1

The Discoveries

1.1 Predictions

In 1934, two astronomers, Walter Baade and Fritz Zwicky, proposed the existence of a new form of star, the neutron star, which would be the end point of stellar evolution. They wrote:

with all reserve we advance the view that a supernova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density.

These prophetic remarks seemed at the time to be beyond any possibility of actual observation, since a neutron star would be small, cold and inert, and would emit very little light. More than 30 years later, the discovery of the pulsars, and the realisation a few months later that they were neutron stars, provided a totally unexpected verification of the proposal.

The physical conditions inside a neutron star are very different from laboratory experience. Densities up to 10^{14} g cm^{-3}, and magnetic fields up to 10^{15} G (10^{11} tesla), are found in a star of solar mass but only about 20 kilometres in diameter (see Chapter 14). Predictions of these astonishing conditions were made before the discovery of pulsars. Oppenheimer and Volkoff in 1939 used a simple equation of state to predict the total mass, the density and the diameter; Hoyle, Narlikar and Wheeler in 1964 argued that a magnetic field of 10^{10} G might exist on a neutron star at the centre of the Crab Nebula; Pacini in 1967, just before the pulsar discovery, proposed that the rapid rotation of a highly magnetised neutron star might be the source of energy in the Crab Nebula.

Radio astronomers did not, however, set out to investigate the possibility that such bizarre objects might have detectable radio emissions. No prediction had been made of the extremely powerful lighthouse beam of radio waves, producing radio pulses as the rotation of the neutron star sweeps the beam across the observer's

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line of sight. The observation of an astonishing and remarkably regular series of pulses was made by radio astronomers who were unfamiliar with the new theoretical concepts and who naturally took some time to connect their observations with predictions concerning some apparently unobservable objects.

1.1.1 X-rays

Another remarkable prediction was that condensed stars, either white dwarfs or neutron stars, should be observable sources of x-rays. Independent predictions were made by Zel'dovich and Guseynov (1964) and by Hayakawa and Matsouka (1964), introducing the concept of binary star systems as x-ray sources. If in a binary star system one star is a condensed object and the other is a more massive normal star that is losing mass through a stellar wind, there might be a very large rate of accretion onto the condensed star, and a hot, dense atmosphere would then develop. This atmosphere would radiate thermal x-rays.

Thermal x-ray emission from the surfaces or atmospheres of neutron stars provides unique information on their diameters, as explained in Chapter 12. There is also pulsed thermal and non-thermal emission, related to the rotation of beamed optical and gamma-ray emission, observed from mostly young pulsars (Chapter 6).

1.2 The Radio Discovery

At the start of the story we may ask why it was that pulsars were not discovered earlier than 1967. Their signals are very distinctive and often quite strong, so that, for example, the 250-ft Lovell radio telescope at Jodrell Bank was eventually used to produce audible trains of pulses from several pulsars. The possibility of discovery had existed for 10 years before it became reality. In fact, it turned out that pulsar signals had been recorded but not recognised when the Lovell telescope was used for a survey of background radiation several years before the actual discovery. The pulsar now known as PSR B0329+54 left a clear imprint on several of the survey recordings. The initial difficulty in the recognition of the pulsar radio signals was that radio astronomers were not expecting to find rapid fluctuations in the signals from any celestial source. An impulsive radio signal received by a radio telescope was regarded as interference, generated in the multitude of terrestrial impulsive sources, such as electrical machinery, power line discharges and automobile ignition, or by atmospheric lightning. Indeed, most radio receivers were designed to reject or smooth out impulsive signals and to measure only steady signals, averaged over several seconds of integration time. Even if a shorter integrating time was in use, a series of impulses appearing on a chart recorder would excite no comment;

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interference of such regular appearance is to be expected and is often encountered from a simple device such as an electric cattle fence on a farm within a mile or two of the radio telescope.

Two attributes were lacking in the apparatus used in these previous surveys: a short response time and a repetitive observing routine, which would show that the apparently sporadic signals were in fact from a permanent celestial source. These were both features of the survey of the sky for scintillating radio sources designed by Antony Hewish, in the course of which the first pulsar was discovered.

1.2.1 Interplanetary Scintillation

Radio scintillation is the fluctuation of radio waves as they traverse turbulent ionised media, particularly the terrestrial ionosphere, the solar system (the heliosphere) and the interstellar medium (see Chapter 19). Hewish was working with a research student, Jocelyn Bell (now Prof. Bell-Burnell) to investigate the effect of the ionised heliosphere on radio signals from quasars. They constructed a large receiving antenna for a comparatively long radio wavelength, 3.7 m, making a transit radio telescope that was sensitive to weak discrete radio sources. At this long wavelength, the inter-planetary scintillation effects are large, but they only occur for radio sources with a very small angular diameter. Scintillation is therefore seen as a distinguishing mark of the quasars, since the larger radio galaxies do not scintillate; Hewish later used the results of a survey with this system to study the distribution and population of these very distant extragalactic sources. The observational technique involved a repeated survey of the sky, using a receiver with an unusually short time constant of less than a second, which would follow the radio scintillation fluctuations. In that pre-digital age, the recordings were made on long paper charts, at the rate of many metres per day.

The discovery was made by Jocelyn Bell within a month of the start of regular recordings in July 1967. Large fluctuations of signal were seen at about the same time on successive days. The characteristics of the signal looked unlike scintillation and very like terrestrial interference (Figure 1.1a). Hewish at first dismissed the fluctuating signal as interference, such as might be picked up from a passing motor car, but Bell persisted in searching the long recordings for any repeat of the signal. For several nights no signals appeared; as we now know, this must have been due to the random occurrence of interstellar scintillation. Then they re-appeared and continued to re-appear spasmodically. Bell soon noticed that that the fluctuating signal was appearing four minutes earlier each day, as expected for a signal of celestial origin observed with a transit telescope, and, in October, Hewish was persuaded that something new had turned up. What sort of celestial source could this be? He and his colleagues then used a recorder with an even faster response time

