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THREE DECADES OF PULSAR ASTRONOMY

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There is now strong evidence supporting the rotating neutron star "lighthouse" model of pulsars. With spin rates up to 600 revolutions per second, and surface magnetic fields of 10^8 T, neutron stars act like powerful dynamoes surrounded by charge-separated magnetospheres. The radiation mechanism is still unknown but is probably related to coherent oscillations within an electron-positron plasma generated by gamma radiation above the magnetic poles. Small variations of observed spin-rate are consistent with the prediction that superfluid neutrons inside neutron stars are contained within a rigid outer crust. Pulsar radiation has been used to probe the interstellar gas and some pulsars act like precise clocks in locations ideally suited to test aspects of general relativity, such as the existence of gravitational waves and geodetic precession. Doppler shifts of pulsar radiation have revealed three planets in orbit about one neutron star, and some pulsars in globular clusters show acceleration due to the cluster dynamics.

Key Words: **Pulsar; Neutron Star; Supernova; Magnetosphere; Quantum Liquid; Vortex Lines; General Relativity; Gravitational Waves; Interstellar Gas**

1 Introduction

Since their discovery at Cambridge[1] in 1967 pulsars have continued to surprise, delight and puzzle the astronomical world and the pulsar story is still far from over. In this brief review, which is the written version of the Vainu Bappu Memorial Lecture given by the Author at Chennai in December 1998, outlines his current understanding of these fascinating stars which explain their importance in opening up a new chapter of astrophysics. Pulsars are neutron stars—most unusual stars whose existence was first envisaged in the 1930s shortly after the discovery of the neutron particle. Little was it realised at that time how these compressed remnants of burnt-out stars, literally the corpses of the stellar population, could have such an astonishing rebirth. In reality, rejuvenated by energy drawn from gravitational collapse, neutron stars embark upon a sprightly new career which provides unique opportunities for extending our knowledge of stars, stellar evolution and the behaviour of matter under extreme conditions far beyond anything that can be achieved in physical laboratories. Unlike any other kind of star, the most remarkable property of pulsars is that they emit sharp bursts of coherent radio waves with clock-like precision at intervals typically of around one second. Sky surveys have now located over 1000 pulsars within our galaxy having pulse-periods ranging from 1.5 ms to 8.5 s and the kind of information that can be obtained from observations will first be summarised.

2 Pulsar Observations

As will be explained in the following section, there is now very strong support for the 'lighthouse' model of pulsars originally proposed by Gold[2] in 1968. On this theory, the pulses are caused by a beam of radiation directed at some angle oblique to the rotation axis of a neutron star so that the pulse period is equal to the rotation period. The angular beamwidths are quite narrow, typically between 5^0 and 20^0 in rotation-longitude.

Beamwidths in latitude are not yet known and may be larger. The average beam profiles are stable, having Gaussian or more complex profiles characteristic for each pulsar. An example of pulses

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*Based on INSA-Vainu Bappu Memorial Lecture delivered at Chennai on 30 December 1998 by the Author, a Foreign Fellow of INSA & NL

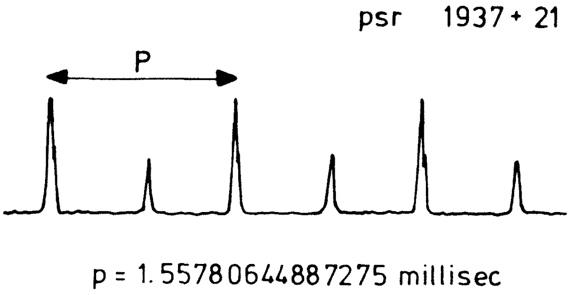

Fig. 1 Typical radio pulses from the pulsar PSR 1937 +21. In this example interpulses occur between the main pulses, indicating that the beam is orientated at a large angle to the rotation axis.

