending studies on such phenomena, we developed an observational and analysis setup using the Ooty Radio Telescope for pulsar timing. As a short term goal, using this setup, we have made timing measurements on 16 newly discovered pulsars with an immediate goal of obtaining their rotational and positional parameters to an useful accuracy. This thesis presents the data over a span of 1 year and results of the timing analysis on 16 pulsars in the southern sky. This project has involved work in software development, monthly observing sessions, data processing/analysis and interpretation of the results. All of these aspects are described in the following chapters.

A brief outline of the thesis is as follows. In the remainder of this chapter we present an overview of pulsar topics relevant to the chapters which follow. Chapter 2 describes the telescope that we used for the observations and the observational details. Chapter 3 describes the software that has been developed and used in the timing analysis. In Chapter 4 and 5 we present and discuss the various results that we have obtained from our timing analysis, as well as from the average pulse profiles.

The work presented in the last chapter (chapter 6) is unrelated to the previous chapters, and it is an attempt to get a handle on the large scale magnetic field of our Galaxy from pulsar observations. Pulsars act as excellent probes of the galactic magnetic field as their radiation is often highly linearly polarised. The plane of polarisation rotates due to the presence of the electron plasma and the magnetic field in the intervening medium; an effect known as 'Faraday Rotation'. Using a model for the electron density distribution in our galaxy and the data on Faraday rotation in directions to the pulsars we have tried to re-examine the various models for the large scale galactic magnetic field. The details and results of this investigation are presented in this chapter.

1.2 Basic Properties of Pulsars

There are currently about 700 pulsars known within our galaxy. Five pulsars have been discovered in our nearest neighbour galaxies namely the Large Magellanic Cloud and the Small Magellanic Cloud. Even though the majority of the galactic pulsars lie very close to the galactic plane, a considerable number of them are seen at large distances from the plane. This is mainly because of the high velocities acquired during their birth; given a typical velocity ~100 km/s they move far from their birthplace during their active lifetime. The total number of pulsars in our galaxy is estimated to be more than 10^5 or so (Lyne et al 1985, Narayan & Ostriker 1990, Deshpande et al. 1995). But the number of detected pulsars is a very small fraction of the above. One of the main reasons is that all surveys are highly sensitivity limited, detecting only those which lie close to the Sun unless they are highly luminous. A second reason is that pulsars can be detected only if their emission cone happens to cross our line of sight.

Pulsars may be grouped into two categories. 'Normal pulsars' which are mostly young, isolated pulsars with rotational periods between 20 milliseconds to 2 seconds. A major fraction of the known pulsars belong to this category. The other class, known as 'millisecond pulsars', are very old pulsars with rotation periods from 1.5 ms to 20ms. Most of these millisecond pulsars are found in binary systems with low mass white dwarf companions. These millisecond pulsars are believed to have been born in a binary system as normal pulsars and subsequently undergone spin-up due to the accretion of matter from the binary companion.