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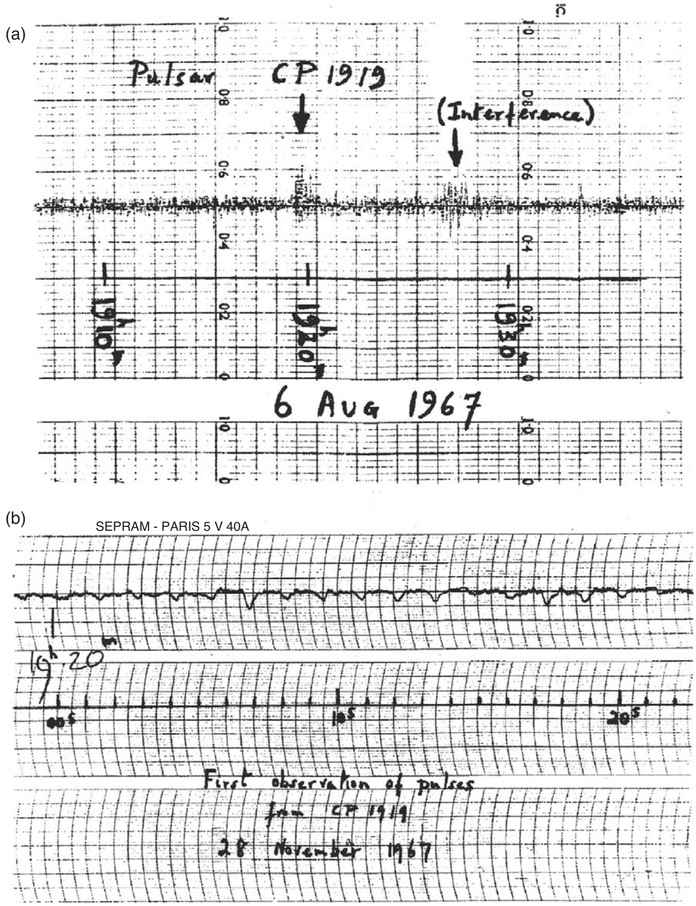

Figure 1.1 Discovery observations of the first pulsar. (a) The first recording of PSR B1919+21; the signal resembled the radio interference also seen on this chart: (b) Fast chart recording showing individual pulses as downward deflections of the trace (Hewish, private communication).

and, in November, they first saw the amazingly regular pulses having a repetition period of about 1.337 seconds. Could they be man-made? Possibly they originated on a space-craft? Possibly they were the first radio signals from an extraterrestrial civilisation?

The last possibility was disturbing. If it became known to the public that signals were being received that might have come from intelligent extraterrestrial sources – the ‘little green men’ of science fiction – the newspaper reporters would descend in strength on the observatory and destroy any chance of a peaceful solution to the problem. So there was intense activity but no communication for two months until, in February 1968, a classic paper appeared in *Nature* (Hewish *et al*. 1968).

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1.3 The *Nature* Letter of February 1968

The announcement of the discovery contained a remarkable analysis of the pulsating signal, which already showed that the source must lie outside the Solar System and probably at a typical stellar distance; furthermore, the rapidity of the pulsation showed that the source must be very small and probably some form of condensed star, presumably either a white dwarf or a neutron star. The location outside the Solar System came from observations of the Doppler effect of the Earth's motion on the pulse periodicity; this phenomenon also led to a positional determination. (see Section 1.10.3). It is particularly interesting to see that the paper specifically mentions a neutron star as a possible origin, when at that time the existence of neutron stars was only hypothetical. Indeed, the flow of speculative theoretical papers that was let loose by the discovery did not even follow up this idea at first, exploring instead every possible configuration of the more familiar binary systems and white dwarf stars.

A few days before the *Nature* letter appeared, the discovery was discussed at a colloquium in Cambridge. The news spread rapidly, and radio astronomers immediately turned their attention to confirming the remarkable results. Only a fortnight separated the first paper and a *Nature* letter from Jodrell Bank Observatory (Davies *et al*. 1968) giving some remarkable extra details of the radio pulses from this first pulsar, now known as PSR B1919+21[1].

The locations and periodicities of three further pulsars were published in *Nature* in April (Pilkington *et al*. 1968). New discoveries of pulsars were made and announced by other observatories within a few months, and by the middle of the year, significant contributions were being made by at least eight radio observatories. In 2021 the catalogue of known pulsars contained nearly 3000 pulsars, suficient for a statistical analysis of their distribution in period and across the sky, and their origins and lifetimes (Chapter 4).

The historian of science will enjoy the story of the theoretical papers that led to the identification of pulsars with neutron stars. It should be remembered that the very compact white dwarf stars were already observable and well understood, while the further stage of condensation represented by a neutron star existed in a theory familiar only to certain astrophysicists who were concerned with highly condensed states of matter. Suggestions based on the more familiar white dwarf stars, and particularly on their various possible modes of oscillation, poured out from the theorists.

[1] PSR stands for Pulsating Source of Radio. The numbers refer to its position, and the letter B refers to the B1950 system of coordinates. More recent pulsar discoveries are often referred to with a J prefix, which indicates the J2000 system of coordinates; in some cases both B and J names are used for the same source.

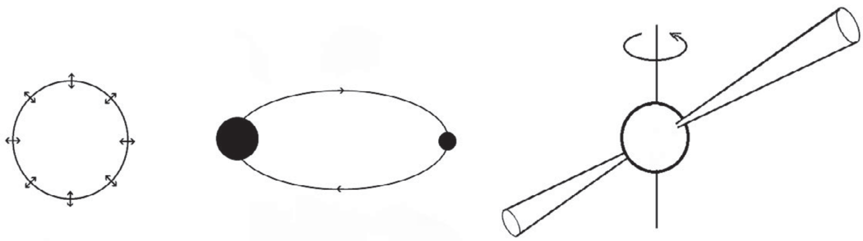

Figure 1.2 Early ideas put forward for the origin of the regular periodicity of pulsars: stellar oscillation, the orbital motion of condensed stars with gravitational focussing, or the rotation of a magnetised white dwarf or neutron star.

