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Summary

As will be evident from looking at the contents of this volume, the Academy Colloquium was an excellent meeting with the majority of the talks given over three and a half days of a very high standard. In the following summary of my impressions I shall attempt to do more justice to the many valuable presentations than was possible in the allotted 15 minutes at the end of the last day.

Well over a year before the meeting, the motivation for its topic was communicated by the chairman to the other members of the scientific organizing committee; and much closer to the meeting he defined the focus of the Colloquium as on the questions of: What can we learn from pulsar timing about:

1. General and Special Relativity. How can we use relativity to study neutron stars (masses, density distribution, parallaxes, etc.)?

2. The internal structure of neutron stars.

These few questions governed the choice of both topics and speakers for the review talks and I take as my task here to assess how far the meeting succeeded in its aims. The first area touched upon was Relativity, and what we have learnt from timing binary and millisecond pulsars.

I Relativistic phenomena

The nature of the theories of Relativity, both Special and General are such that neither terrestrial experiments nor astronomical observations have ever *taught* us anything (new) about them. What they have done is to provide *tests* of the predictions of these theories to higher and higher levels of accuracy. Among the various predictions verified in earlier days may be listed time dilation, the bending and retardation of radiation when passing close to massive bodies, the gravitational redshift, and of course the precession of the perihelion of Mercury which was known even before but not understood in Newtonian theory. And as everyone here knows, it was the discovery of the Hulse-Taylor binary pulsar B1913+16 with its special combination of spin and orbital characteristics that ushered in a new era of testing of relativistic gravity. A few more binary systems suitable for similar tests have been found since then, and the accuracies achieved in timing measurements have become so high that proper motion and galactic acceleration must also be taken careful account of, not to mention the cluster potential in the case of systems in globular clusters.

Testing different theories of gravity means comparing observations with predictions in a way that can discriminate between them. And it is here, as we learnt from various speakers on this subject, that Damour's work with Deruelle, and with Taylor and others later, has made a profound contribution as a user interface between theoreticians and observers. The particular approach used has made it possible to isolate a number of independent, potentially measurable "post-Keplerian" parameters which are not inter-related by built-in theoretical constraints. They take different values in different theories of gravity, and Gilles Esposito-Farèse explained how some tensor-scalar theories of gravity which were strictly equivalent to GR in weak field conditions (solar-system experiments) are nevertheless ruled out by binary pulsar tests. Jon Bell talked about the PPN formalism (the weak field, slow-motion, predecessor to PPK) and said that three of its ten parameters related to Lorentz invariance and conservation laws have already had severe limits put on them using pulsar data, one of them being as accurate as any null measurement in physics to date. The clearer and clearer message from all the results so far is that GR has been vindicated to amazing precision and alternative theories of gravity are falling by the wayside.

Including the recent discovery of J1518+4904 reported by Nice at this meeting, there appear to be five certain double neutron star binaries known to date. The similarities and differences in the values of their spin rates, and their orbital periods and eccentricities, provide important clues to the evolutionary histories of these systems. As testers of theories of gravity however, the proper motion, distance and even the orbit inclination to the line of sight affect the performance of any given system. For example, the orbit of B1534+12 lying nearly in the line of sight amplifies the Shapiro delay within the orbit, and this enabled the first purely strong-field test. The larger inclination of the orbit of B1913+16 allowed only a mixed test of the strong-field and radiation aspects of gravity. On the other hand, the proper motion of B1534+12 makes a substantial (20%) contribution (*à la* Shklovskii) to the observed orbital period derivative; and as pointed out by Bell and Bailes this limits the verification of gravitational wave emission to a precision of 7% of the predicted value or so unless the distance estimate to the system can be improved. Also as suggested by them, this effect looked at the other way, provides a new method of determining binary pulsar distances. Turning to orbital eccentricity, the 10% or so increase in this parameter for B2127+11C over that of B1913+16 is expected according to Taylor to make it a much better system for tests of gravitational radiation.

