PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Pulsars and Physics

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Phil. Trans. R. Soc. Lond. A 1992 **341**, 177-192
doi: 10.1098/rsta.1992.0092

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Twenty-five years of active pulsar research have yielded a quite unexpected harvest of physical effects. These range from pleasing corroborations of well-established physical principles in unfamiliar environments to direct verification of the general theory of relativity. Pulsars have the potential for advancing our understanding of high energy nuclear physics and relativistic plasma physics. They have also enlarged our horizons in atomic physics, quantum electrodynamics and solid state physics. As extremely compact sources of regularly pulsed, high brightness radio waves, they provide excellent probes of the interstellar medium and globular clusters. The large variety of connections between pulsars and physics is illustrated with examples taken from each of these areas.

1. Pulsars and physics

When this discussion meeting was conceived in 1990; there were two intentions. The first was to celebrate a quarter century of pulsar research. The discovery of pulsars on 28 November 1967 (Hewish *et al.* 1968) was the third of the triad of quite unexpected astronomical discoveries (the other two being the identification of quasars and the detection of the microwave background) that inaugurated modern astrophysics. It is perhaps hard now to communicate the excitement generated by this discovery (a fascination that filtered through to me, a first-year Cambridge undergraduate at the time), but some idea can be gleaned by noting the speed with which confirming observations were completed (Davies *et al.* 1968) and the extraordinary diversity of theoretical responses (some of which made 'little green men' seem almost conservative) that it engendered. As this meeting makes quite clear, this enthusiasm was not misplaced. We now know of over 500 pulsars, including five in the Magellanic clouds and 11 in the globular cluster 47 Tuc. They have periods ranging from 1.5 ms to ≈ 5 s and surface magnetic fields ranging in strength from $\approx 3\times10^{8}$ to $\approx 10^{13}$ G. Their emission can vary on timescales as short as 10 μs with brightness temperature in excess of 10^{30} K (Manchester, this symposium).

The second goal of the meeting was more serious and this was to review the relationship between pulsars and physics. This relationship is a symbiotic one in which neither partner is viewed as simply a donor and neither as a pure beneficiary. What is most extraordinary, and I doubt that any of the pioneers of this field had an inkling that this would happen, is how comprehensive this relationship has become. There is a hardly a subdiscipline of physics that has not been called upon in our attempts to understand pulsars and as this involvement is so often at a very basic level, we can see why pulsars make much marvellous pedagogic tools and effective antidotes to the disease of overspecialization rife among modern physicists.

Phil. Trans. R. Soc. Lond. A (1992) **341**, 177–192
Printed in Great Britain

Table 1. *Newtonian dynamics*

topic	reference
advances	
two-body problem	Taylor[a]
three-body problem	Phinney[b]
N-body problem	Phinney[b]
Galactic dynamics	Taylor[a]
gravitational ionization and recombination	Phinney[b]
prospects	
Solar System ephemerides	Standish & Hellings (1989)

[a] This symposium. [b] Personal communication.

What ought to be attractive to physicists is that pulsar astronomy has so often produced unambiguous, quantitative results unbuffered by 'interpretation' and the inconclusive analyses of selection effects. (In this respect, the study of pulsars compares quite favourably with cosmology, for example.) In some investigations, pulsars have been used with spectacular success as signal generators, radio sources of remarkable compactness and clocks of unique stability. In others, they have been used to probe extreme physical conditions within and around neutron stars that are beyond those attainable in terrestrial laboratories. Here the comparison between observation and theory is currently less harmonious and it may well turn out that this is the area where the next spate of advances in understanding will be concentrated.

The making of lists is among the most primitive of scientific urges, and one that I have been unable to resist. I have chosen to organize this summary by physics subdiscipline and to use tables to distinguish areas where there have already been advances from those where there seem to be good prospects for further enlightenment. Of course, these lists are in no sense complete; they are only intended to give enough examples to demonstrate the scope of the connection between pulsars and physics. I shall attempt to give the most useful references to assist the reader in finding out more about these topics, giving preference to contributions to this volume where possible.

2. Newtonian dynamics (table 1)

As we approach the end of the twentieth century, no credit accrues from solving the two-body problem. Nevertheless we have found nearly 30 binary pulsars (as anticipated by Hewish *et al.* (1968)). It is remarkable that, even at the newtonian level, we have corroboration of the Kepler solution at a level of better than one part in 10^5. By contrast, optical, double-line spectroscopic binary orbits are typically only $\approx 1\%$ accurate. The newtonian three-body problem must be treated by using perturbation theory and is of fundamental interest when resonances are present. This is probably the case for the supposed plants orbiting PSR 1257+12 (Wolszczan & Frail 1992) whose orbits are in a near 3:2 resonance (similar to the Uranian moons Titania and Oberon) (Rasio *et al.* 1992). (Curiously, planets were one of the first explanations put forward for the fundamental pulsar periodicity (Burbidge & Strittmatter 1968).) I say 'probably', because the predicted dynamical evolution has yet to be verified, and as, for example, Gil & Jessner (1992) have pointed out, it is possible to contrive alternative explanations, in this case based on precession of a

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single pulsar. We have learnt to be prudent. However, if we presume that the planetary explanation is substantiated, then further planets can be sought and studies of the long-term stability of the system may constrain speculations about its origin.