from the most rapid pulsar is shown in Fig. 1. In this case interpulses are seen roughly half way between the main pulses indicating that the beam axis lies at a large angle to the rotation axis so that radiation is received from opposite sides of the pulsar. This is a relatively rare phenomenon. Individual pulses, on the other hand, can vary in both intensity and shape, sometimes showing a fine structure on timescales as short as nanoseconds. Some pulsars show sub-pulses within the overall profile which drift steadily across the pulse-window, reappearing and repeating this process in a fairly regular fashion. The radiation intensity is generally strongest at frequencies in the region of 100 MHz, decreasing monotonically up to 10 GHz, with some flattening towards still higher frequencies. Strong linear polarisation is typical, the plane of polarisation swinging through angles which can approach 180^0 across each pulse, and circularly polarised components near the centre of the pulse are often found. At present 8 pulsars have been found to emit pulsed radiation in the optical, X-ray or gamma ray bands.

Except in one or two rare instances, all pulsars have been found to be slowing down. The rate of change of period $\mathrm{d}P/\mathrm{d}t$ defines a characteristic age given by $P/(\mathrm{d}P/\mathrm{d}t)$. Typical ages are in the range 10^6-10^8 years indicating that pulsars are relatively young objects on a stellar timescale. The youngest have ages of 10^3-10^5 years; in general these also have short periods and some are found within supernova remnants as would be expected according to the neutron star model. Paradoxically, pulsars having the very shortest periods, the millisecond pulsars, have characteristic ages of about 10^9-10^{10} years, which must exceed their true age. These are frequently members of binary systems, as revealed by a periodic Doppler variation of pulse rate, and they clearly represent a separate population as will be described later.

Much of the interstellar gas is ionized and radio pulses are dispersed during propagation through large distances in this tenuous plasma. Although the plasma density is not very well known, dispersion provides a useful estimate of the distances to pulsars. These are typically in the range 1-10 kiloparsec, from which it may be estimated that the total number of active pulsars within the galaxy must amount to 10^5-10^6.

Millisecond pulsars have the most stable periodicities and when allowance has been made for a number of systematic effects they keep time as well as atomic clocks. Allowance must, of course, be made for the regular slowing down, the orbital motion of the earth and temporal variations of the interstellar medium. The latter can be removed by dual-frequency measurements. Slower pulsars on the other hand, especially the youngest, are less stable and can suffer sudden decrease of period of up to one part in 10^6 in less than one day. Since isolated rotators must conserve total angular momentum, this behaviour indicates some kind of redistribution of angular momentum within the star and this provides important clues about the inner structure of neutron stars.

3 The Lighthouse Model

The concept of a star composed of neutrons follows from consideration of the state of matter under extreme compression. At normal pressures free neutrons are unstable and decay into protons, electrons and anti-neutrinos within about 10 minutes. This beta-decay process is reversed at exceptionally high density because electrons obey the Pauli exclusion principle and are constrained to occupy states of very high energy. Loosely speaking, the particle wavelength must be very small in order to fit the electronic wavefunctions into the available volume, leading to states of correspondingly high energy. For densities exceeding about 10^{15} kg m^{-3} it becomes energetically unfavourable for neutrons to decay since this would lead to a state of higher energy. A mixture of protons and electrons therefore converts to neutrons via inverse beta-decay. This process occurs in the cores of sufficiently massive stars when their nuclear fuel is exhausted and internal pressure can no longer support gravitational pressure. Gravitational collapse then leads to neutron matter at a density of $\sim 10^{18}$ kg m^{-3}. The collapse is violent due to the kinetic energy of in-fall and also the release of neutrinos. The outer layers of the star are blown out explosively to generate a supernova, hence neutron stars are created within supernovae. This was conjectured in the 1930s, following the discovery of the neutron, but at that time there seemed to be little hope of detecting radiation from such tiny objects, the radius of a neutron star being only about 10 km.