Next to the spectacular confirmation of the precise amount of gravitational radiation to be expected from neutron star binaries, the most impressive GR results in my view are the mass determinations of all six stars in three of the five systems, four of which are incredibly accurate values. In the other two systems, which are wide binaries, the large orbital periods (days instead of hours) reduce the amount of gravitational radiation expected, thus precluding or making very difficult the detection of the relativistic decay of their orbits. But precessions of periastrons yield total masses of systems and these have been determined to an accuracy of a few percent. Two more binaries, with low mass companions, have also yielded mass estimates. They were included in a plot of measured neutron star masses shown by Taylor at the meeting.

The remarkable closeness of all the values in Taylor's plot suggests very strongly that as the errors in these and other methods of determination are reduced, all neutron star masses will end up in the neighborhood of the Chandrasekhar mass minus the binding energy, as is not unreasonable to expect. If this happens, there will be little or no information to be gained from the mass determinations about the equation of state of neutron matter, as was also noted by van Paradijs in his talk later in the Colloquium. Some indication of the spread of masses at birth, as distinct from changes due to accretion, is however already evident from an intercomparison of the six accurate values, three of which relate to spun-up pulsars.

Matthew Bailes talked about the dearth of such double neutron star binaries in the galaxy—only about 5 in 700 or more known pulsars—saying that this indicated a very high disruption rate, which in turn would require substantial kicks in 25 to 50% of all SN explosions. A consequence of this related to GR was that the estimated number of Galactic ns-ns mergers (of interest to LIGO say) was definitely below 10^{-5} per year and probably only around 10^{-6} per year. Another consequence is that the spin axes are likely to be tilted with respect to the orbit normals and should cause a change in shape and/or polarisation structure of the pulse with time due to geodetic precession.

Arzoumanian reported on observations of B1534+12 and said that although the pulse shape variation expected from orbital-phase dependent aberration was not detected, a significant long term change was seen and has been interpreted as due to the expected precession. Although not discussed at this meeting, strong evidence has been accumulating that the pulse of B1913+16 is also changing slowly with time at a rate roughly consistent with the expected precession. But the difficulties of interpretation of the observed changes have so far precluded any quantification of the tilt angles. So much for testing General Relativity and using it to find out things.

II Newtonian phenomena

Still staying with binaries, there were several very interesting presentations dealing with observations of what we might call purely Newtonian phenomena. Simon Johnston discussed the results of continued observations of 1259−63, the remarkable binary pulsar with a Be star companion of ten solar masses and six solar radii. The new development was that the fit for the first observed orbit does not work for the second one. Neither tidal or frictional drag, nor GR effects, can explain the observations which are now interpreted in terms of classical spin-orbit interaction.

Another neutron star binary with a B star companion of similar mass is J0045−7319 in the Small Magellanic Cloud. Vicky Kaspi reported on the significant deviations from a simple Keplerian orbit which indicate an advance of the pulsar's periastron as well as spin-orbit coupling. Both effects are believed to arise out of a rotationally induced equatorial bulge in the companion coupled with a substantial tilt of its spin axis with respect to the orbit normal. There are several more very nice results which have come out from timing this particular pulsar. The B star's rotation must be retrograde to enable enough coupling to the tidal potential to decrease the orbital decay time scale to a mere half million years. As this is only a fraction of the characteristic age of the pulsar, its spin rate at birth must have been close to its present period of around a second! Although other lines of evidence have suggested for years that most pulsars will not have a very short period at birth, this is perhaps the first time that there is direct observational evidence of a long initial period. Finally, both the inclination of the spin axis of the B star with respect to the orbit, as well as its being retrograde provide compelling evidence for a birth kick of at least 100 km/s if not much greater.

The evidence provided by this system for a substantial kick at birth is perhaps considered the most important result from the timing of this pulsar. I would like to add that an equally if not more important result may be the circumstantial evidence that the long period at birth was also a result of the kick. See later.

Very interesting timing results on the binary system J0437−4715 containing the nearest and brightest millisecond pulsar were reported by Manchester. The secular acceleration associated with its enormous proper motion of 140 mas/yr accounts for most of its period derivative and affects the field estimation. What is more, it causes a clearly measurable change in the orbit inclination with time.