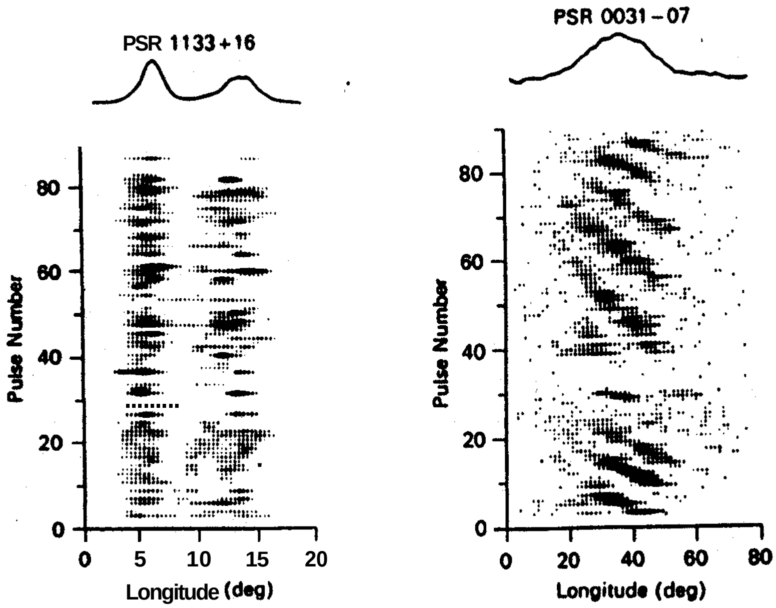

Figure 1.1: Longitude-time diagram of the pulsars PSR 1133+16 and PSR 0031-07 showing the variations in shape and intensity of a series of individual pulses. The integrated profile is shown on the top. Each horizontal series of dots represents one pulse; the size of the dots indicates the intensity. Subpulses or bursts of enhanced emission covering 3-10 degrees of longitude can be seen in most pulses. In the case of PSR 0031-07, well-organised drift bands can be seen.

1.2.1 Characteristics of the Pulses

One of the hallmark characteristic of pulsars is their highly periodic pulse emission. The time interval between two successive pulses corresponds to one rotational period, which in usual notation is referred to as 360° of longitude. Although lots of variations in intensity and shape are seen in individual pulses, if a few hundreds of consecutive pulses are summed up synchronously with the pulse period one obtains a very stable integrated profile, establishing a distinguishing characteristic for each pulsar. In some pulsars, in addition to the main pulse, an interpulse is seen close to half the rotation period. In these pulsars, it is believed that the magnetic axis would be nearly orthogonal to the rotation axis of the neutron star and hence the emission is seen from both the poles.

Normally, individual pulses consists of one or more components called subpulses (see fig 1.1). These subpulses may be considered as the basic units of emission having an almost gaussian shape and a width of 3-10 degrees of longitude. These subpulses occur at varying longitudes within the pulse window. If the subpulses are stronger and occur more frequently at a particular longitude, then components or peaks would be formed when many pulses are averaged to form a integrated profile. Depending upon the intensity and

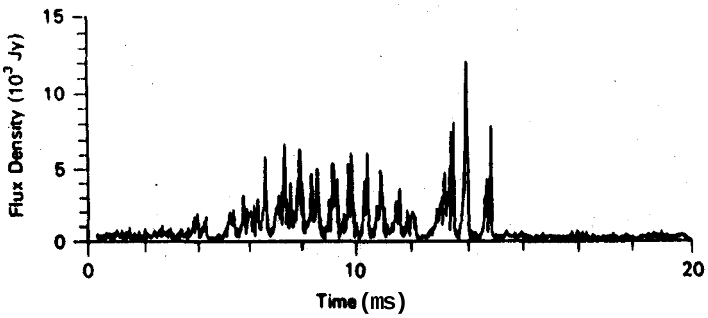

Figure 1.2: Microstructure of the pulse **from PSR 0950+08** recorded at 111.5 MHz and smoothed to a time resolution 28 μs. [After **Hankins, 1971**].

position of the subpulse, the shape of the pulse varies from simple profiles with just a single peak or one component to complex profiles containing **upto** five components which may partially overlap. **Subpulse** intensities are found to be very well correlated over wide frequency intervals and **their** widths are found to be correlated with their intensity - the stronger subpulses tending to be narrower. An mteresting phenomenon observed in some pulsars is that these subpulses drift systematically across the pulse window, for example, first appearing at the trailing edge of the profile and then drifting toward the leading edge (Drake & Craft 1968). A detailed classification scheme is used for different profile shapes: type ' S_t & S_d' for core and **conal** single profiles, **cD, cT, cQ** for conal double, triple and quadruple respectively. Pulsars having more than four components are classified **as** multiple 'M' and type 'C' for complex **profiles** and type 'D' for pulsars with drifting subpulses (Lyne & Manchester 1988, **Rankin 1983a,b**).