1.4 Oscillations, Orbits, Rotation

Although the identification of pulsars with rotating neutron stars is secure, it is of considerable interest to recall the two other possible explanations for the source of the periodicity of the pulses that were discussed during the first few months after the discovery (Figure 1.2). The very precise periodicity might be due to the oscillation of a condensed star or to a rapidly orbiting binary system. Both explanations were wide of the mark; nevertheless, the discovery of the pulsars did stimulate new work on oscillations, involving a re-examination of the equation of state of condensed matter, while the binary theory soon found application in the x-ray pulsars and, later, in the relativistic dynamics of the binary pulsar discovered in 1974.

1.4.1 Oscillations

In 1966, shortly before the discovery, Melzer and Thorne showed that a white dwarf star could have a resonant periodicity of about 10 s, for radial oscillation in the fundamental mode. No means of driving the oscillation was proposed. The period was determined by a combination of gravity and elasticity, but it was not far from the simple result of calculation using gravity alone. Dimensional arguments show that the period is independent of radius and proportional to $(G\rho)^{-\frac{1}{2}}$, where ρ is the density and G is the gravitaional constant; for example, a white dwarf with density 10^7 g cm^{-3} would have a period of about 10 s if gravity alone provided the restoring force. Elasticity, which is in fact the dominant force in condensed stars, reduces the periodicity in white dwarfs to the order of 1 s. No shorter period seems to be possible for a fundamental mode, and higher order modes could not give such a simple pulse. The discovery of a pulsar with period 0.25 s among the first four therefore ruled out the oscillating white dwarf as a possible origin.

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Melzer and Thorne had also calculated the period of oscillation of neutron stars. Here the fundamental modes of radial oscillation had periods in the range 1–10 ms, and no possibility seemed to exist for lengthening the periods by the necessary two orders of magnitude.

The oscillation theories were soon completely overtaken by the discoveries of two short-period pulsars, the Vela (89 ms) and Crab (33 ms) Pulsars, whose periods lay in the middle of the impossible gap between the theoretical oscillation periods of white dwarfs and neutron stars.

1.4.2 Planetary and Binary Orbits

Let us suppose that the pulsar period P is the orbital period of a planet, or satellite, in a circular orbit, radius R, around a much more massive condensed star with mass M (in units of the solar mass $\mathrm{M}_\odot$). Then

$$R \approx 1500 M^{1/3} P^{2/3}\ \mathrm{km}. \tag{1.1}$$

It is therefore just possible for a satellite to orbit a solar-mass white dwarf star of 1500 km radius with a period of 1 s, but the orbit would be grazing the surface. It would be more reasonable to consider a neutron star as the central object, when periods down to 1 ms would be possible. There are, however, two insuperable objections to the proposition that orbiting systems of this kind provide a model for pulsars.

The main difficulty concerns gravitational radiation, which is due to the varying quadrupole moment of any binary system. The energy loss through gravitational radiation would lead to a decrease in orbital period. A general formulation of the time scale τ of this change was given by Ostriker (1968) for a binary system with masses M and ϵM, with angular velocity $\Omega = 2\pi/P$:

$$\frac{1}{\tau} = \frac{1}{\Omega}\frac{\mathrm{d}\Omega}{\mathrm{d}t} = \frac{96}{5}\frac{\epsilon}{(1+\epsilon)^{1/3}}\frac{(\mathrm{G}M)^{5/3}}{c^5}\Omega^{8/3}. \tag{1.2}$$

For a satellite in a 1 s orbit, with mass m, where $\epsilon = m/M$ is small, and $M = 1.0\mathrm{M}_\odot$,

$$\tau = 2.7 \times 10^5 \epsilon^{-1}\ \mathrm{s}. \tag{1.3}$$

The time scale was evidently far too short unless the satellite mass was very small. Pacini and Salpeter (1968) soon established that early observations of the stability of the period showed that m must be less than $3 \times 10^{-8}\mathrm{M}_\odot$.

Even the improbable hypothesis that such a small mass could be responsible for the radio pulses faced a second problem. The satellite would be orbiting in a very strong gravitational field, which would tend to disrupt it by tidal forces. Pacini and Salpeter showed that, even if it were made of high tensile steel, it could not withstand

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these forces unless it was smaller than about 20 m in diameter. An added problem would be that the satellite would be liable to melt or evaporate in the very high radiation field of a pulsar.

The same situation evidently obtained *a fortiori* for a binary system, for which a very rapid change in period would be expected. Planetary and binary systems were therefore eliminated as possible origins for the clock mechanism of pulsars. Gravitational radiation itself does, however, recur in the pulsar story; PSR B1913+16 was eventually found, which is itself a member of a binary system with the short orbital period of $7\frac{3}{4}$ h, in which the orbital period decreases due to gravitational radiation at the rate of 30 ms per year (see Section 1.10.4).

1.4.3 Rotation and Slowdown

The maximum angular velocity Ω of a spinning star is determined by the centrifugal force on a mass at the equator. An estimate is easily obtained by assuming that the star is spherical with radius r; the centrifugal force is then balanced by gravity when

$$\Omega^2 r = \frac{\mathrm{G}M}{r^2}. \tag{1.4}$$

This is, of course, the same condition as for a satellite orbit grazing the surface. If the star has uniform density ρ, then the shortest possible rotational period P_{min} is roughly

$$P_{\mathrm{min}} = (3\pi/\mathrm{G}\rho)^{1/2}. \tag{1.5}$$

A period of 1 s therefore requires the density to be greater than 10^8 g cm^{-3}, which is just within the density range of white dwarf stars. Neutron stars, on the other hand, can rotate with a period as small as 1.5 ms, as demonstrated by the discovery of the first 'millisecond' pulsar PSR B1937+21.

The limit on rotational angular velocity is somewhat more severe than in this simple argument, because the star will distort into an oblate spheroid and tend to lose material in a disk-like extension of the equatorial region. The white dwarf theory was therefore already on the verge of impossibility for the first pulsars; the discovery of the short-period pulsars at once ruled it out completely.

The identification of pulsars with rotating neutron stars required the pulses to be interpreted as a 'lighthouse' effect, in which a beam of radiation is swept across the observer. This idea was supported by the observation by Radhakrishnan and Cooke (1969) that the plane of polarisation of radio waves from the Vela Pulsar swept rapidly in position angle during the pulse, in agreement with simple models of beamed emission. The radio source must then be localised, and directional, as well as powerful. This led Gold (1968) to his seminal note in *Nature*, in which he suggested the identification with rotating neutron stars, the existence of a strong magnetic field, which drove a co-rotating magnetosphere, and the location of the radio source within the magnetosphere, probably close to the velocity-of-light cylinder. He also pointed out that rotational energy must be lost through magnetic dipole radiation, so that the rotation would be slowing down appreciably.