Looking at pulsars from the receiving end, there is the analogous problem of understanding planetary motions in our Solar System. This is no more straightforward in practice than solving the Schrödinger equation for multi-electron atoms and differences in philosophy and output exist for the two principal ephemerides in use. The millisecond pulsars, whose pulses can be timed with microsecond accuracy, may eventually be useful for determining the masses of Mercury, Saturn and Pluto which dominate barycentric uncertainties (Standish & Hellings 1989). Tied up with this problem is the 10 year old possibility that an array of millisecond pulsars might be allowed to vote on primary time standards, although this hasn't happened yet largely because the accuracy of conventional clocks have kept apace with the pulsars (Taylor, this symposium).

The discovery of pulsars in globular clusters is revolutionizing our astronomical understanding of these enigmatic relicts of the early stages of galaxy formation. It now appears that binary stars have always been common in globular clusters and consequently control the dynamical evolution after the core of the cluster collapses (Phinney, this symposium; Phinney & Kulkarni 1992). These stars naturally interact with one another both tidally and as point particles and evaluating the cross sections for these processes has turned into a major computational enterprise.

Single globular cluster pulsars (and the barycentres of binaries) can also be used as probes of the gravitational potential. The acceleration can only be measured with a substantial unknown error because pulsars have an intrinsic slow down which is indistinguishable from their kinematic acceleration. However, the rate of change of acceleration, known as the jerk, is much larger than the intrinsic contribution from $\ddot{P}$, and there is the prospect of determining this eventually for a large fraction of globular cluster pulsars. Although the data will always be sparse, there is optimism that the mass distribution in globular cluster potential wells will be inferred. (There are obvious similarities to be found in probing nuclear potentials with fast particles and some of the nuclear physics methodology may carry over to this case.)

3. Fluid dynamics (table 2)

The most exotic fluid dynamical application to pulsars is surely the core which is believed to be superfluid. As we can only observe this fluid by having the neutron star perform essentially macroscopic experiments for us, it is to be expected that this fluid behaves mostly classically. Nevertheless, some genuine microscopic issues are crucial. Foremost among these must be the nature and strength of the pinning of the quantized vortex lines to the nuclear lattice. It is this interaction which is believed to control the response to glitches (Lyne, this symposium). Magnetic flux is also quantized and as we know that the field is not parallel to the angular velocity, the commutability of the flux and vortex tubes becomes an issue, as yet not understood (Srinivasan *et al*. 1990).

Classical fluid dynamics is heavily involved in understanding neutron star formation. Most pulsars are thought to have their origin in type II supernova explosions associated with comparatively young, high mass stars. When the central pressure support of the star fails, the core implodes and the surrounding envelope will

Table 2. *Fluid dynamics*

topic	reference
advances	
superfluid core	Pines & Alpar (1992)
supernova collapse	Mayle (1990)
convection-induced eccentricity	Phinney (this symposium)
prospects	
supernova recoil	Bhattacharya & van den Heuvel (1991)
accretion induced collapse	Bhattacharya & van den Heuvel (1991)
neutron stellar pulsations	Reisenegger & Goldreich (1992)

undergo radial inflow followed by a bounce and radial ejection. Although a few numerical simulations of type II supernovae have been 'successful' (Mayle 1990), we are still some way from being confident about the details.

Real explosions, in contrast to most numerical simulations, are unlikely to be spherically symmetric, and small asymmetries that develop near marginal stability may be amplified. This will cause the star to recoil. Until recently, it was thought that these velocity kicks are quite small, ≈ 100 km s^{-1} compared with typical ejecta speeds, ≈ 10000 km s^{-1}. However, there is now evidence that some pulsars are formed with speeds that may be as high as 2500 km s^{-1} (Frail & Kulkarni 1991). If this interpretation holds up, then it is of considerable interest to determine what are the distinctive features of these pulsars which dictate this behaviour. One possibility is that an alternative supernova mechanism, perhaps accretion-induced collapse of a white dwarf in a binary system, is responsible. This in itself poses a distinct, though analogous, fluid dynamics problem to understanding type II supernovae.