If pulsar binaries are rare, multiple systems should be even rarer, as in fact they are. Wolszczan discussed observations on B1257+12, the first such system found several years ago. In addition to the three confirmed inner planets whose orbital perturbations have been seen, a fourth possible outer one is suspected from the residuals. Evidence for planets around other pulsars he said was not convincing. An interesting point he made was that timing noise observed in various pulsars could be due to "junk" in orbit around them. Steve Thorsett described continued observations of the only other multiple system known that is associated with a pulsar and which is in the globular cluster M4. No less than four derivatives of the spin frequency have been measured, the second being too large to be due to timing noise, and of such a value that the first derivative will change sign in 2001! The data are inconsistent with acceleration in the cluster field and indicate the presence of a third object with a mass $< 0.015\ M_\odot$—a brown dwarf?—in a wide orbit only a part of which has been sampled so far. It was estimated that two more years of data should tell us for sure.

III Timing accuracy

All of the interesting results mentioned so far depended for their success on the steadiness of the spin and slow-down rates of pulsars and the accuracy of the clocks used for timing them. The present state of the art of timekeeping was covered by Petit who also compared the stability of atomic clocks with that of millisecond pulsars. As of now, the relative superiority depends on the time scale involved, atomic clocks being better for periods of months or shorter, and millisecond pulsars winning over years. The most recent progress has resulted from the use of "Cesium fountains" which have enabled reaching a stability of 3×10^{-15}; and a goal believed to be achievable in the not too distant future has been set at 10^{-16}.

Even if pulsars are stable rotators, their signals get mauled in passage through the interstellar medium as very nicely explained by Don Backer in his Primer on Interstellar Weather. The movement of inhomogeneities in the electron density distribution gives rise to both diffractive and refractive scintillations including some long term changes such as the DM for Vela which has a linear gradient with time. Multiple frequency observations do not solve all problems because different frequencies sample different volumes of the ISM resulting in scattering making DM a function of frequency! Disturbances close to the pulsar can also play havoc as in the case of the Crab where the movements of filaments in the Nebula cause wild variations in DM and also changes in the scattering and flux density. Lestrade describing timing observations carried out at Nancay noted that refractive interstellar scintillation can cause long term flux variations and that dispersion delay variations dominate the time of arrival analyses as seen by an anticorrelation with flux variations.

Unconnected with problems associated with propagation, there is an unpredictable aspect of pulsar timing behavior due to internal causes, namely glitches and timing noise. These were discussed by Lyne who presented an impressive amount of data obtained over the years. About 50 glitches have been observed so far, three quarters of them in the last ten years, and three young pulsars out of 21 accounting for half the total number of glitches. The largest and most recent glitch was observed in the pulsar B1930+22 in June 1996 and has a value for $\delta\nu/\nu$ of 4.5×10^{-6}. These sudden increases in rotation rates are followed by relaxations which have both a short term and a long term behavior, but which tend to leave a small permanent change in frequency derivative. Glitch "activity" (defined as the total frequency change in glitches divided by total observation time) is greatest for pulsars with ages 10,000 to 30,000 years and for greater ages falls off roughly as the frequency derivative.

Timing noise, or irregularities in pulse arrival times, while present to some extent in all normal pulsars, is greatest in young pulsars with large slow-down rates. Both positive and negative period second derivatives are found but a comparison with glitch activity suggests that in younger pulsars timing noise could be mostly recovery from glitches seen or unseen. Both glitches and timing noise are attributed to the loose coupling of the neutron superfluid to the crust. Sudden unpinning of the superfluid in the crust appears the most likely cause of glitches, with the post glitch relaxation giving information on the amount of fluid in the star and the transfer of angular momentum from the core.

IV Neutron superfluid

Following an overall review of neutron star interiors by Srinivasan, Ali Alpar discussed superfluid dynamics in neutron stars. While starquakes could work for smaller glitches such as seen in the Crab, they cannot explain the larger and more frequent glitches typical of Vela. He elaborated on his work with others on the superfluid vortex unpinning model which suggests that the Crab would evolve to becoming like Vela with the growth of the region of trapped vortices. An interestingly different scenario was put forward by Link who used both quakes and vortices. Sudden heating in the neutron star interior leads to angular momentum transfer from the core superfluid to the crust causing the spin jump. The difference between the Crab and Vela type glitches is attributed to temperature effects with the spacing depending on the quake frequency.