The early measurements of the period of the first pulsar PSR B1919+21 showed that no change was occurring larger than one part in 10^7 per year. This limit was very close to the actual changes that were measured a few years later, but the early null result could be used only to show that the stability of the period was in accord with the large angular momentum of a massive body in rapid rotation. Pacini (1968) showed that for a white dwarf, the limit on slowdown implied a magnetic field strength at the poles of less than 10^{12} G (10^8 tesla). He considered only magnetic dipole radiation in free space, which radiates away the rotational energy W at a rate

$$\frac{\mathrm{d}W}{\mathrm{d}t} = \frac{2\Omega^4}{3c^3} M_\perp^2 = \frac{\Omega^4}{3c^3} r^6 B_0^2 \sin^2\alpha, \tag{1.6}$$

where $M_\perp \sim r^3 B_0 \sin\alpha$ is the component of the magnetic dipole moment orthogonal to the rotation axis, B_0 is the polar magnetic field at the stellar surface and α is the angle between the dipole axis and the rotation axis.

The slowdown of the Crab Pulsar was first measured by Richards and Comella (1969). From October 1968 to February 1969, the period lengthened uniformly by 36.48 ± 0.04 ns per day, i.e. by over 1 μs per month. The rate of change was consistent with the known age of the Crab Nebula, confirming the association of the pulsar with the supernova explosion observed in AD 1054. Furthermore, the rate of change could be applied to the neutron star theory, giving an energy output from the spin-down alone that was sufficient for the excitation of the continuing synchrotron radiation from the Crab Nebula. This coincidence was the final proof of the identification, as pointed out in Gold's second *Nature* letter (1969).

The rate of rotational slowdown is now routinely measured for every newly discovered pulsar, and many continue to be monitored closely over many decades. For some young pulsars, the second differential is also obtainable, allowing investigation of the physics of the slow-down process (Chapter 5).

In retrospect, it is intriguing to consider what deduction might have been made from the measured variations of rotation period of the Vela Pulsar, if it had happened (as it nearly did) that those measurements had preceded those of the Crab Pulsar. The period of the Vela Pulsar was observed to be increasing slowly from November 1968 to February 1969, at the rate of 11 ns per day, but, at the end of February, a discontinuous decrease in period occurred, amounting to 200 ns. The change was known to have occurred in less than a week (Radhakrishnan & Manchester 1969; Reichley & Downs 1969). By the time that this anomalous step was announced, the neutron star theory was already firmly established, and the decrease in period was regarded as an aberration rather than the typical behaviour. The step, or 'glitch', was at first interpreted on the basis of an abrupt change of moment of inertia, due to an overall shrinkage or a change of ellipticity in a 'starquake'; it is now understood as the independent rotation of a superfluid within the neutron star (Chapter 15).

1.5 The Identification with Neutron Stars

Unknown to the theorists exploring the possibility that pulsars were white dwarf stars, and apparently also unnoticed by Hewish, Franco Pacini had already published a paper containing the solution to the nature of pulsars, again in *Nature* and only a few months before the discovery. This was the paper (Pacini 1967) in which he showed that a rapidly rotating neutron star, with a strong dipolar magnetic field, would act as a very energetic electric generator that could provide a source of energy for radiation from a surrounding nebula, such as the Crab Nebula. His work, and the original proposal by Baade and Zwicky, pointed the way to the subsequent discovery of the Crab Pulsar in the centre of the Nebula.

The two papers by Pacini and Gold set out very clearly the case for identifying the pulsars with rotating neutron stars. Between them, the two papers contained the basic theory and the vital connection with the observations. The remarkable part of the story is that the two men were working in offices practically next door to one another at the time of Gold's paper, since Pacini was visiting Cornell University; nevertheless, Gold did not even know of Pacini's earlier work, and there is no reference to it in his paper (Gold 1968). Collaboration was, of course, soon established, as may be seen in a paper from Pacini only a month later (Pacini 1968). These two should clearly share the credit for establishing the linkage between pulsars and neutron stars.

The confusion of theories persisted until the end of 1968, even though the correct theory had been clearly presented. Unfamiliarity with the concept of a neutron star seems to have been the main barrier to understanding, at least for the observers; it is interesting to see that both Hewish and Smith wrote forewords to a collection of *Nature* papers towards the end of 1968 in which they favoured explanations involving the more conventional white dwarf stars. The issue was settled dramatically by the discoveries of the two short-period pulsars: Vela, by Large, Vaughan and Mills (1968b), with a period of 89 ms, and the Crab, by Staelin and Reifenstein (1968), with a period of 33 ms (Comella *et al*. 1969). Only a neutron star could vibrate or rotate as fast as 30 times per second. Furthermore, as pointed out by Pacini and Gold, a rotation would slow down, but a vibration would not. Very soon a slowdown

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was discovered in the period of the Crab Pulsar (Richards & Comella 1969), and the identification with a rotating neutron star was then certain. Furthermore, both the Crab and the Vela Pulsars are located within supernova remnants, providing a dramatic confirmation of the Baade–Zwicky prediction.

It happened almost 50 years after the discovery of pulsars that a white dwarf was found to be behaving almost exactly like a standard neutron star pulsar (Marsh *et al.* 2016). This was AR Sco, already well-known as a variable star in a binary system with an M star as companion. Pulses at a repetition period of 1.95 minutes were observed over the whole spectrum from radio to x-rays. This white dwarf pulsar is one of group of highly magnetised white dwarfs with magnetic dipole moments comparable to those of normal neutron star pulsars.

1.5.1 Physics of the Neutron Star

In Chapter 13 we review the physics of the neutron star itself. The general picture of a rapidly-rotating, highly-condensed and highly-magnetic star has been amply confirmed. Pulsar masses have been found to be mainly concentrated within the remarkably small range of 1.2–1.5$M_\odot$; higher masses, up to 2$M_\odot$, are found in some binary systems; these provide a useful constraint on the equation of state of the neutron fluid. The polar magnetic field is found to be of order 10^{12-15} G for normal pulsars and 10^{8-9} G for the millisecond pulsars (Chapter 10).