Another fluid dynamical research area with many novel features (general relativity, abrupt compositional discontinuities, strong magnetic field, solid phases, etc.), is neutron star pulsation theory (Reisenegger & Goldreich 1992). Although compelling observations of pulsation have yet to be reported, it is not impossible that phenomena like X-ray quasi-periodic oscillation and drifting subpulses (Manchester, this symposium) might involve normal modes of the star. Seeking a small vibrational signal in a strong rotational modulation is the opposite of what is needed in helioseismology, and post-glitch timing data might be scrutinized with this in mind.

A new application of fluid dynamics is to understanding the measured eccentricities of those binaries which are believed to have undergone tidal circularization. The presence of finite convecting elements allows the orbit, to which they are coupled by tidal stresses, to develop a significant epicyclic contribution. The eccentricities predicted from this mechanism have been computed through an ingenious application of the fluctuation–dissipation theorem and appear to reproduce the observed correlation with orbital period (Phinney, this symposium). This may help us to quantify the theory of tidal circularization in close binary systems.

4. Magnetohydrodynamics (table 3)

In convention magnetohydrodynamical (MHD), theory, it is widely assumed that the electrical conductivity is effectively infinite so that the magnetic field is 'frozen' into the moving fluid. The liquid core of a neutron star is formally superconducting and so it might be thought that there would be no dissipation. However, there is

Table 3. *Magnetohydrodynamics*

topic	reference
advances	
dynamos in nascent neutron stars	Thompson & Duncan (1992)
buoyant escape of core field	Goldreich & Reisenegger (1992)
MHD wind models	Coroniti (1990)
prospects	
stability of $\gtrsim 10^{16}$ G fields	Thompson & Duncan (1992)

circumstantial evidence that the fields decay in some pulsars (Kulkarni). In principle, understanding field decay ought to be a pure physics question. Recent calculations have uncovered flaws in earlier treatments. For example, the rate of buoyant escape of magnetic flux in an electron degenerate fluid turns out to be surprisingly slow because it is controlled by the rate at which cold electrons can combine with protons to maintain β equilibrium (Goldreich & Reisenegger 1992).

A quite different problem concerns the structure of the (presumably) relativistic hydromagnetic wind that is formed beyond the light cylinder. In the case of the Crab Nebula, observational arguments suggest that this becomes particle-dominated (Kennel & Coroniti 1984). Describing the formation of this wind may involve modifications of classical MHD including the incorporation of inertial drift (Mestel, this symposium). However, unless our ideas about the structure of the magnetosphere are hopelessly misguided, this cannot be the case well within the light cylinder (cf. Mestel). One possibility is that the alternating magnetic field reconnects along neutral surfaces, heating the particles, and conceivably also creating electron–positron pairs (Coroniti 1990).

This in turn raises a further interesting possibility, that of resurrecting models in which the coherent radio pulses originate beyond the light cylinder in the ultrarelativistic outflowing wind (Michel 1971). (Developing this model involves relativistic radiative transfer as well as relativistic MHD (Arons 1979).) Many of the observed pulse properties can be qualitatively reproduced by a wind emission model, notably polarization swings, drifting subpulses and interpulses. It also gives a beaming fraction of order unity and a large emitting area as some observations (cf. Manchester, Kulkarni, this symposium; Wolszczan & Cordes 1987) indicate is the case. Now I know of no compelling reason to doubt the conventional magnetic vector model and suspect that it is essentially correct. However, it seems important to develop observational arguments *against* the alternative, relativistic wind models in much the same way that it was possible to reject the (otherwise attractive) light cylinder models (Smith 1971; Manchester & Taylor 1977).

As is the case with the Sun, the surface magnetic field of a pulsar may be very much weaker than that found in the interior. It is possible to conceive of fields as large as $\approx 10^{16}$ G being present without substantially changing the radius and moment of inertia of a neutron star (Thompson & Duncan 1992). The dynamical effects of the associated magnetic stresses are largely unexplored and, in view of our failure to come up with compelling physical explanations for glitches (Lyne, this symposium) and γ-ray bursts (Higdon & Lingenfelter 1990), further study of this possibility seems well motivated.

Table 4. *Electrical engineering*

topic	reference
advances	
structure of aligned rotators	Mestel[a]
return currents	Mestel[a]
gaps	Mestel[a]
prospects	
structure of oblique rotators	Michel (1991)
differential isorotation and drifting subpulses	Michel (1991)

[a] This symposium.

5. Electrical engineering (table 4)

Many electrical engineers have looked at the well-posed, classical electromagnetic problem of the aligned rotator and expressed considerable surprise at the failure of astrophysicists to solve it. It is still not understood (Mestel, this symposium). Nevertheless, despite the large variety of global magnetospheric models now on offer (Michel 1991), some general principles have emerged and these impact pulsar emission models.