Following the discovery of pulsars and the introduction of the lighthouse model it was realised that only neutron stars could spin fast enough to explain the high pulse rates without fragmentation, and the detection of a pulsar within the Crab Nebula, a well known supernova remnant, confirmed the theory. In addition, the characteristic age of around 1000 years was in good agreement with the occurrence of the supernova in the year 1054 as reported in ancient records. Quantitative confirmation was obtained from the spin-down energy loss assuming that the neutron star had a mass comparable to that of the sun. In fact the discovery solved a mystery about the nebula which had been a puzzle for many years. The nebula emits diffuse light and X-rays known to be synchrotron radiation which requires a continuous supply of relativistic electrons with energies up to 10^8 MeV. Such particles could not be a relic of the supernova explosion as their radiation lifetime is much shorter than the known age of the nebula. The loss of kinetic energy estimated from the spin-down agrees excellently with that needed to maintain the population of radiating electrons.

The mechanism which converts rotational energy into pulsed radiation and an outflow of relativistic particles is not yet fully understood but the magnetic field of the neutron star must play a key role. Hence neutron stars must be regarded as giant electrical dynamoes. Gravitational collapse assuming conservation of magnetic flux leads to fields of the order of 10^8 Tesla so that typical electric fields at the surface of the star must be $\sim 10^{13}$ Vm^{-1} for an average pulsar rotating once per second. In fields of such magnitude electrostatic, rather than gravitational forces dominate the motion of charged particles. Charges are pulled from the surface and guided along magnetic field lines so as to form a charged magnetosphere. Unlike laboratory plasmas, this will be charge-separated, the positive and negative zones being determined by the direction of the local electric field where charges are released. The charge density adjusts to cancel the electric field component parallel to the direction of the magnetic field. The high conductivity of the magnetosphere ensures that it corotates with the star in regions where the magnetic field lines form closed loops attached to the surface, but this cannot persist beyond a certain distance. At a radial distance $R=Pc/2\pi$ the magnetosphere would be moving at the speed of light, in violation of relativity. This condition defines a cylinder, the speed of light cylinder, beyond which corotation is impossible. Field lines which intersect this cylinder are tracks along which particles stream outwards and escape from the star and the corotating magnetosphere is constrained to looped field lines within the cylinder. The complications of relativistic plasma physics are such that even for the simple case of a neutron star with a dipole magnetic field aligned with the rotation axis, no self-consistent analytical model has yet been obtained. One obvious difficulty with this aligned rotator is that charged particles of the same sign stream from each magnetic pole, a situation which leads to instability unless some return current exists within the magnetosphere.

The high intensity of radio emission, and its strong linear polarisation whose plane swings systematically through some well maintained angle from the leading to the trailing edge of each pulse, indicates a coherent radiation process involving the organised motion of groups of charge. Some mechanism producing a beam directed along the magnetic axis seems the most likely possibility. It was initially thought that bunches of charge near the speed of light cylinder might be responsible but this now seems very unlikely. An argument against this is the lack of any characteristic dependence of the pulse shapes upon the periodicity. The radius of the speed of light cylinder varies from about 700 km for the fastest pulsar to 40,000 km for a typical one yet the pulse profiles are remarkably similar over this range. It is more reasonable to envisage emission from nearer the surface and evidence now points to regions not more than about 1000 km from the star above the polar caps. The escape of particles along open field lines from the magnetic poles implies that the charge density cannot build up sufficiently to cancel the local electric field so charges in these zones are accelerated and emit gamma radiation. These high energy photons generate electron-positron pairs, which are further accelerated, and a cascade of particles develops until the density of the resultant electron-positron plasma is sufficient to reduce the electric field to a value which quenches the process. In a sense, the voltage generated by the pulsar dynamo is effectively short-circuited by the newly created pair plasma in the vicinity of the polar caps, which involves currents of the order of 10^{11}A. Plasma instabilities might form in the outflowing pair plasma and relativistic Langmuir oscillations, or Alfven waves, could then provide the organised motion of charges required to emit coherent radiation. If the outflow of plasma is also relativistic the radiation will be beamed along the direction of the local magnetic field in the same way that synchrotron radiation is beamed along the direction of motion of the energetic particles. On this model, illustrated in Fig. 2, the emitted frequency should decrease with height above the surface since the pair plasma density will fall as the outflow diverges. Good evidence for this is the observed systematic increase of pulse width with decreasing radio frequency which follows quite well the variation predicted for a simple dipole magnetic field and an emission region extending from 100 – 1000 km above the surface.