A number of pulsars undergo abrupt changes in their pulse shape to some other stable form. They remain in this state for hundreds to thousands of periods and change back to the original shape abruptly. This phenomenon is known **as** 'mode changing', and is commonly seen in type C pulsars and is understood as a redistribution of the emitting regions in the neutron star (**Rankin** 1986). In some **pulsars,** observation with high **time**-resolution show further fine structures in time of the order of few microseconds within the subpulse. These are known as **'micropulses'** (**Hankins** 1971, 1972) (fig 1.2). In relatively old pulsars, the intensity of the pulse **goes** below the detection limit from a few periods to hundreds of periods and then resumes back to normal intensity level. This phenomenon is commonly known as 'nulling'. Until recently, these were considered **as** 'last gasps of dying pulsars', whereas now it appears that pulsars do not null by simple virtue of their age (**Rankin** 1986.)

In general the shape of the integrated profile is frequency dependent in the sense that the separation between the components follow the relation, A4 $\propto \nu^{-p}$, where the separation index, p, is typically about 0.2 at low frequencies. In most cases there is a break frequency above which the separation still follows a power law, but a steeper one. Also, it is found that the width of the components decrease with increasing frequency.

1.2.2 Polarisation

The integrated profiles of a number of pulsars have essentially complete linear polarisation. The polarisation position angle often varies smoothly through the profile, with the total change less than or about 180°. Such position angle variation was observed first by Radhakrishnan and Cooke (1969) for the Vela pulsar. This led them to suggest the "rotating vector model" in which the direction of the polarisation vector corresponds to the direction of the magnetic field lines (seen as projected onto the sky) sampled by an observer as the neutron star rotates. But in some pulsars such smooth and monotonic behaviour of the position angle of the linear polariition is not seen. A more careful analysis of data showed that such a nonmonotonic behaviour was due to the presence of very nearly orthogonal modes. Backer and Rankin (1980) pointed out that both modes may be present at all times, but their relative dominance may change with longitude within the pulse window and hence seriously disrupt the average angle behaviour. When allowance is made for such 'flips' in the polarisation mode, the individual modes show a behaviour which is fully consistent with the prediction of the rotating-vector model of Radhakrishnan and Cooke (1969). But this model, of course, cannot explain the presence of an orthogonal mode p o l a r i i perpendicular to the projected magnetic field.. Cheng and Ruderman (1979) attributed these effects to an "adiabatic walking" of the polarisation as the radiation propagates through the magnetoactive plasma in the magnetosphere.

Circular polarisation is also observed, but in the integrated profile it rarely exceeds 20 percent of the total intensity. In most cases, the handedness of the circular polarisation is seen to reverse sign very close to the centre of the pulse (Rankin 1983). In some cases, there is also a weak symmetric circularly polarised component.

1.3 The Emission Mechanism

Although many models for emission have been proposed so far, this is one of the least understood aspects of the pulsar. There is no single theory that explains all the following observed features of the pulsar emission:

- extremely high brightness temperatures of the order of 10^{23} to 10^{26} K.
- occasional intense pulses from a few pulsars, implying brightness temperatures as high as 10^{30} to 10^{31} K
- stable mean pulse profile consisting of one or more (upto 5) components
- systematic decrease of the pulse width with increasing radio frequency and rotation frequency