Pulsars are giant unipolar inductors that create large potential differences $\approx BR(\Omega R/c)^2$ across the open field lines, where B is the surface field R is the stellar radius and Ω is the angular velocity. For young, high field pulsars like the Crab pulsar, the induced voltage can be as large as $\approx 3\times10^{16}$ V. The associated electric field has a divergence which must be satisfied by a space charge density $-(\boldsymbol{\Omega}\cdot\boldsymbol{B})/2\pi c$. These voltages drive current flow through the magnetosphere with opposite sign between polar and equatorial regions so that there is no net loss of charge from the star. Current closure within the highly conducting neutron star is no problem. However, current closure within or beyond the magnetosphere is more problematical. In some models this should occur in a highly dissipative region with the creation of a large flux of γ-rays. This is not observed, although, as discussed below, recent reports from the Compton Observatory of pulsed γ-rays from PSRs 1509–58 and 1706–44 (in addition to the Crab and Vela pulsars), does suggest that $\gtrsim 1\,\%$ of the total rotational energy extracted is dissipated within the magnetosphere.

Currents of both sign must leave the star. The negative charge carriers are presumably electrons. However, the positive charge carriers may be either positrons or ions. Positrons can be freely created within 'gaps' within which relativistic electrons either radiate γ-rays by the curvature process or inverse Compton scattering of stellar photons. These γ-rays can then pair produce on either real or virtual photons, derived from the star or the magnetic field respectively, to initiate an electron–positron cascade. As always, boundary conditions are important. It is now believed that ions can be freely removed from the surface (see below). This obviates the introduction of surface gaps in 'anti-pulsars' in which the magnetic moment is anti-parallel to the angular velocity.

Spinning neutron stars must lose both angular momentum and rotational energy (in the ratio $1:2\pi/P$ if the star is uniformly rotating). Understanding the partition of this angular momentum flux between mechanical and electromagnetic forms is just as important as understanding the nature of the energy flux (Mestel, this symposium).

One very strong observational clue may come from the drifting subpulses. It has long been tempting to associate these with differential rotation of the field lines when there are electric fields parallel to the magnetic field. Unfortunately, there does not seem to be a particularly good explanation of the relationship between the charged particles responsible for the coherent radio emission and the magnetic field. This apparently straightforward electrodynamics problem deserves further attention.

6. Plasma physics (table 5)

The study of pulsars has generated many novel plasma physics problems. The most immediate of these are concerned with the actual emission process. It is quite remarkable that despite all the successful applications of pulsars, we still do not have even a rudimentary consensus as to how they radiate. What is worse, only a few astrophysicists appear to be still working on this problem.

Possible emission mechanisms have been classified as maser processes, antenna mechanisms (wherein giant bunches of charge are formed and radiate by the curvature process like giant electrons) and reactive instabilities (Melrose, this symposium) in which the natural growth rate exceeds the natural bandwidth of the growing waves and a phase-coherent structure can be formed. Objections have been voiced to each of these mechanisms. For example, giant bunches of charge appear to disperse very quickly and, furthermore, it is not clear that any radiation they emit would be capable of propagating through the surrounding plasma (although it may be that the high brightness plasma modes are emitted and that these mode-convert to transverse electromagnetic waves at a larger radius where the plasma is more tenuous). Similarly, streaming instabilities appear to grow too slowly to account for the observed high brightness temperature. Maser mechanisms, long a favourite of Soviet (and former Soviet) astrophysicists, have fewer problems overall. Particularly promising are mechanisms based upon a relativistic electron (or positron) cyclotron resonance in the outer magnetosphere (Kazbegi *et al.* 1992).

An equally important application of plasma physics is to the propagation of the radiation out of the magnetosphere. Much of the observed polarization and frequency structure may be imprinted in this journey. For example, Wilson & Rees (1978) (cf. also Sincel & Krolik 1992) have argued that the very escape of low radio frequency emission from the Crab pulsar allows a lower bound of $\gamma \gtrsim 10^4$ to be placed upon the Lorentz factor of the outflowing wind from the apparent absence of destructive induced Compton scattering.

A more recent extension of these ideas is to the eclipsing pulsars, notably PSR1957+020 and PSR1744-24A. In both systems, an extended cloud of electrons around the pulsar's companion star appears to be responsible for eclipses. Many explanations have been put forward for the eclipse, although so far they all have difficulty in accounting quantitatively for the observations. I would like to describe a new explanation, namely that the eclipse is caused by stimulated Raman scattering (Thompson *et al.* 1992). In this process, transverse electromagnetic waves propagating within an effectively unmagnetized plasma, can excite longitudinal electrostatic modes. The excited waves must satisfy energy and momentum conservation, namely that

$$\omega = \omega' + \omega_L, \quad \boldsymbol{k} = \boldsymbol{k}' + \boldsymbol{k}_L,$$

where the prime denotes the scattered transverse mode and the subscript L denotes the electrostatic wave. When the radio flux density is sufficiently powerful, the rate