The neutron star was at first considered to comprise a simple neutron fluid with a density comparable to that of nuclear material, within a solid lower-density crystalline crust. The observation of glitches demonstrated that part of the fluid is a superfluid, which interpenetrates the crust and can rotate at a different speed; the interaction between these components is responsible for the step change in rotation rate.

The rapidly-rotating, highly-magnetised neutron star is surrounded by an energetic and electrically charged *magnetosphere* that co-rotates with the star and that extends out to a radial distance at which its linear velocity approaches the velocity of light. The magnetosphere, first analysed by Goldreich and Julian (1969) for a star in which the rotation and magnetic axes are aligned, has proved to be very complex, as may be seen from the 94 pages of 'pulsar electrodynamics' in Mestel's classic work *Stellar Magnetism* (2003). It is often remarked that the origin of the radio, optical, x-ray and gamma-ray pulses through which we have gained so much astrophysical understanding itself remains a mystery; many pages of this book will be concerned with assembling the evidence that is slowly leading to an understanding of the source, or sources, of pulsar radiation.

1.6 High-Energy Photons

1.6.1 Optical Pulses from the Crab Pulsar

The possibility that pulsars might emit pulses of light as well as radio was tested on the first pulsar, PSR B1919+21, as early as May 1968. In the excitement, some over-optimistic positive results were reported at first from both Kitt Peak and Lick Observatories, but eventually every attempt was abandoned without any detection of optical pulsations or variation of any kind in several radio pulsars. Photometric equipment had, however, been assembled for searches for periodic fluctuations in white dwarf stars and, on 24 November 1968, a recording of the centre of the Crab Nebula was made by Willstrop (1969) in Cambridge without prior knowledge of the discovery of the radio pulsar a few days earlier in the USA. Although this recording was subsequently found to show the optical pulsations of the Crab Pulsar, it was stacked away with others for off-line computer analysis, and the discovery went instead to an enterprising team at the Steward Observatory in Arizona who were among three groups of observers fired with enthusiasm by the radio discovery of the Crab Pulsar.

The discovery of the optical pulses by Cocke, Disney and Taylor (1969) was published in a *Nature* letter; less usually, the actual event of the discovery was recorded on a tape recorder that was accidentally left running at the time. The excitement of the appearance of a pulse on a cathode ray tube, after a few minutes of integration, is well conveyed by the uninhibited (and unprintable) remarks of the observers. The discovery was made on 16 January 1969. Only three nights later, the light pulses were observed by two other groups, at McDonald Observatory and Kitt Peak Observatory. Shortly afterwards, a new television technique was applied to the 120-inch reflector at Lick Observatory, and a stroboscopic photograph of the pulsar was obtained. This showed two contrasting exposures, made at pulse maximum and minimum (Figure 1.3).

Subsequent observations have, of course, given very much more detail about the pulse timing, pulse shape, spectrum, and polarisation of these optical pulses; as might be expected, these are recorded in less dramatic form than the first paper by Cocke, Disney and Taylor, and their accidental historic tape recording.

1.6.2 X-ray Pulses from the Crab pulsar

The final link in the chain of discoveries about the Crab Pulsar was the extension of the spectrum into the x-ray and gamma-ray regions. The observations were necessarily made from above the Earth's atmosphere. In 1969 there was no x-ray telescope orbiting the Earth in a satellite, so that the only possibility lay in rocket flights. Astonishingly, two such rocket flights were successfully made, within a

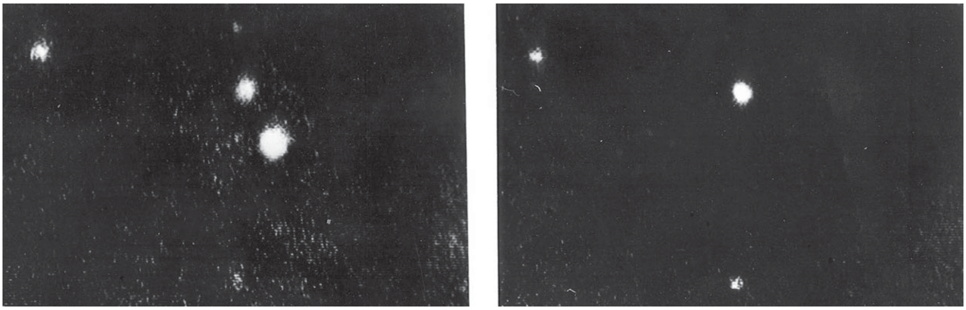

Figure 1.3 The Crab Pulsar. This pair of photographs was taken by a stroboscopic television technique, showing the pulsar on (left) and off (right) (Lick Observatory, reproduced by kind permission of the Royal Astronomical Society).

week of one another and only three months after the discovery of the optical pulses. The first was made by a team from the Naval Research Laboratory in Washington (Fritz *et al*. 1969) and the second from the Massachusetts Institute of Technology (Bradt *et al*. 1969). Both were completely successful, showing that the pulsed radiation extended to x-ray energies of several kilovolts; in fact, the total power radiated in the x-ray region was found to be at least 100 times that in visible light. The shape of the pulses was very nearly the same in x-rays as in light.

The Crab Nebula had been known and studied for several years as a source of x-rays. After the two rocket flights designed especially for the detection of periodic pulses had demonstrated the existence of the pulsar within the nebula, the recordings of an earlier rocket flight were re-examined; they showed that the pulses had been recorded but not recognised. This flight was in March 1968 (Boldt *et al*. 1969). Even this prediscovery recording turned out not to be the earliest, since a balloon-borne experiment in 1967 designed to measure the spectrum of the Crab Nebula up to x-ray energies of 20 keV was found to have recorded the periodic 'light curve' of the pulsar (Fishman, Harnden & Haymes 1969). There was sufficient accuracy in the periods obtainable from these two earlier experiments to show that the pulsar had been slowing down at the same average rate prior to the discovery as afterwards.