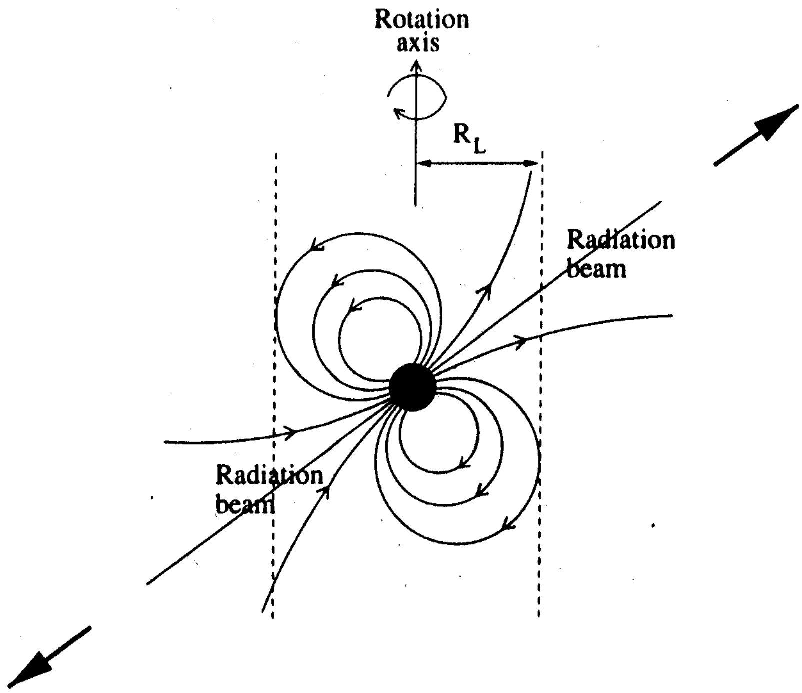

Figure 1.3: The schematic picture of a rotating, magnetised neutron star

- an **"interpulse"** located about half way between the main pulses
- drifting subpulses, micropulses, nulling & mode changes
- erratic **pulse-to-pulse** amplitude fluctuations
- continuous swing in the linear polarisation vector
- **90°** (orthogonal) transitions in the position angle of the linear polarisation vector and circular polarisation emission

The schematic picture of the pulsar is shown in fig (1.3). The magnetic field of the neutron star probably has significant multipole structure within a few stellar radii of the surface, but further out it is assumed to be dipolar. Goldreich and Julian (1969) considered this dipole magnetic field to be aligned with the rotation axis and argued that it would act **as** a homopolar inductor capable of generating high voltages $\sim 10^{16}$ volts. This electric field is strong enough to pull out electrons and protons from the surface in spite of,very strong gravitational force. Because of the strong magnetic field, these charged particles are forced to move along the field lines and thus **co-rotate** with the star. However, **co-rotation** cannot persist beyond the surface where the tangential velocity equals the velocity of light – that is beyond the so-called light ***cylinder,*** which has a radius

$$R_L = \frac{c}{\Omega} \approx 5 \times 10^9 P \qquad (cm) \tag{1.1}$$

The charged particles trapped in the magnetic field lines which close within the light cylinder will form a co-rotating magnetosphere, while those in "open field lines" will be accelerated to ultra-relativistic energies and flow out of the light cylinder. In a complementary model, Ostriker and Gunn (1969) considered an inclined dipole. In this, the main energy loss mechanism is due to the emission of magnetic dipole radiation whose luminosity will be determined by the strength of the perpendicular component of the magnetic field and the angular velocity of the neutron star. Even though, these models have served as the foundation for much of the understanding of pulsars, they don't explain the observed pulsed emission.

The rotating vector model (Radhakrishnan and Cooke, 1969; Komaseroff 1970) explained the pulsed emission and the observed linear polarisation. The accelerating charged particles would be constrained to move along the field lines because of the strong magnetic field. Since the field lines diverge from the polar cap, these particles will emit curvature radiation. This radiation will be linearly polarised and the direction of the polarisation is along the projected magnetic field line near the polar cap. But this model cannot produce emission near the centre of the pole as the curvature of the field would be zero. Hence, the emission would be in a hollow cone. The double pulse observed in some pulsars, the pulse width, as well as the polarisation could be explained by this model. Two years later, Sturrock (1971) pointed out that the relativistic wind from the pulsar will consist mainly of electron-positron pairs. These very high energy particles accelerated along the open field lines will produce very high energy gamma rays. These gamma rays are unstable against the creation of electron-positron pairs because of the strong magnetic field near the pulsar. Each of these particles in turn will produce more gamma rays which will produce more electron-positron pairs *etc.*. Thus a cascade develops. This seminal idea was the basis for the polar cap gap model due to Ruderman and Sutherland (1975).