Table 5. *Plasma physics*

topic	reference
advances	
two stream instability	Melrose[a]
mode conversion	Melrose[a]
radiation reaction instability	Goldreich & Keeley (1971)
maser processes	Kazbegi *et al.* (1992)
prospects	
sustenance of interstellar turbulence spectrum	Higdon (1986)
pulsar eclipse mechanisms	Thompson *et al.* (1992)

[a] This symposium.

of growth of Langmuir waves exceeds their damping rate due to ion–electron collisions or loss from the eclipse region and there will be parametric growth of the scattering waves and efficient scattering of the incident transverse electromagnetic wave. This requires a flux density

$$S \gtrsim 4\times10^{-4} n_{e6}^{\frac{1}{2}}\, T_6^{-\frac{3}{2}}\, \nu_9 \,\mathrm{erg\,cm^{-1}\,s^{-1}\,Hz^{-1}},$$

where $n_{e6} = n_e/10^6\ \mathrm{cm^{-3}}$ is the electron density, ν_9 is the electromagnetic wave frequency in gigahertz and $T_6 = T/10^6\ \mathrm{K}$ is the temperature. When this condition is satisfied, the pulsar is likely to be eclipsed. At lower flux density, when damping is important, the pulses are more likely to be attenuated. One characteristic of stimulated Raman scattering is that when the Langmuir waves are generated by a collimated beam of radiation, they grow most rapidly at the largest angle to the beam for which they will not be subject to Landau damping. This means that the electromagnetic waves in the beam will be scattered through finite angles and the pulses will appear to be attenuated (rather than smeared as would be the case if the Langmuir waves had an isotropic distribution) because the extra propagation times for the scattered waves amounts to several pulse periods.

Now measurements of the dispersion measure near ingress and egress allow us to make fairly accurate estimates of the electron density. We find that the required electrostatic modes can grow sufficiently to eclipse the low-frequency radiation in PSR 1744-24A and to attenuate the high-frequency emission. In the case of the other eclipsing pulsar, PSR 1957 ± 20, only the eclipse at low frequency can be attributed to Raman scattering. If this explanation is confirmed by future observations, it will provide one of the few non-trivial and quantitative applications of plasma physics to plasmas outside the Solar System.

Further on the journey to Earth, scattering by interstellar turbulence causes scintillation. As we discuss below, analysis of this scintillation leads us to infer that the power spectrum of plasma density fluctuations has a similar slope to that of the Kolmogorov spectrum of velocity fluctuations in fluid turbulence. However, the conditions under which the interstellar density fluctuation spectrum is established are quite different from those appropriate for fluid turbulence, which is approximated as incompressible (Higdon 1986). In addition, observations of scintillation allow us to infer, at least in principle, the 'inner scale' – the short wavelength cut-off to the spectrum. This presumably occurs where the rate of dissipation is comparable to the turnover frequency. These are all relatively well posed, though unsolved problems in plasma physics.

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Table 6. *Optics*

topic	reference
advances	
temporal scintillation	Hewish,[a] Narayan[a]
refractive scintillation	Hewish,[a] Narayan[a]
interstellar caustics	Romani *et al.* 1987
prospects	
primordial magnetic field	Rees (1987)
pulsar imaging	Wolszczan & Cordes (1987)
solar wind probe	Narayan[a]

[a] This symposium.

7. Optics (table 6)

One of the most immediate applications of optics to pulsars was to insterstellar scintillation (Scheuer 1968; Hewish, Narayan, this symposium). Density fluctuations in the interstellar gas lead to refraction and scattering of pulsar waves. This creates a diffraction pattern through which the observer moves, creating large-amplitude intensity fluctuations. Analysing the temporal and frequency structure of these fluctuations allows us to infer the character of the density fluctuations. This process is reasonably well understood when the scattering can be regarded as confined to a single thin screen. Multiscreen propagation is less comprehensible. Path integrals and numerical simulation are both useful in attempts to describe multiscreen propagation. Occasionally, large-scale density fluctuations may dominate the scattering (Fiedler *et al.* 1987; Hewish), which may cause two-dimensional caustic structures to form (Romani, *et al.* 1987). In principle, the study of scintillations allows us to set limits on the size of the emission region (cf. Wolszczan & Cordes 1987). This should be valuable input in models of the emission mechanism. Even more dramatic 'superresolution' is conceivable in the future (Narayan).

A rather different potential use of pulsars is as a probe of the solar wind, particularly at large heliospheric latitude. Linearly polarized, pulsed radiation will, among other effects, be subject to dispersive delay and Faraday rotation and this may provide an estimate of the strength of the toroidal magnetic field in the solar wind.

