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The discovery of pulsars

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} gauss (10^{11} tesla), are found in a star of solar mass but only about 20 kilometres in diameter. Again, predictions of these astonishing conditions were made before the discovery of pulsars. Oppenheimer & Volkoff in 1939 used a simple equation of state to predict the total mass, the density and the diameter; Hoyle, Narlikar & Wheeler in 1964 argued that a magnetic field of 10^{10} gauss 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 emission. 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 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.

Condensed stars, either white dwarfs or neutron stars, were predicted to be observable sources of X-rays. Independent predictions were made by Zel'dovich & Guseynov (1964) and by Hayakawa & 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.

The first X-ray astronomical observations were of the Sun and of the Crab Nebula. A more powerful source, Sco X-1, was a surprise discovery (Giaconni *et al.* 1962). This was soon identified with a visible star whose spectrum fitted that of a binary partner undergoing mass loss. A much greater surprise came from the X-ray satellite UHURU, launched in 1970. Two pulsating sources were discovered, catalogued as Hercules X-1 and Centaurus X-3 (Giaconni *et al*. 1971). The explanation of these new sources combined the neutron star concepts, already confirmed by the radio discoveries, with the binary star proposals, opening a new field in astrophysics.

The new field of gamma-ray astronomy was opened by the satellite observatories SAS-2 and COS-B in the 1970s, followed by the Compton Gamma-ray Observatory in 1991. The technical challenges of this high energy range are immense. The photon flux is small, and individual photons must be distinguished from cosmic ray particles, and measurements made of their time and directions of arrival, and their energies. It was again a surprise to find that pulsars could be detected in such a high energy regime. Two gamma-ray observatories, AGILE and Fermi, are now in operation, observing a large number of pulsars at energies up to around 100 GeV. The spectral range available for studying neutron stars now extends from radio (down to 10 MHz) to high gamma-rays (above 100 Gev), covering over 20 decades of the electromagnetic spectrum, a wider range than for any other astronomical object.

1.1 The radio discovery

The spectacular growth of radio astronomy during the 30 years following the Second World War was marked by the introduction of a series of new observational techniques, each of which opened unexplored fields of research. Each advance in technique was applied initially to a specific problem, but such was the richness of the radio sky that each new technique guided the observers into unexpected directions. Examples of such serendipity are provided by most of the major discoveries in radio astronomy. An investigation of the radio background, undertaken by J. S. Hey and his colleagues as an extension of their meteor radar work, yielded as a complete surprise the first discrete radio source, Cygnus A. New techniques in radio telescopes, designed to investigate radio galaxies and measure their positions and diameters, led unexpectedly to the discovery of quasars. The added bonus, which so often follows an adventure into a new observational technique, has its example par excellence in the discovery of the pulsars.

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 can be used to produce audible trains of pulses from several pulsars. The possibility of discovery had existed for ten years before it became reality. In fact, it turned out that pulsar signals had been recorded but not recognised when this 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. A similar story can be told for radio pulses from the planet Jupiter. These were discovered in 1954, although recordings made five years previously contained unrecognised signals from Jupiter. An even more remarkable pre-discovery recording exists for the X-ray pulses from the Crab Pulsar. These were found on records from a balloon flight, which pre-dated the actual discovery rocket flights by two years. The signals were recorded, but not recognised.

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; interference of such regular appearance is to be expected, and is often encountered from such a simple device 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 radio scintillation designed by Anthony Hewish, in the course of which the first pulsar was discovered.

1.2 Interplanetary scintillation

The familiar twinkling of visible stars, due to random refraction in the terrestrial atmosphere, has three distinct manifestations in radio astronomy, in which the refraction is due to ionised gas. Random refraction, causing scintillation of radio waves from celestial sources, occurs in the terrestrial ionosphere, in the ionised interplanetary gas in the Solar System, and in the ionised interstellar gas of the Milky Way Galaxy. In all three regions the radio waves from a distant point source traverse a medium with fluctuations of refractive index sufficient to deviate radio rays into paths which cross before they reach the observer, giving rise to interference and hence to variations in signal strength. All three types of radio twinkling, or ‘scintillation’, were discovered and investigated at Cambridge, and in all three investigations Hewish played a key part. Coincidentally, the theory of interstellar scintillation is important for pulsars, which now provide its most dramatic demonstration; the coincidence is that it was an investigation of interplanetary scintillation that led to the discovery of pulsars, even though the discovery was a by-product rather than the purpose of the investigation.