Contrary to the Goldreich-Julian model, Ruderman and Sutherland (1975) pointed out that because of the very high binding energy of the neutron star crust, even the large electric field generated near the surface will not be able to pull out the positive ions. This may develop a magnetospheric gap above the polar cap across which the potential differencewill be about 10^{12} volts. They showed that such a voltage gap would periodically discharge in a time scale of a few microseconds due to electron-positron cascade as argued by Sturrock (1971). Depending upon whether the magnetic moment of the neutron star is parallel or antiparallel to the spin angular momentum, electrons or positrons respectively will get accelerated in the gap and move out along the open field lines. It is these particles close to the polar cap that produce the observed curvature radiation quite consistent with the observed variation of the linear polarisation. This model and its extension by Cheng and Ruderman (1979) gives satisfactory explanations for many observational details such as microstructure of pulses, the drifting subpulses, nulling, the switching between orthogonal modes of polarisation etc.. In the pair creation model of Sturrock (1971) and Ruderman and Sutherland (1975) when the voltage generated by the pulsar drops below a critical value, copious pair production will cease and the star will stop working as a radio pulsar (in the framework of the gap model, the gap will stop sparking).

Although most of the pulsars have been detected at radio frequencies, few pulsars emit pulsed radiation at optical, X-ray and gamma ray frequencies. Crab pulsar has been found to emit at all frequencies. According to Pacini and Rees (1970), the optical radiation is due to incoherent synchrotron radiation from near the light cylinder.

Observed luminosities (assuming conical beams) are in the range of 10^{25} to 10^{28} ergs s^{-1} for most pulsars. If we assume a source area of 10^{15} cm^2, across which the light travel time is 1 msec, the specific intensities corresponding to these luminosities are extremely high (10^4 to 10^7 ergs cm^{-2} s^{-1} Hz^{-1} $Sterad^{-1}$) and the brightness temperatures are in the range 10^{23} to 10^{26} K. Observations of microstructure with characteristic time scales of the order of 100 μs in several pulsars, and also the occasional intense pulses from the Crab pulsar, imply brightness temperatures as high as 10^{30} to 10^{31} K. Such high brightness temperatures would demand the radio radiation to be ***coherent.*** According to **Ruderman** and Sutherland, high coherence is achieved if the emission comes from ***bunches*** of charged particles emitting curvature radiation.

1.4 The Interstellar Medium

Pulsars are excellent probes of the interstellar medium. Various propagation effects in the intervening medium that the pulsar signals suffers on the way to the observer give a lot of information about the medium. For example, the distribution of electron density, the interstellar magnetic field and the small-scale structures present in the interstellar medium.

1.4.1 Interstellar Absorption

The broad band nature of pulsar emission makes possible the study of various absorption processes occurring in the galactic disk. At low frequencies, free-free absorption of pulsar radiation by thermal electrons in the interstellar medium gives information about the electron density distribution in the galaxy. In the spectra of a number of pulsars low-frequency cut-offs are observed, but part of the turn-over at the low frequency could be due to processes intrinsic to the pulsar itself.