Studies of Faraday rotation caused by the interstellar medium have shown that the interstellar field has surprisingly long-range order in the disc (Lyne & Smith 1989). Specifically, there is a large-scale vector component. (Observations of pulsar rotation measures are more important than those of interstellar optical polarization in this regard, because the latter do not tell us about the field direction.) In a parallel theoretical development, Kulsrud & Anderson (1992) have argued that galactic dynamos are ineffectual. Granted both deductions, we are left with a strong case for a primordial magnetic field, presumably of cosmological origin (Rees 1987). If true, this has enormous implications for physics.

8. Atomic physics (table 7)

The realization that pulsars were endowed with surface magnetic fields of $\approx 10^{12}$ G stimulated discussion of a new type of atomic material (Ruderman 1971). Under these circumstances, it is the magnetic interaction that dominates the

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Table 7. *Atomic physics*

topic	reference
advances	
strong Zeeman effect	Ruderman (1971)
surface cohesion	Neuhauser *et al.* (1988)
strong field opacity	Miller & Neuhauser (1991)
prospects	
neutron stellar atmosphere	Romani (1987)

hamiltonian and the Coulomb interaction that is the perturbation. The atoms are extremely elongated and are thought to assemble themselves as close-packed rods. The actual physical state of the surface then depends upon the interatomic binding, and to calculate this requires a very careful Hartree–Fock calculation. It now appears that the surface may not be a solid (Kössl *et al.* 1988) and that ions do not adhere strongly to it (Neuhauser *et al.* 1989).

The advent of X-ray spectroscopy of neutron star surfaces (Finley *et al.* 1992) demands a far more careful study of radiative transfer in neutron star atmospheres (Romani 1987; Miller 1992), which in turn necessitates improved opacities for both magnetized and unmagnetized surfaces (Miller & Neuhauser 1991).

9. Solid state physics (table 8)

The outer crust of a neutron star provides a splendid examplar of the principles of solid state physics. The standard 'nearly free electron' model turns out to be an even better approximation than it is for terrestrial metals. For this reason, we should have some confidence that we can compute the transport properties adequately accurately (modulo some uncertainty about the density of lattice defects, dislocations, etc.). We should then be in a position to pronounce upon the thermal and magnetic evolution of the crustal regions (Bhattacharya & van den Heuvel 1991). However, matters turn out to be not so simple. One example is provided by the analysis of Hall effects, which cause magnetic field lines to change in a manner reminiscent of vortex lines in hydrodynamical turbulence (Goldreich & Reisenegger 1992). This may lead to a cascade of magnetic energy from large to small scale where ohmic loss can be important so that the total magnetic energy is diminished.

Observationally, our understanding of the evolution of pulsar magnetic moments is in turmoil (Kulkarni, this symposium). There is now considerable doubt that the field strengths of normal, old pulsars decay at all. Conversely, magnetic field decay does appear to occur in recycled pulsars. I am also impressed by the circumstantial evidence for field growth in three supernova remnants. For example PSR1951+32 in the young supernova remnant CTB80, has an anomalously small dipole moment. PSR 1509-58 has a timing age of only 1800 years despite being in a remnant, MSH 15-52, some 20 pc across. (However, see Thorsett (1992) for a proposed identification with SN 179 AD.) Finally, PSR 1758-24 is located on the periphery of a fairly young remnant and, must have travelled with a mean speed of several thousand kilometres per second to reach this position (Manchester *et al.* 1991). All of these considerations motivate more study of this problem.

Another example of a deceptively subtle physics problem is the thermal response of a pulsar to a glitch (van Riper 1992). In some glitch models, substantial heat will

Table 8. *Solid state physics*

topic	reference
advances	
magnetic transport properties	Yakovlev & Urpin (1981)
Hall turbulence	Goldreich & Reisenegger (1992)
prospects	
magnetic evolution of neutron stars	Bhattacharya & van den Heuvel (1991)
neutron star plate tectonics	Ruderman (1991)

Table 9. *Quantum electrodynamics*

topic	reference
advances	
magnetic pair production	Erber (1966)
prospects	
pair annihilation from stellar surface	Mészáros (1992)
cyclotron radiation from stellar surface	Mészáros (1992)

be liberated which will quickly diffuse through the interior. However, this heat will then slowly leak through the more poorly conducting surface layers and may produce a faint, X-ray afterglow. Any such observation would be a very powerful diagnostic of the physical processes at work.

Ruderman (1991) has recently discussed the mechanical implications for the crust of strong pinning of vortex lines. This can drive subduction and upwelling analogous to geophysical processes. It can also lead to magnetic evolution of the dipole moment with both increase and decrease of the magnetic inclination angle.