1.6.3 Gamma Rays

X-ray observations, and the gamma-ray observations that have now been made of many, mostly young, pulsars including the Crab and Vela Pulsars, involve detecting the arrival times of individual photons. A large optical telescope might record over 100 photons per pulse from the Crab Pulsar, but at the highest gamma-ray energies, a satellite-borne gamma-ray telescope might receive only one photon per hour. Nevertheless, precise timing over long observing sessions allows detection of

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the periodicity and construction of the pulse profile. The techniques of gamma-ray telescopes, and the further extension of the spectrum to TeV energies by Cerenkov atmospheric shower detectors, are described in Chapter 2.

Both the Crab Pulsar and the Crab Nebula are observable almost continuously from radio frequencies at 30 MHz to gamma rays at above 100 GeV. Unpulsed radiation in the TeV region is observed from part of the Crab Nebula that is energised by a stream of particles emitted by the pulsar; this and other pulsar wind nebulae are described in Chapter 18.

The difficulty of relating the apparently random arrival of photons from a gamma-ray source to an underlying periodicity is illustrated by the source known as Geminga. This is one of the brightest gamma-ray sources in the sky, but without a radio detection, no periodicity could be found. Eventually the period of 237 ms was discovered in soft x-ray recordings, where the photon flux is very much greater, and a re-examination of the gamma-ray observations then showed the same periodicity (see Jackson *et al*. 2002 for an account of the x-ray and gamma-ray observations). Despite many attempts and some positive reports, no optical or radio pulses have yet been definitely observed from Geminga.

1.7 Millisecond Pulsars

For the first 15 years after the initial discoveries, the number of known pulsars grew to over 300. It seemed that the periods were distributed mainly from 100 ms to one second, and the rates of slowdown indicated that the pulsars with the shortest periods were the youngest. A monotonic slowdown through some millions of years would bring a pulsar towards its death when its period reached around one second. The search techniques seemed to be well matched to the population. This simple picture was disrupted by the discovery in 1982 of the pulsar B1937+21 by Backer and his collaborators (Backer *et al*. 1982): this pulsar has a period of only 1.56 ms, i.e. it is rotating 642 times per second. This was the first of the 'millisecond' pulsars, with periods mainly below 10 milliseconds and, significantly, with very low rates of slowdown. Search techniques that are sensitive to pulse periodicities as short as one millisecond have developed as computer speeds and data storage have improved (Chapter 3).

PSR B1937+21 was originally observed as a strong, highly-polarised radio source with a steep spectrum; the pulses were only discovered after an intensive analysis of recordings made with a very short integrating time constant. More general searches yielded only two more millisecond pulsars before the end of the decade, but new techniques involving rapid data sampling and Fourier analysis then began to yield many more. A further complication in this search was the discovery that a large proportion of the millisecond pulsars are in binary systems with short orbital periods, so that the observed pulsar period varies rapidly as the line-of-sight

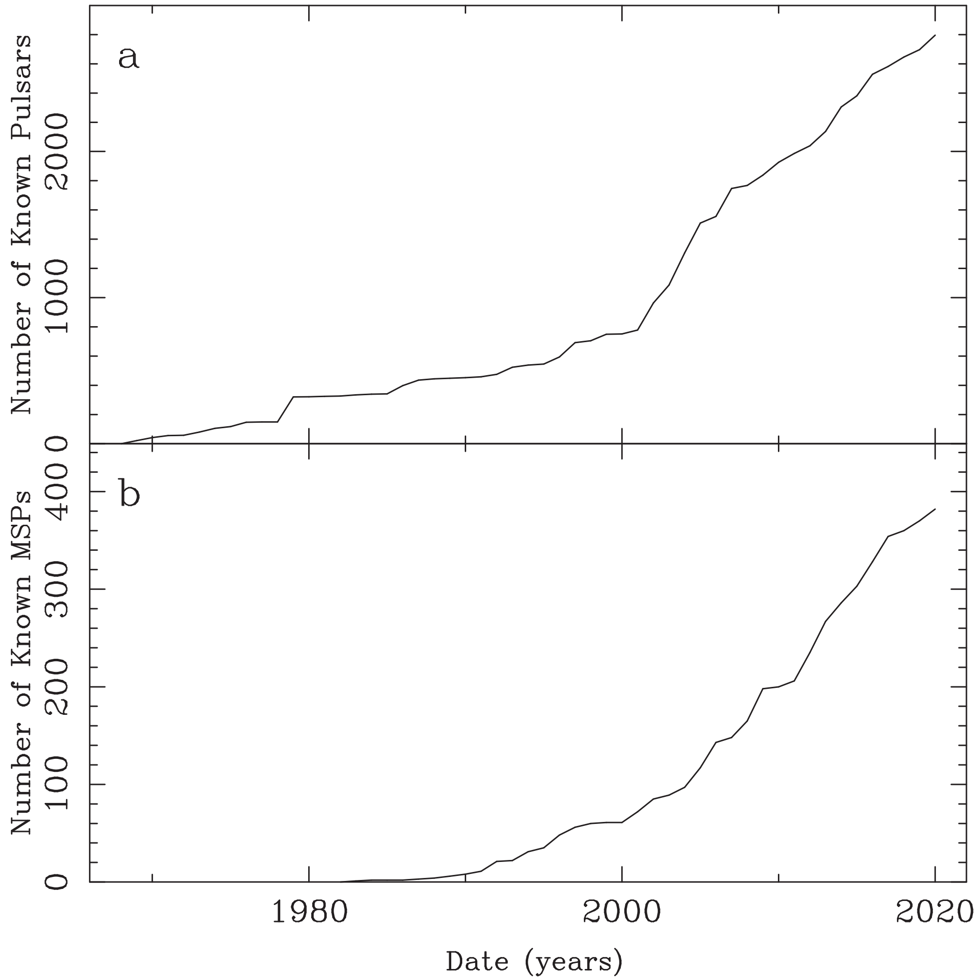

Figure 1.4 The time-line of the number of known pulsars: (a) all pulsars; (b) millisecond and other recycled pulsars with period < 30 ms.

velocity varies round the orbit. A major step forward was made by the gamma-ray observatory Fermi, carrying the Large Area Telescope (LAT), which confirmed and extended a list of discrete gamma-ray sources found by earlier satellite observatories; many of these were then found in radio observations to be millisecond pulsars. Furthermore, the gamma-ray observations could then be re-examined using the periodicities found by radio, and many of the discrete sources turned out to be pulsating at GeV energies with pulse shapes similar to the radio profiles (Chapter 8).