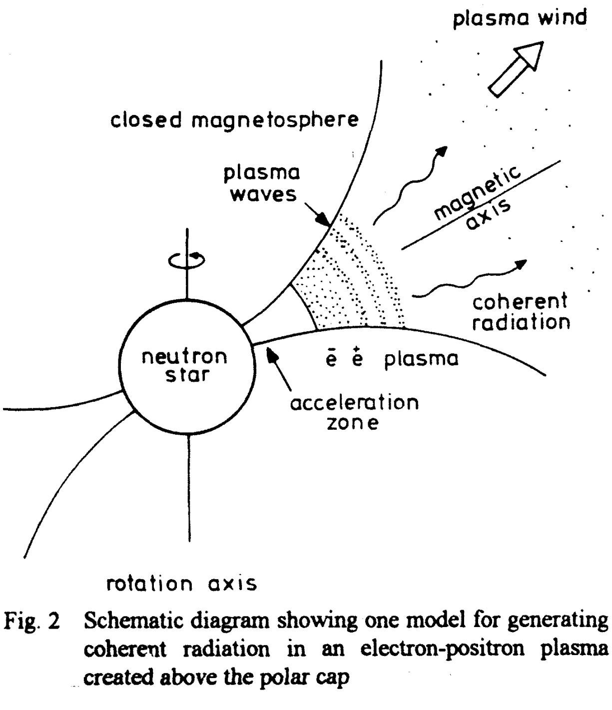

Fig. 2 Schematic diagram showing one model for generating coherent radiation in an electron-positron plasma created above the polar cap

A small number of the youngest pulsars, those having ages of less than about 10^5 years, also emit pulses of light, X-rays or gamma radiation. The pulse shapes are not quite the same as the radio pulses and the radiation intensity does not demand a coherent mechanism. Models of the corotating magnetosphere indicate two zones where large electric fields could generate pair plasmas. One occurs close to the poles as described above and another also exists further out towards the boundary between the closed and open magnetic field regions. It is generally believed that the outer zone is responsible for incoherent radiation at the highest frequencies emitted by young neutron stars.

As mentioned earlier, the millisecond pulsars differ from typical pulsars in having much larger characteristic ages and their magnetic fields are considerably weaker, being 10^4-10^5 T as compared to 10^8-10^9 T. They frequently occur in stellar binaries and are believed to have acquired their special properties by interaction with their binary partners. When one member of a binary evolves to become a neutron star through a supernova explosion it may subsequently collect additional mass and angular momentum from its companion, particularly if the latter evolves to a red giant. This can substantially increase the rate of spin and the accreted material might also be responsible for reducing the external magnetic field, either submerging it beneath the surface or by rearrangement in some kind of plate tectonics. Thus, despite their high spin rate, they are not particularly strong radio emitters and their large characteristic ages are due to a lower rate of energy loss as compared to typical pulsars. Lone millisecond pulsars must be those which ultimately lost their companions due to disruption of the binary system. One notable feature is that the pulse profiles, when scaled according to periodicity, are indistinguishable from those of typical slow pulsars. Evidently the same radiation mechanism is at work and it is interesting that the pair-plasma density derived from the electrodynamic model previously described is also quantitatively similar.