Observations of the 1420 MHz spectral line of neutral hydrogen in absorption against continuum sources have led to a "two-component" model for the interstellar medium. The two components are: (1) relatively cold, dense and isolated regions known as clouds and (2) a hotter, less dense intercloud medium. The optical depth for neutral hydrogen absorption is proportional to N_H/T_s, where N_H is the column density of hydrogen atoms and T_s is the "spin" or excitation temperature for 1420 MHz hyperfine transition. Therefore, most of the absorption takes place in cold, dense clouds. One of the principal problems in HI-absorption measurements against ordinary continuum sources is the determination of the emission contributed by neutral hydrogen within the antenna beam, the so-called 'expected profile'. Absorption measurements against pulsars are not troubled by this problem, because the expected profile can be determined during the portion of the period when the pulsar is 'off', which is not possible with the absorption against continuum sources. Absorption features are always narrower than the emission features, which gives strong support to the "two-component" model for ISM.

Where absorption is detected, an approximate distance to the neutral hydrogen cloud can be inferred from the velocity extent of the absorption using the model for the differential rotation of the galaxy. This provides an independent method of determining distances to pulsars without using dispersion measure. But these observations are sensitivity limited, because most of the pulsars have low mean flux density.

1.4.2 Interstellar Dispersion

Dispersion is the most noticeable effect of the interstellar medium on the observed pulses. Much of the gas in the interstellar medium is ionised and the group velocity for propagation of a radio wave through this plasma is a function of its frequency. For a homogeneous, isotropic medium the group velocity is given by

$$v_g = c\left(1 - \frac{f_p^2}{f^2}\right)^{1/2} \tag{1.2}$$

where f_p is the plasma frequency and f is the wave frequency. For continuous signals the varying velocity with frequency won't be observable, but the pulsed nature of pulsar emission makes it possible to evaluate the degree of dispersion from the difference in pulse arrival times at two different frequencies, which is given by

$$t_2 - t_1 = \frac{e^2}{2\pi m_e c}\left(\frac{1}{f_2^2} - \frac{1}{f_1^2}\right)\int_0^L n_e dl \tag{1.3}$$

where $\int_0^L n_e dl$ is known as the dispersion measure (DM) of the pulsar. Dispersion measures for known pulsars range from 2 pc cm^{-3} to more than 1000 pc cm^{-3}. Variation in the DM over a period of time indicates that a region of excess density has moved into or out of line of sight and the magnitude of the change can be used to estimate the density and scale-sizes of the electron 'clouds'.

If the distance to a pulsar is known, a value for the mean free electron density in the path to the pulsar can be obtained. Alternatively, if the distribution of free electrons in the galactic disk is known, the DM gives a value for the distance to the pulsar. From the pulsar dispersion measures, there is evidence for three components to the dispersion: (i) nearby intervening ionized hydrogen (HII) regions; (ii) a thin disk associated with ionisation from hot, young stars; and (iii) a large halo whose scale height exceeds the scale height of pulsar population (Manchester & Taylor 1977). Recently more comprehensive models of the galactic tiistribution of free electrons have been developed (Taylor & Cordes 1993).

1.4.3 Faraday rotation and the Galactic Magnetic field

The radiation from pulsars is often found to be highly linearly polarised, which can bc considered as the sum of two equal-amplitude, opposite handed, circularly polarised signals. In the presence of a magnetic field, the index of refraction will be sliglitly different for the two opposite circular polarisations. Hence this effect makes the plane of polarisation of the linearly polarised wave rotate along the path, an effect known as 'Faraday Rotation'. This effect is cumulative and so even the weak interstellar magnetic fields can rotate the plane of polarisation substantially given long distances. The angle of rotation (in radians) after traversal of a path L is

$$A4 = 0.812X^2 \int_0^L n_e B \cos\theta dl \tag{1.4}$$

where B is the magnetic flux density in μG and θ is the angle between the line of sight and the direction of the interstellar magnetic field, λ is the observing wavelength (m) and L is in parsecs. The rotation measure (RM) is then defined as

$$\Delta\phi = RM\lambda^2 \tag{1.5}$$

so that

$$RM = 0.812 \int_0^L n_e B \cos\theta \, dl \tag{1.6}$$

The rotation measure is positive for fields directed towards the observer and negative for fields directed away and the amount of rotation increases with decreasing frequency.