The improving success of search techniques, including the gamma-ray discoveries, is illustrated in Figure 1.4, which shows the time-line of the total number of known pulsars.

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1.8 Binary Pulsars

The discovery of binary millisecond pulsars nicely substantiated a theory that linked the longer-period so-called normal pulsars, via the x-ray pulsars, to the whole class of millisecond pulsars. The x-ray pulsars were known to be binary systems, in which one component is a star with a large and expanding envelope spilling material onto a condensed star, heating part of the surface (or an accretion disk) to temperatures around 10^{6-7} K. The accretion process transfers angular momentum from the binary orbit to the condensed star, spinning it up to a periodicity approaching one millisecond.

The evolutionary scenario, which we develop in Chapter 10, starts with a binary pair of ordinary but massive stars. The more massive of the two evolves faster and eventually collapses and explodes as a supernova, leaving a normal pulsar at its core. The explosion may disrupt the binary, leaving the pulsar as one of the 'normal' population. But if there is no disruption, the second star eventually evolves, its atmosphere expands, accretion onto the first neutron star starts, and a rapidly rotating x-ray pulsar is born. Finally the second star completes its evolution and explodes, leaving a second neutron star, which may itself become a pulsar. The first star is now a millisecond pulsar in a double neutron star system, while the second rotates at the slower rate of a normal pulsar.

Complete confirmation of this theory came in 2003, with the discovery of a binary pulsar (PSR J0737−3039A/B) in which both components are pulsars, with periods of 23 milliseconds and 2.8 seconds, respectively (Lyne *et al*. 2004). Although both masses in several double neutron star systems had previously been determined, this was the first in which both rotation periods could also be found. The orbital period of this pair is only 2.4 h, which is among the shortest known of any double neutron star system.

1.9 Clocks and Relativistic Physics

A pulsar regarded as an isolated spinning inert massive star should be a precise clock. Pulsars almost follow this description, and the timing of their pulses has become a major part of observational pulsar astronomy. In Chapter 5 we describe the techniques that provide consistent monitoring of pulse arrival times, with an accuracy that in many cases reaches 100 nanoseconds. Rotation periods may be quoted to 14 places of decimals consistently over some years, leading to very accurate positions and precise orbital parameters of binary pulsars. The behaviour of close binary systems, involving strong gravitational fields, provides the most accurate tests of general relativity. The precise timing of pulsar rotation is the major basis of research in many observatories around the world.

1.10 The Growth of Pulsar Astronomy

The half century following the discovery of pulsars saw a spectacular expansion into many branches of astrophysics, as will be evident throughout this book. Here we give a brief outline of the main topics, with a guide to the chapters in which we deal with each subject.

1.10.1 Search and Discovery

The advent and growth of massive computer power has enabled the development of three vital aspects of radio search techniques: broad bandwidth, pattern recognition, and telescope multi-beaming. These are essential elements of the Square Kilometre Array (SKA), but they are already yielding new discoveries of pulsars at low levels of flux density and covering large solid angles of the sky. Chapter 2 describes the very different techniques in x-ray, gamma-ray and TeV (Cerenkov) photon detection. Chapter 3 describes the new receiver systems and massive data analysis that have become possible through digital technology.

1.10.2 The Source of the Radiation

Extensive descriptions and analyses of the complex characteristics of the radio pulses, and of the somewhat simpler high energy pulses, have been made, with the intention of unravelling the physical processes of particle acceleration and beamed radiation. We describe the individual radio pulses, and the profiles obtained by integration over some hundreds of pulses, in Chapter 8. The very high brightness of the radio emission is only explicable as coherent emission from an assembly of many charged particles in a small space, possibly with dimensions of only a few metres. In contrast, the high energy emission (x-ray and gamma-ray) is accounted for as the incoherent sum of radiation from high energy particles in a different, more extended region (Chapters 16 and 17).

These emitting regions are located in an extended atmosphere, the magnetosphere, driven by the magnetic field of the neutron star to co-rotate with the neutron star. The configuration of the magnetosphere is understood in broad outline, although the details are only accessible through a complex computation (Chapters 13 and 16).

1.10.3 Positions: The Earth's Orbital Motion

Remarkably accurate positions are available for most pulsars, from their unique quality of emitting a precise tining signal. The orbital motion of the Earth causes a

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roughly sinusoidal annual modulation of pulse arrival times, with amplitude reaching eight minutes for a pulsar near the Ecliptic plane. The amplitude and phase of this variation provides a measurement of pulsar position, as described in Section 5.1. Several astrometric results have followed from pulsar timing: proper motion is often measurable, giving transverse velocities; small effects on the Earth's orbit due to the planets and even to an asteroid can be measured; the combination of positions derived from timing with positions measured by long baseline interferometry has provided an accurate link between the two fundamental celestial coordinate systems.

Interpretation of these results requires a detailed geometrical analysis, allowing for the rotation of the Earth and its orbital motion. This is achieved in a complex analysis program which is used in common by observatories worldwide.

1.10.4 Relativistic Effects

Pulsars act as ideal clocks, providing unique tests of relativistic theory. Most notably, there are substantial relativistic effects in the tightly bound binary orbits of millisecond pulsars, including the loss of orbital momentum through gravitational radiation; the classic example is PSR B1913+16, which has a highly elliptical orbit with a period of $7\frac{3}{4}$ h (Weisberg & Taylor 1984; see Chapter 5). The loss of orbital energy, which is observed as a decrease in orbital period, gives a remarkably accurate value for the total mass of the system.

A further observable relativistic effect in binary systems is the delay in pulse travel time, known as the Shapiro delay, that occurs in the gravitational field of the pulsar's companion. The delay depends on the mass of the companion; provided the geometry of the orbit can be found from pulse timing through the orbit, both the companion mass and that of the pulsar itself can be found.