4 The Interior Structure of Neutron Stars

Neutron stars are not, of course, simply uniform spheres of matter at nuclear density. Neutron matter cannot exist under reduced pressure near the stellar surface where there should be a lattice structure of the stable nuclei of iron under extreme compression. At deeper levels these nuclei become progressively enriched with neutrons until they merge into almost pure neutron matter. Even in this state there are sufficient electrons and protons to ensure high electrical conductivity and the protons should be superconducting. At temperatures below 10^9 K neutrons form Cooper pairs, leading to a Bose condensate. This behaves as a quantum liquid, or superfluid. Thus neutron stars are expected to have a rigid outer shell, about 1 km in thickness, surrounding a superfluid interior containing the bulk of the mass. The latter must exceed 1.4 times the mass of the sun which is the Chandrasekhar limit defining the mass required for gravitational collapse of burnt-out stellar cores and the occurrence of supernovae. Depending upon the equation of state, and as explained later this is uncertain towards the centre, the radius of the star will be 10-15 km.

Quantum laws forbid the uniform rotation of a superfluid at constant angular velocity, which raises the interesting question of what happens to the original angular momentum of the collapsing core. The answer is that it is transformed into a paraxial array of quantised vortex lines, each $\sim 10^{-12}$ cm in radius and separated by ~0.01 cm. In this arrangement a uniform array of vortices mimics bulk rotation of the fluid at constant angular speed. Slowing down of the star then corresponds to migration of the vortices towards the outer shell to which the angular momentum is transferred. This process is not necessarily a smooth exchange as the vortices become pinned at their ends to individual nuclei. Stresses develop as migration is hindered until either the crust fractures or catastrophic unpinning occurs. Angular momentum may thus be suddenly supplied to the shell leading to an impulsive increase of angular velocity. This process is believed to explain sudden decreases of pulse period which have been observed for at least 20 pulsars. The decreases are usually small, typically amounting to no more than a few parts in 100 million, but jumps up to one hundred times greater have been seen in a few cases. Not unexpectedly, larger jumps have been found in only the younger pulsars which are slowing down more rapidly. Following a large jump the periodicity recovers to nearly its former value on a time scale of days to months and this confirms the existence of a superfluid interior. At the large matter densities involved the friction exerted by an ordinary liquid would not allow differential rotation between the shell and the inner fluid to persist for more than a fraction of a second.

Near the inner cores of neutron stars it is possible that matter exists in even more exotic states. Condensates of pions, kaons or quarks have been proposed. In fact the equation of state is not yet sufficiently well defined to rule out the possibility of quark stars composed almost entirely of such material. Future observations which might bear on these questions are the rates of cooling and the shortest periods found. For pulsar periods significantly shorter than the present limit of 1.5 millisec even neutron stars would fragment. Alternatively, X-ray measurements of surface temperatures might show that cooling is too fast to be explained by neutrino emission from neutron matter. As yet, while soft X-ray emission has been detected, the temperatures are not low enough to necessitate such theories and there are problems in distinguishing between thermal emission from the surface or non-thermal radiation from higher levels in the magnetosphere.

5 Pulsar Clocks

Some pulsars provide highly accurate clocks in environments which are well-suited to precision tests of general relativity, including the strong-field regime of relativistic gravity. Since Einstein first conceived his famous theory a number of alternatives have been proposed, such as the scalar-tensor theories, and it is important to know whether any evidence exists that the original theory requires modification. In this context the discovery of the first binary pulsar by Hulse and Taylor[3] in 1975 was a major advance. This pulsar has a period of 59 millisec and is in a binary orbit of period 7.75 hours with a maximum orbital velocity slightly in excess of 300 km/s. The binary companion is undetectable in any band and is believed to be another neutron star, presumably a pulsar not beamed towards the

Earth. The orbit is so compact that the neutron stars approach to within one solar radius of each other. Pulse arrival times can be measured to a precision of a few microseconds in 5-minute observations and have been carried out systematically since 1975. The orbital period is found to be decreasing, corresponding to shrinkage of the orbital radius by 3.5 m per year, which indicates a steady loss of kinetic energy. This agrees precisely with the energy radiated by gravitational waves according to Einstein's theory (see Fig. 3) and confirms general relativity to an accuracy of better than one per cent. In addition, of course, it verifies the existence of gravitational waves. The orbital parameters of the binary also enable the masses of the neutron stars to be calculated. These turn out to be 1.441 and 1.387 solar masses, in excellent agreement with the Chandrasekhar limit which specifies the mass above which the gravitational collapse of stellar cores must occur.