Hewish was working with a research student, Jocelyn Bell (now Professor Bell-Burnell). They constructed a large receiving antenna for a comparatively long radio wavelength, 3.7 m, making a transit radio telescope which was sensitive to weak discrete radio sources. At this long wavelength the inter-planetary scintillation effects are large, but they occur only 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.

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

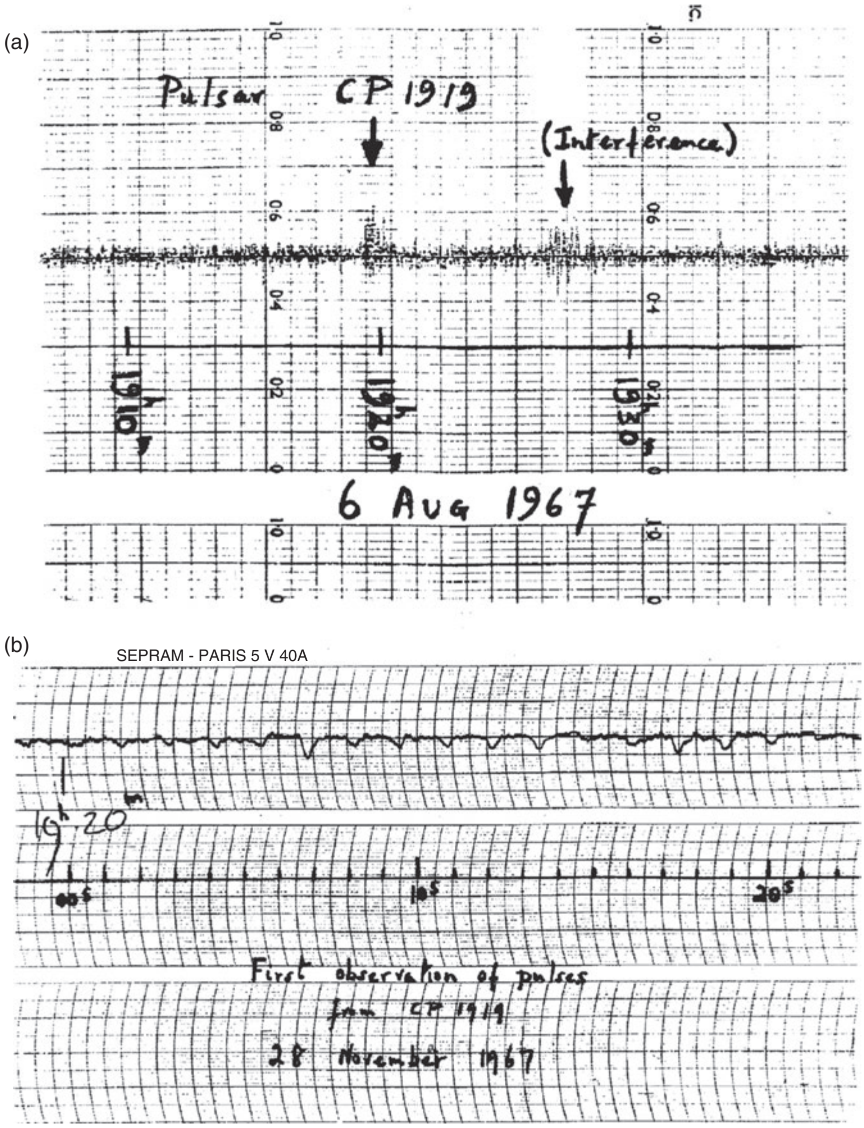

Fig. 1.1. Discovery observations of the first pulsar. (a) The first recording of PSR B1919+21; the signal resembled the radio interference also seen on this chart. (b) Fast chart recording showing individual pulses as downward deflections of the trace (Hewish *et al.* 1968).

interference (Figure 1.1a). Hewish at first dismissed the fluctuating signal as interference, such as might be picked up from a passing motor car. 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. It soon became clear that the fluctuations were occurring four minutes earlier each day, as expected for a signal of celestial origin observed with a transit telescope and, in October, Hewish concluded 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 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).