The last of the presentations in this group was by Sauls who talked about proximity effects on neutron superfluidity in the inner crust. Instead of being one continuous entity the neutron sea is separated into pieces interspersed by np matter. The scattering of the Cooper pairs at the interfaces and subsequent loss of a fraction of them reduces drastically the number available for superfluidity in the n region. As a result both gap and pinning energies are reduced greatly. Following this was a discussion session with several contributors and led by David Pines. The aim was to understand "to what extent do pulsar glitches probe crustal superfluidity, core-crust coupling and the EOS of dense matter". My own impression at the end of considerable discussion was that it was highly inconclusive. There was no clear consensus, and I for one was not much wiser after than before.

V Internal structure & EOS

An excellent tutorial by Chris Pethick dealt with neutron rich matter at subnuclear densities and its implication for neutron star crusts. The bulk and surface properties of such matter were discussed and non-spherical shapes predicted for the nuclei in the crust (... spaghetti, lasagna...). The main points were that at low density, the nuclear attributes of neutron star crusts are determined directly by properties of nuclei, like their masses, that can be obtained in the laboratory. But at increasing density, a greater degree of theory is required to deduce these attributes. On the matter of experimental data, Gerry Brown discussed the most recent conclusions from the interpretation of heavy-ion collision experiments at CERN and GSI Darmstadt which indicate a softening of the EOS at 2 to 3 times nuclear matter density. He made a case for negative kaon condensation which would lead to a soft EOS and give a maximum neutron star mass of 1.5 $M_\odot$ and a corresponding radius of 7 km.

On the matter of constraining the EOS several presentations touched on possible observational probes. Jan van Paradijs discussed the masses and radii of neutron stars, and as already mentioned concluded that masses do not tell us anything definite. On the other hand, the radius relates to the red shift and hence to the luminosity, and thus X-ray bursts could be used to constrain radii. A different form of X-ray emission also leading to constraints are the newly discovered "kiloHertz" quasi periodic oscillations in low mass X-ray binaries. Michiel van der Klis described remarkable observations with NASA's RXTE satellite of six sources (now ten) which displayed oscillations in the range 500 to 1200 Hz. Most of the sources showed double peaks separated by a few hundred Hz, and which move up and down in frequency together. In an exceptionally interesting presentation, Fred Lamb described a new model aimed at explaining these observations. In this Sonic Point model, the higher frequency is the Keplerian one at the sonic point at the inner edge of the accretion disk, and the lower is the beat between this and the 150 to 500 Hz spin frequency of a weakly magnetic (10^7 to 10^9 Gauss) neutron star, a millisecond pulsar in the making! A relativistic treatment of the problem shows that if the kiloHertz QPOs are indeed Keplerian frequencies, their measurement will provide new bounds on masses and radii of neutron stars, in turn constraining the EOS at high densities.

One more very fine contribution connecting X-rays and the EOS by Bhaskar Datta illustrated GR effects (frame dragging) of rotation on disk and boundary layer luminosities for disk accretion on to low magnetic field neutron stars. The X-ray emission will depend on the thinness of the boundary layer which in turn depends on the EOS. Finally on the topic of X-rays, a very important all sky monitoring programme using BATSE was reported on by Tom Prince. Half of the 43 known X-ray pulsars were detected and an impressive data base on their timing and spectral behavior has been accumulated, which is available to the public.

VI Magnetic field

I come now to the last—but far from least important—topic, namely the magnetic fields of neutron stars on which there were seven presentations all devoted to aspects of their evolution. Dipankar Bhattacharya set the scene by reviewing the current models for the evolution of the field subsequent to its creation at or soon after the birth of the neutron star when it attains its canonical value of 10^{12} G. The present belief is that this value remains constant for the rest of the life of the star unless it is a member of a binary system, when interaction with the companion appears to result in the decay of the dipole field strength. Among the mechanisms for this decay, in roughly decreasing order of credibility (mine), are the outward transport of magnetic fluxoids to the crust during spin down followed by ohmic decay due to impurities in the inner crust, and movement of crustal plates towards the equator where poles come together and reconnect. A second class of models where the initial magnetic field is all in the crust, invokes enhanced resistivity due to heating during accretion, or the screening of the field by the accreted diamagnetic plasma burying it, the latter scheme being unlikely to succeed because of Rayleigh-Taylor instabilities with microsecond time scales.