One of Einstein's classic applications of his theory was his explanation of the precession of the orbit of the planet Mercury, which amounts to 5.7 arcseconds per year of which 0.43 arcseconds is due to the curvature of spacetime. It is interesting to compare this with the precession of the orbit of the binary pulsar which is observed to be 4.2 degrees per year! A further effect, which may soon be confirmed, is geodetic precession of the spin axis of the pulsar. This should occur if the spin axis is not perpendicular to the plane of the binary orbit, and it is analogous, in general relativity, to spin-orbit coupling in atomic theory. Such precession of the spin axis would change the orientation of the pulsar beam relative to the Earth and should therefore produce some variation in the average pulse profile. For the binary pulsar PSR 1913 +16 precession of the spin axis would be 1.2^0 per year. There is already evidence of a systematic narrowing of the beam profile and if this continues, the pulsar may disappear from view within 20-30 years. Conversely, precession of the companion neutron star might eventually cause this to become detectable on a similar timescale. More than 40 binary pulsars have now been found, several having eccentric orbits suitably aligned for further tests of relativity theory and it is clear that this will remain an active field of pulsar research in the future. The precision of the best pulsar clocks is ultimately limited by galactic kinematics, such as differential galactic rotation, which alters the distance to any pulsar in an unpredictable way. At present this appears to be the dominant factor so it is unlikely that timing accuracies can be significantly improved.

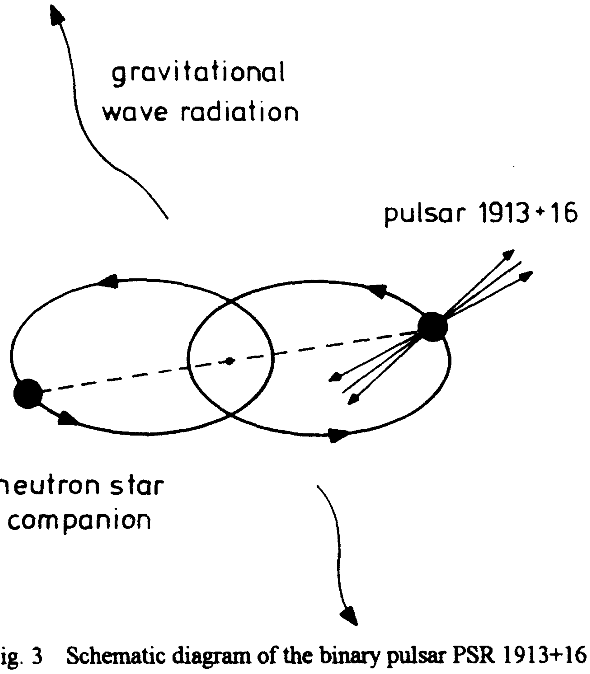

Fig. 3 Schematic diagram of the binary pulsar PSR 1913+16

Timing of the millisecond pulsar PSR 1257+12 over two years during 1990-1992 revealed a small quasi-sinusoidal modulation on a timescale of 2-3 months. Wolszczan and Frail[4] showed that this could be explained by small changes of position induced by orbiting planets. Continued observations have confirmed that three planets are present, two having masses about four times that of the Earth with orbital periods of 66 and 98 days, and a much lighter one with a period of only 25 days. No further pulsars accompanied by planetary systems have yet been found but other examples are likely to be detected in due course.

As one more application of pulsar timing it is interesting to note that strong constraints can already be placed on any possible variation of the gravitational constant *G* with time. It has sometimes been conjectured that the fundamental constants might change on a timescale comparable to the age of the Universe. This is definitely not the case for *G* as observations of PSR 1913+16 show that any fractional variation is less than a few parts in 10^{12}

per year. This constraint will, of course, become even tighter as timing measurements are continued.