10. Quantum electrodynamics (table 9)

The discovery of pulsars opened the door to observation, either direct or indirect, of certain elementary processes that are quite unrealizable under laboratory conditions. Under the high photon density conditions present above a cooling neutron star, the opacity for a γ-ray to create an electron–positron pair is significant. Furthermore, the analogous process involving virtual photons associated with the transverse component of the magnetostatic field can also occur and may provide the easiest, and therefore the dominant mechanism for discharging strong electric fields which can develop within the magnetosphere.

More generally, it has been argued (Mestel, this symposium) that magnetospheres must contain a significant amount of dissipation, associated with cross-field currents. This is likely to involve a broader range of QED process (Mészáros 1992).

Recent observations of γ-ray processes from active pulsars are encouraging (Arons 1992). The pulsar 1509-58, with its unusually strong magnetic field (10^{13} G) has been observed to have a broad γ-ray spectrum extending up to 2 MeV (Fishman 1992) and 100 MeV pulsations have just been found in EGRET observations of PSR 1706-44 (Kniffen *et al.* 1992). Most intriguing of all, the enigmatic γ-ray source ‘Geminga’ has just been shown to be a radio-quiet pulsar (Halpern & Holt 1992). This may be dissipating a very high fraction of its spin-down energy in the form of γ-rays as anticipated by Ruderman & Cheng (1988).

In another development, SIGMA observations of the Crab pulsar, are reported to show a feature at 545 keV, which may be associated with blue-shifted electron–positron annihilation (Sunyaev *et al.* 1992). (When one allows for the gravitational redshift from the stellar surface, the blue shift may be close to 20%.) At the very least, this report should make us curious about the radiative transfer in an annihilation zone closer to the stellar surface. We might also inquire as to why pulsed cyclotron lines have not been reported from pulsars. Intense irradiation of the polar caps should cause rapid excitation of Landau states which might be detectable in a pulsar like PSR 1509-58.

11. Physics at nuclear density (table 10)

In this category we find the deepest connection between pulsar observations and physics. There was an early recognition by Migdal that the neutrons within a pulsar should be able to pair and form a superfluid state. However, our modelling of this phenomenon has undergone a steady evolution, aided and abetted by upper limits on pulsar cooling and the ever-surprising monitoring of glitches (Lyne, this symposium). Two principal superfluid phases are identified, an isotropic state in the inner crust and an anisotropic state at higher density within the fluid core. The former state is much better understood and real calculations of the gap energy appear to be converging (Clark *et al.* 1992).

Observations of cooling X-rays from young neutron stars can provide a check on our understanding of the interior structure. For a long while it has been thought that the dominant heat loss from a neutron star interior is due to neutrino emissivity by the modified URCA process, in which a bystander particle has to participate to conserve momentum. Needless, to say this happens at a slower rate than the direct URCA process. However, as Pethick reports in this symposium, there are now some equations of state in which the protonic fraction exceeds $\frac{1}{9}$, the critical condition for direct URCA cooling (without bystanders) which is much faster. If this turns out to be generic, then it is unlikely that we will ever be able to perform spectroscopy of a cooling neutron star.

Of course determining the structure of the stellar core is a well-posed problem in theoretical physics requiring detailed understanding of hadronic interactions at supranuclear density. As Pethick also discusses, three-body interactions are now realized to be very important in determining the cold equation of state. In addition, many exotic possibilities have been discussed, e.g. pion and kaon condensates (Politzer & Wise 1991), quark stars (Alcock *et al.* 1986) and Q-stars (Bahcall *et al.* 1990).

The most quantitative comparisons of theory with observation come from pulsar glitch data. Here there have been spectacular observational advances. There are now many more strongly glitching pulsars known and their post-glitch frequencies have been carefully monitored (Lyne, this symposium). Patterns, however, are hard to find as each glitching pulsar appears to be different. Four recent discoveries seem particularly noteworthy. Firstly, there is the ‘slow glitch’ discovered in the Crab pulsar. Here, it appears that a pulsar is speeding up over a timescale of several hours. All other glitches are unresolved. Secondly, there is the observations that all post-glitch relaxation can be empirically fit by simple exponential functions. This is just what would be expected from a simple frictional interaction between different interior components proportional to the relative angular velocity between the

Table 10. *Physics at nuclear density*

topic	reference
advances	
superfluidity	Clark *et al.* (1992)
superconductivity	Pethick[a]
interpretation of glitches	Pines & Alpar (1992)
neutron star cooling	Tsuruta (1992)
prospects	
three-body interactions	Pethick[a]
pion/kaon condensates	Politzer & Wise (1991)
quark stars	Alcock *et al.* (1986)
Q-stars	Bahcall *et al.* (1990)

[a] This symposium.