In practice, the RM is found by measuring the difference in position angle at two wavelengths λ_1 and λ_2, so that

$$RM = \frac{\phi_2 - \phi_1}{\lambda_2^2 - \lambda_1^2} \tag{1.7}$$

To obtain accurate rotation measures, position angle measurements should be made at two widely separated frequencies. Together with the DM of the pulsars, the RM can be used to estimate the mean longitudinal field (in μG) weighted by the electron density, given by

$$\langle B_{||} \rangle = \frac{\frac{e^3}{2\pi m^2 c^4} \int_0^L n_e B_{||} dl}{\int_0^L n_e dl} = 1.232 \frac{RM}{DM} \tag{1.8}$$

demonstrating that pulsars are very useful tools for studying the galactic magnetic field. Apparently, the pulsar magnetosphere does not contribute any significant Faraday rotation, hence it becomes an ideal tool to study the galactic magnetic field.

1.4.4 Interstellar Scattering

The interstellar gas contains irregularities of electron density having a wide range of physical scales. Pulsar radiation traverses three distinct plasma regions: the interstellar and the interplanetary medium, the magnetosphere and the ionosphere. Random variations of the electron density lead to a fluctuation of refractive index which result in scattering of incoming radio waves, causing distant radio sources to scintillate. While scintillation due to the ionosphere and the interstellar medium may be confused, especially at radio frequencies, that due to the interstellar plasma is readily distinguishable by its longer timescales (of the order of minutes) and the much smaller radio bandwidth (typically < 1 MHz) over which intensity fluctuations are correlated. This effect has been analysed by using a simple method in which the perturbing medium is collapsed into a thin scattering screen situated between the pulsar and the earth (Scheuer 1968, Manchester & Taylor 1977). The scattering is associated with scale-sizes of the order of Fresnel zone radius $r_f = \sqrt{fD}$, where f is the frequency of the signal and D is the distance of the scattering screen from the observer (Backer 1989).

The temporal modulation known as diffractive interstellar scintillation (DISS) is a result of the relative motion of the observer, the medium and the pulsar. The spectral features can be described statistically by a characteristic frequency bandwidth and a characteristic time span over which the observed intensities decorrelate. These quantities are known as the decorrelation bandwidth (Af_s) and decorrelation time (t,) respectively. A simple analysis (e.g. see Manchester & Taylor 1977) shows that

$$\Delta f_s \propto \frac{f^4}{DM^2} \tag{1.9}$$

and

$$t_s \propto \frac{f}{\sqrt{DM}} \tag{1.10}$$

where f is the observing frequency and DM is the dispersion measure. The modulation in frequency arises from the frequency dependence of the location of the maxima and minima in the diffraction pattern.

DISS is only observed if the source diameter is less than the scale of the diffraction pattern at the earth. Otherwise, patterns from different parts of the source overlap and cancel out. Scintillation is only observable for those radio sources whose angular diameter is less than the scattering angle, typically 10^{-7} arcsec (Stinebring & Cordes 1990). So far pulsars are the only sources known to exhibit strong DISS (Rickett 1990).

In addition to the above effect, the propagation of the pulsar radiation along direct and scattered ray paths causes the pulse to be asymmetrically broadened in time. The observed pulse profile is therefore a convolution of the actual pulse shape with a truncated exponential whose characteristic time width τ_s is $(2\pi\Delta f_s)^{-1}$ (Lyne & Smith 1990) i.e.

$$\tau_s \propto \lambda^4 DM^2 \tag{1.11}$$

In addition to DISS, the early pulsar observations showed slow variations (days to years) in the apparent intensity. Rickett et al. (1984) proposed that refractive interstellar scintillation (RISS) may produce the slow intensity variation in pulsars, and possibly in compact extragalactic sources. RISS is thought to be due to focussing or defocussing of rays from the source by inhomogeneities with scale sizes larger than the **Fresnel-zone scale** (eg. 10^{11} to 10^{15} cm).