6 Pulsars as Probes of the Interstellar Gas

Propagation of pulsar radiation through the interstellar medium leads to various phenomena which can provide useful information about conditions along the line of sight and also about pulsars themselves. As mentioned earlier in Section 2, the ionised interstellar gas is dispersive so that pulses arrive later at lower radio frequencies. The differential delay is proportional to the mean electron density along the line of sight and hence gives an estimate of pulsar distances when the density is known. Alternatively, for pulsars at known distances, such as those in globular clusters, the mean density can be found. The presence of a magnetic field also causes birefringence and Faraday rotation of the plane of polarisation of linearly polarised pulsar radiation can be used to find the strength and direction of the component of magnetic field along the line of sight. Faraday rotation has been measured for over 200 pulsars indicating typical interstellar magnetic fields of a few nano Tesla.

Another effect, which was soon recognised in the early pulsar observations, is intensity scintillation due to clouds of varying density which randomly scatter pulsar radiation. Except for rare instances of unusually large scattering towards some radio galaxies, pulsars are the only sources to show this phenomenon. This is because of their tiny physical size which provides radiation of extremely high spatial coherence. Random diffraction due to small-scale clouds, combined with refraction by larger clouds, generates intensity variations on a wide range of timescales from minutes to years. Observations of the radio frequency spectrum of scintillation and its variation with time give unique information on the scales of turbulence involved and also on the overall distribution of plasma within the Galaxy. In general, because of their violent origin in supernova explosions, neutron stars move through the interstellar medium at speeds which are large compared to the motion of the solar system or the medium itself. Pulsar diffraction patterns are thus swept past the Earth at speeds which reflect the motion of neutron stars and speeds can be estimated from the scintillation timescale. Typical values of around 400 km/s are found, some ten times larger than bulk motions of the interstellar clouds.

A different method of probing gas along the line of sight can be exploited for a few binary pulsars having compact orbits so aligned that the pulsar is observed periodically through the atmosphere of its companion. Seven binary pulsars have been found in which the pulses are totally occulted during part of the orbit. Just before and after the eclipse large increases of dispersion occur indicating ionised gas surrounding the companion star. In one case changes of Faraday rotation are also observed, so both the magnetic field and density of the stellar atmosphere can be obtained.

7 The Future

This brief review has touched on some important aspects of thirty years of pulsar research. It is now abundantly clear that pulsars have more than realised their potential as a new class of stars offering great possibilities for deepening our understanding of astronomy and astrophysics. Ranging from general relativity, stellar evolution and the structure of our Galaxy, through relativistic plasma physics, electrodynamics, quantum fluid dynamics, solid state and particle physics, they have proved to be amazingly versatile tools for extending our knowledge and broadening our horizons. Setting aside the possibility of any new surprises, and history suggests that this is high, there are many directions for continued research likely to be rewarding. Is neutron matter the ultimate state prior to collapse into black holes or could there also be quark or pion stars? Searches of greater sensitivity with improved computing techniques are necessary to seek pulsars having even higher spin rates than millisecond pulsars which might demand material more tightly bound than neutron matter. Some pulsars already provide clocks comparable with the best atomic clocks. Perhaps some group of millisecond pulsars will provide the future primary time standard. Continued timing should, in any case, lead to more accurate masses of the planets Mercury, Saturn and Pluto the uncertainty of which currently limits the accuracy of the location of the barycentre of the Solar System. For young pulsars subject to small changes of spin rate continued timing is essential to study the variations closely and hence to learn more about the nature and strength of the pinning of quantised vortex lines to the outer shell. One of the outstanding problems is the overall structure of the magnetosphere and the electrodynamic mechanisms which generate coherent beamed radiation. Possibly a compact eclipsing binary exists in which both members are detectable pulsars in suitable orbits to probe the magnetosphere directly as discussed in Section 6. Then there is the question of drifting sub-pulses which characterise some pulsar beams. Is this really a set of narrower beams moving steadily about the magnetic axis or does it point to another periodic process within neutron stars? Obviously there is much fundamental work to be done on pulsars in the future and there are great opportunities for the recently completed GMRT in India.

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