Table 11. *General relativity*

topic	reference
advances	
neutron star masses	Taylor[a]
periastron advance	Taylor[a]
gravitational radiation	Taylor[a]
Shapiro effect	Taylor[a]
verification of general relativity	Damour[a]
gravitational wave background limits	Taylor[a]
$\dot{G}$ limits	Taylor[a]
high velocity pulsars	Kulkarni[a]
prospects	
geodetic precession	Taylor[a]
black hole–neutron star binary	Saslaw *et al.* (1968)
lense–thirring precession	Blandford & Coppi (1992)

[a] This symposium.

components and apparently incompatible with more complex physical models. In particular, any temperature variation during the recovery seems improbable. The third discovery is of three separate relaxation times in the Vela pulsar (Pines & Alpar 1992). This implies, in this pulsar at least, that there are at least three separate loosely coupled interior components. Most modern models postulate only one component decoupled from the main star and associated with superfluid neutrons in the inner crust. Finally, there is the observed association of glitching and restlessness with rapidly decelerating pulsars, suggesting that either youth or the strength of the torque is important for triggering glitches (Lyne).

12. General relativity (table 11)

In addition to verifying that slowly moving neutron stars follow newtonian orbits with considerable precision, pulsar timing of more rapidly moving stars, in particular those in the first binary pulsar, PSR 1913+16, have been used to exhibit the special relativistic and gravitational redshifts. This is pleasant corroboration of our expectations, but we would probably have attached little fundamental significance to a discrepant measurement. Where we start to learn something new is with the measurement of the general relativistic advance of preiastron in this system and also PSRs 2127+11C, 1534+12. These measurements furnish a combined component mass $\approx 2.8M_{\odot}$, consistent with the hypothesis that supernovae create neutron stars with masses exclusively in the range 1.3–1.5$M_{\odot}$ as we have independently concluded is likely to be the case. (Note that this requires application of a non-trivial generalization of the formula for the perihelion advance of the planet Mercury as the two bodies are of comparable mass.)

The measurement of the neutron star masses also provides input for the prediction of the rate of orbital decay due to the emission of gravitational waves. As is well known, the general theory of relativity has been verified to a half per cent (Taylor, this symposium). There can be no significant dipolar contribution to the gravitational wave emission. The precision of this test is unlikely to improve significantly because of our relative ignorance of the newtonian gravitational field of our Galaxy. This agreement is so striking that most physicists are prepared to answer the question posed in Will's (1986) popular book, *Was Einstein right?*, in the qualified affirmative.

The nature of the qualifications is itself a matter of scientific study (Damour, this symposium). The constraints imposed by all of the experimental relativity tests are so strong that it is very difficult to fashion a viable physical theory alternative to general relativity. Indeed, some concern was expressed as to whether or not there was any real point in this exercise as only a convincing violation would now cause us to doubt general relativity and if such a violation were reported then its very nature would be even more constraining. Nevertheless in one 19-parameter framework, fifteen additional tests are, in principle, possible using binary pulsar observations. It should also be noted that these systems provide a direct demonstration of the strong principle of equivalence as bodies do appear to travel along geodesics independent of the (*ca.* 10%) contribution of gravitational binding energy to their masses.

On a much more speculative level, there are some intriguing possibilities for the future. The discovery of apparent high velocity pulsars, if correctly interpreted, is encouraging for those involved in the LIGO project as they furnish strong evidence for quite asymmetric collapses, propitious for the generation of gravitational waves (Kulkarni, this symposium). Secondly, we can at least think about what might be learnt from a 'dream binary system', comprising a millisecond pulsar in orbit about a massive black hole and observed with inclination $i \approx \frac{1}{2}\pi$ (cf. Saslaw *et al.* 1968; Naraya *et al.* 1991). Multiple images should be detected close to eclipse and it is, in principle, possible to verify the presence of non-spherical terms in the Kerr metric from the extra arrival time delays that it produces. Crossing a caustic surface formed by a Kerr hole would be particularly exciting.

Finally let us speculate that the theory of vortex line pinning is flawed. It is then possible that neutron star interiors contain two or three loosely coupled components with distinct angular velocities. If, for example, a series of glitches, forced the angular velocities to become non-parallel, then the two components should undergo mutual Lense–Thirring precession. Calculations of this effect predict a precession period of approximately seven pulse periods quite insensitive to the internal structure (Blandford & Coppi 1992). It might be possible to detect this periodicity in a strongly glitching pulsar like the Vela pulsar.

13. Conclusion

The focus of pulsar research has evolved over 25 years from trying to understand how they work (and this remains a splendid unsolved problem) to using them as wonderfully versatile tools for studying basic physics and astronomy as I hope this summary brings out. Most of the ways in which this has happened were not anticipated. It is hard to believe that this box of delights will suddenly snap shut. The next quarter century should be just as interesting.

The President and Council of the Royal Society are to be thanked for their support of this Discussion Meeting. I acknowledge financial support from the US National Science Foundation under grant AST 89-17765 and the National Aeronautics and Space Administration under grant NAGW 2372.

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