Relativistic effects measurable in the orbit of a binary pulsar system often provide more than one independent measurement of the component masses, and the agreement of the results is in effect a rigorous test of relativistic theory. No departure from standard general relativity has yet been found.

Gravitational waves originating in the early Universe are expected to be measurable as a small effect on large scale distances within the Galaxy. The consequent effect on pulse arrival times is expected to be correlated over a group of pulsars. Observations of this effect are very demanding, requiring timing accuracies measured in nanoseconds and extending over several years. Several international timing networks are engaged in the search for this effect.

1.10.5 The Interstellar Medium

Interstellar scintillation, discovered in the first observations of pulsars, was later joined by three other phenomena that have revolutionised our understanding of the ionised interstellar plasma. These are pulse lengthening, dispersive pulse delay, and Faraday rotation, all of which can be observed on the lines of sight to all radio pulsars. Dispersive delay is valuable in determining pulsar distances; if a model is available for the distribution of electron density along the line of sight to a pulsar, then the delay, measured by comparing pulse arrival times at different radio frequencies, gives a direct measurement of distance, since there is a linear relation between the integrated electron content along the line of sight and the so-called dispersion measure (DM). On the other hand, the distance of the pulsar may be known by other means, in which case the DM values of a set of pulsars may be used as a means of determining the electron density distribution in the Galaxy. In Chapter 19 we outline the theory of scintillation due to diffraction and refraction in the ionised interstellar medium (ISM) and describe observations of the dynamics, scale and dependence on radio frequency of scintillation.

Faraday rotation is also a dispersive phenomenon. Pulsar radio signals are often highly linearly polarised, and Faraday rotation is observed as a frequency dependence of the plane of polarisation. The rotation is related to the product of the line of sight component of the interstellar magnetic field and the electron density, so that the combination of measurements of Faraday rotation and dispersion measure give a direct measurement of the magnetic field (Chapter 20).

There are, of course, complications. The distribution of electrons in the interstellar medium is far from uniform, and interpretation of dispersion measures and Faraday rotations has proved to be complicated and challenging. Nevertheless it can be regarded as a happy chance that the scintillation phenomenon that led to the original pulsar discovery has proved to be our most valuable tool in investigating the interstellar plasma.

1.10.6 The Population of Pulsars

Understanding the relationship between pulsars and the other stellar populations of the Galaxy requires surveys with known and consistent sensitivity limits covering most of the sky. Determining distance has proved difficult, and limited sensitivity has largely confined population studies to distances less than the distance of the centre of the Galaxy. The distance of some pulsars within about 1 kpc[2] of the Sun can be measured by conventional astrometry, extended in the radio regime by very long baseling interferometry (VLBI). Larger distances can be estimated by observing the dispersive propagation delay of radio pulses in the ionised interstellar medium and using a model of the distribution of electron density.

Although the pulsar surveys are necessarily limited by sensitivity and various selection effects, a useful model of the distribution of pulsars within the Galaxy has

[2] 1 kiloparsec (kpc) = 3.08×10^{19} m. At this distance, a star has a parallax of 1 milliarcsecond.

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been constructed. There is a total population of between 10^5 and 10^6 active pulsars in the Galaxy. Most of them are concentrated in the plane of the Galaxy within a layer about 1 kiloparsec thick and within a radial distance of about 10 kiloparsecs from the centre. Measurements of their motion show that they have high velocities, presumably originating in their violent births, and are mostly moving away from the plane at a rate of order 200–300 km s^{-1}, so that the distribution is consistent with an origin within 100 parsecs of the galactic plane; this is to be expected if they represent the end product of the evolution of massive stars.

The millisecond pulsars (Chapter 10) represent a smaller population of older pulsars. Re-cycling by spin-up in binaries occurs much less frequently than the birth of normal pulsars, and re-cycled pulsars are only observable as a considerable population because of their long life. They are found throughout the Galaxy but much less concentrated towards the plane than are the younger pulsars. Many millisecond pulsars are also found in globular clusters, where the spin-up process is also seen at work in a concentration of x-ray binaries.

The first pulsar to be found in a globular cluster was PSR B1821−24 (period 3 milliseconds), in the cluster M28 (Lyne *et al*. 1987). Several other globular clusters were later found to be rich fields of millisecond pulsars (Chapter 8). Using the 20 pulsars then known in the globular cluster 47 Tucanae, Freire *et al*. (2001c) analysed their dynamics and their dispersion measures to delineate the distribution of masses and ionised gas within the cluster (Freire *et al*. 2001a).

Many observers have speculated on the possibility of observing a pulsar in a distant galaxy such as the Andromeda Nebula M31, which presumably has a similar population to our Galaxy; this may prove to be within reach of the largest radio telescopes, such as FAST. Such an observation would provide a measurement of the electron density in inter-galactic space. There are already several pulsars known in the Magellanic Clouds; the first of these, PSR B0540−69, was found as an x-ray pulsar and is now observed over a wide spectral range (de Plaa *et al.* 2003).

1.10.7 Fast Radio Bursts

The detection of weak radio signals from pulsars requires integration, which tends to smooth out and lose any short impulsive signals. The advent of fast sampling and digital recording preserved impulsive signals, although even then these were often rejected as man-made interference. In 2007, Duncan Lorimer was reanalysing recordings from a Parkes pulsar survey, and found an intensive isolated burst that showed the frequency dispersion characteristic of interstellar propagation (Lorimer *et al*. 2007).

A few hundred such fast radio bursts (FRBs) have been observed, most of which have large dispersion measures, indicating a location at cosmological distances.

The nature of their source is unknown, although a magnetar (Chapter 11) located in our Galaxy has been observed as a repeating source of FRBs. The energy in an FRB, which is usually only a few milliseconds long, is phenomenal; a single burst from a distant galaxy, if radiated isotropically, represents an energy output of 10^{43-45} ergs, comparable to the total energy released by the Sun in 1000 years.

The relation between pulsars and FRBs is as yet unproven, although the link with a magnetar is tantalising. There are properties of the radio emission in young pulsars that are reminiscent of the rotating radio transients (RRATs) and radio emission from magnetars, but there are important differences too. We will consider the growing field of variability in pulsars in Chapter 9, including the relation to FRBs and gamma-ray bursts.

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