The movement of neutron star crustal plates was the brainchild of Mal Ruderman who has pursued the consequences of such readjustments for many years now. Apart from the diminution of the dipole field strength mentioned above, there are numerous other consequences (e.g., shape change of the pulsar beam) which Mal has been investigating and which he discussed in a presentation following Dipankar's. A pitch for much higher field strengths at birth than generally believed was made by Shri Kulkarni who suggested that many pulsars may be born with 10 to 1000 times the canonical value of 10^{12} Gauss. As supporting evidence for this hypothesis were cited weak plerions in most SN remnants, break frequencies $< 10^{11}$ Hz, and soft gamma ray repeaters, the last of which were to be explained as neutron stars with fields around 10^{15} G which have evolved to periods of 8 seconds or so in times of the order of 10^4 years.

Among the contributed papers on this topic was one by Muslimov on the field evolution in millisecond pulsars, and another by Itoh on a Monte Carlo simulation to investigate the claimed velocity-field correlation, which it failed to find support for, like several previous investigations. Frank Verbunt reported on an improved population synthesis of single radio pulsars with $B > 10^{11}$ G, which confirmed that the time scale for field decay was > 30 Myr, and that a fair number of neutron stars are born with velocities less than 200 km/s. The derived birth rate is compatible with formation in OB associations from progenitors with $M > 10$ $M_{\odot}$, and with no need for a second population in addition to those formed directly from Type II supernovae.

The more difficult question of how the neutron star field was created in the first place was tackled by Sterl Phinney in his characteristically original style. That he also provided an explanation of the spin of the neutron star in the bargain made this easily the star (unavoidable) contribution to the Colloquium. Also the one most difficult to follow in real time because of the large number of complicated physical phenomena in stellar evolution which were dealt with in typical rapid fire sequence. The message that I was left with at the end was that in the course of the evolution most of the angular momentum ends up in the envelope and the core of the progenitor is left with very little. The resulting huge differential rotation drives something known as the Balbus-Hawley instability to create the magnetic field. On collapse, the field will have a value of less than 10^{12} G going up to 10^{13} G, if the progenitor goes through a bare He star phase, and it is conjectured that if there is convection in young neutron stars, the field could go up to 10^{14}–10^{15} G.

But as far as the spin is concerned, it is unlikely to be less than 1 second and probably very much slower if due only to angular momentum conservation. An alternative mechanism is needed to explain short periods and it was pointed out that the asymmetric kicks now recognized as being essential to explain pulsar velocities, are surely likely to also impart angular momentum to the star and spin it up. The physical model is uneven removal of neutrino momentum by convection cells, and a correlation of short periods with high kick velocities is predicted by the model. But it seems to me that if the spin due to angular momentum conservation happens to be non-negligible, then the impulse could either add to or subtract from the rate depending on the kick direction. We saw earlier that in the case of pulsar J0045−7319 it was deduced that the direction of the kick must have been such as to change the direction of the orbit. Perhaps it was also such as to counter the "conserved" spin of the neutron star making it as slow at birth as deduced from the considerations described earlier.

One final thought is regarding the developments that have taken place since the Bonn Pulsar Symposium in 1980. I came away from that meeting after listening to Ed's and Joe's talks there, convinced that even if the relative number of binaries was very small, their study would teach us a great deal even about single pulsars. The discussions at this meeting seem to have amply justified that expectation. And that brings to an end my summary of the scientific part but not of the whole programme.

VII Good times

At the end of the second day, a delightful boat trip along the beautiful canals of Amsterdam was laid on and followed by a magnificent conference dinner in arguably the very best restaurant in the city. Ed, our host, took this opportunity to entertain us with the history of Anton Pannekoek, who 75 years ago founded the Institute now named after him. It was a fascinating story about a very independent and colorful character which most of us participants were quite unaware of, and so glad to hear. I would also like to mention here Matthew Bailes' impromptu post-prandial contribution in which he expressed so well what all visitors to the Pannekoek Institute have felt, namely the warm, friendly and scientifically stimulating atmosphere that Ed has engendered there. And the same is true for meetings organized by Ed, of which the present one was an excellent example. I am sure I speak on behalf of all the participants and guests in expressing our appreciation and thanks for a rewarding and enjoyable Colloquium.

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