Observations of the effects of both RISS and DISS are **useful** probes of the ISM and are essential to constrain theoretical models of the scattering medium. DISS observations can also be used to determine the space velocities of pulsars, **which** when combined with estimates of the distances that pulsars have travelled from their birthplace in the galactic plane, gives an information of pulsar ages. The high spatial coherence of pulsar radiation leads to the formation of extremely fine-scale diffraction patterns, which provides information on the size of pulsar emission regions.

1.5 Pulsar Timing

One of the most outstanding properties of pulsars is the regularity of the rotation period. Careful measurements of pulse arrival times over long intervals show that the pulsar period is more stable than 1 part in 10^{12}. The pulse arrival measurements must be corrected for a number of effects, **such** as the motion of the Earth around the Sun, dispersive delay at the observing frequency **and** for relativistic clock correction. If the period of the pulsar is known to sufficient accuracy, it can be used to predict the pulse arrival times in advance. However, over an interval of a few months the measured arrival times begin to show significant departure from the predicted arrival times. The difference between the predicted and the measured arrival times (residuals) fall on a parabolic curve, indicating that the pulsar period (if it was assumed constant) is changing at a uniform rate over the span of the observations. This rate, called the 'period derivative', is found to be positive in general, **i.e.** the pulsar slows down. Most of the pulsars have period derivatives of the order of 10^{-15} ss^{-1}. Millisecond pulsars have period derivatives 4–5 orders of magnitude smaller.

Although the period stability of pulsars is very high, apart from the secular slow-down there are departures seen especially in the case of young pulsars. Such pulsars are subject to 'glitches', which are sudden and apparently unpredictable change in the period. Glitches are believed to result from sudden transfer of angular momentum from the interior superfluid to the outer crust. So far, glitches have not been detected in millisecond pulsars which are believed to be old recycled neutron stars. In addition to glitches, some pulsars show small random fluctuations in the residuals, known as 'Timing Noise'.

The remarkable stability of pulsar periods, particularly of the millisecond pulsars, allow many interesting effects to be measured such as the change in position, or proper motion of the pulsar due to its space velocity. But the most remarkable results have come from the study of binary pulsars giving conclusive evidence for Einstein's General Theory of Relativity (Taylor et al. 1992). Pulse arrival times from a binary pulsar, in addition to the period and period derivative, **also** reflect the orbital motion of the pulsar with respect to the binary system barycentre. A detailed analysis of the pulse arrival time variations expected for pulsars in binary systems has been given by Blandford & Teukolsky (1976).

The first discovered binary pulsar PSR1913+16 is found to be in a highly eccentric orbit. At periastron the pulsar velocity exceeds 0.1% of the velocity of light and it approaches within a solar radius of its companion.

Another remarkable result which has come from pulsar timing is the first detection of extra-Solar System planetary companions to a star. The millisecond pulsar PSR1257+12 was found to have three planetary companions with close to Earth masses and with orbital periods of about two and three months (Wolszczan & Frail 1992). This discovery opens up the possibility of using pulsars as tools for studying the formation of planetary systems.

High precision comparisons between 'pulsar time' and terrestrial atomic time show that over intervals of several years, some millisecond pulsars have fractional stabilities comparable to those of the best atomic clocks (Taylor 1991). Hence, observations of millisecond pulsars would prove to be very useful as diagnostic tools - helping to establish frequency and time standard.

Summary of this chapter

- We have briefly discussed the basic properties of pulsars, the various mechanisms proposed to explain their .emission, the observed polarisation characteristics, the variety in the observed pulse shapes and the classification schemes based on these.
- We have also discussed the propagation effects the pulsar signal suffers as it traverses the interstellar medium.
- An introduction to Pulsar Timing is given in the last section.