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 typical stellar distances; 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. 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. (PSR stands for Pulsating Source of Radio. The numbers refer to its position, and the letter B refers to the 1950 system of coordinates.) Celebrations of the discovery of pulsars were somewhat marred by allegations that Cambridge had withheld publication of its results instead of making all information freely available at the moment of discovery. The trouble seems to have been caused by a statement in the original *Nature* announcement that three other pulsars had been detected, and that their characteristics were being investigated. The statement was evidently made merely as supporting evidence for the astrophysical interpretations advanced in the *Nature* letter but it led to a bombardment of requests for advance information on the location and periodicities of these three further pulsars. Hewish refused to give further details until his measurements were complete; the results were published in *Nature* in April (Pilkington *et al.* 1968). His action was entirely in accordance with normal scientific protocol but it was misinterpreted as a deliberate obstruction by some would-be observers. New discoveries of pulsars were made and announced by other observatories within a few months. By the middle of the year, significant contributions were being made by at least eight radio observatories.

The historian of science will also enjoy the story of the theoretical papers that led to the identification of pulsars with neutron stars. It should be remembered that 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.

1.4 Oscillations and orbits

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. 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 Hulse–Taylor binary pulsar discovered in 1974.

1.4.1 Oscillations

In 1966, shortly before the discovery, Melzer & 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; 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, reduces the periodicity 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 rules out the oscillating white dwarf as a possible origin.

Melzer & Thorne had also calculated the period of oscillation of neutron stars. Here the fundamental modes of radial oscillation had periods in the range 1 to 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 $M_\odot$). Then

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

It is therefore just possible for a satellite to orbit a 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 $\Omega = 2\pi/P$:

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

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

$$\tau = 2.7 \times 10^5 \left(\frac{M}{m}\right) \text{ s}. \tag{1.3}$$

The time scale was evidently far too short unless the satellite mass was very small. Pacini & Salpeter (1968) soon established that early observations of the stability of the period showed that m must be less than 3×10^{-8} solar masses.

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 & Salpeter showed that, even if it were made of high tensile steel, it could not withstand 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 $7\frac{3}{4}$ hours, in which the orbital period decreases due to gravitational radiation at the rate of 30 ms per year (see Chapter 6).

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

$$\Omega^2 r = \frac{GM}{r^2}. \tag{1.4}$$

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

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

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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 disc-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 & Cooke (1969) that the plane of polarisation of radio waves from the Vela Pulsar swept rapidly in position angle during the pulse, which agreed with some 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 period on 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 which 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 the limit on slowdown implied a magnetic field strength at the poles of a white dwarf less than 10^{12} gauss (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 & 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).

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 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 interpreted on the basis of a change of moment of inertia, due to an overall shrinkage or a change of ellipticity in a 'starquake' (Chapter 7).

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 the first 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.

In June 1968, *Nature* published the first letter from Gold, of Cornell University, which set out very clearly the case for identifying the pulsars with rotating neutron stars. Between them, the two papers from Pacini and Gold 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 men 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 short-period pulsars now known as the Vela and the Crab Pulsars. The experimental test was simple: theories involving white dwarf stars might account for pulsars with periods of about 1 s, and possibly even for $\frac{1}{4}$ s, the shortest period then known, but the Vela Pulsar discovered in Australia by Large, Vaughan and Mills (1968), had a period of only 89 ms, while the Crab Pulsar, discovered in the USA by Staelin & Reifenstein (1968) had the even shorter period of 33 ms. 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 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.

1.6 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 & Taylor (1969) was published in a *Nature* letter; less usually, the actual event of the discovery was recorded on a tape recorder which 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 1.2).

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 & Taylor, and their accidental historic tape recording.

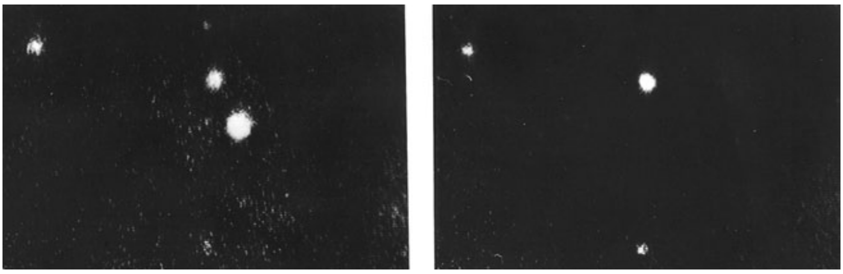

Fig. 1.2. The Crab Pulsar. This pair of photographs was taken by a stroboscopic television technique, showing the pulsar on (left) and off (right). (Lick Observatory, reproduced by kind permission of the Royal Astronomical Society.)