Pulsar throws up problems

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In the 9th November issue of *Nature* Ables *et al.*[1] report detailed measurements of the properties of the millisecond pulsar PSR 0021−72A discovered by them more than a year ago[2] in the globular cluster 47 Tucanae, one of several hundred compact stellar systems orbiting around the disc of our galaxy. Their results indicate that this is indeed the most remarkable of all radio pulsars discovered so far. The pulsar has a spin period of 4.5 milliseconds, and the arrival times of the pulses show a periodic modulation, suggesting that the pulsar is in a binary system with an orbital period of only 32 minutes and a large eccentricity (~ 0.32)!

A very close orbit such as this is expected to show strong general-relativistic effects, and indeed Ables *et al.*[1] have been able to measure two important relativistic parameters of the orbit—the rate of periastron advance $\dot{\omega}$, and the amplitude γ of 'Einstein delay' which arises from a combination of the gravitational redshift and the transverse Doppler shift in the orbit. These measurements have enabled Ables *et al.*[1] to obtain a complete solution for the parameters of the binary system and, in particular, to determine the mass of the pulsar and its companion. These turn out to be $\sim 1.4\,M_\odot$ and $\sim 0.8\,M_\odot$, typical for a neutron star and a white dwarf respectively.

However, there are several surprising implications of this result. The first of these is that we are viewing the orbit almost face-on: the angle i between the line of sight and the normal to the plane of the orbit is only ~ 0.38 degrees. The *a priori* probability of viewing an orbit so nearly face-on is very small, $\sim 2\times 10^{-5}$!

One encounters further surprises in trying to understand the origin and evolution of this object. Millisecond pulsars in the galactic disc, as well as in globular clusters, are best understood as being spun up owing to accretion from a mass-donating companion in a binary system[3–5]. The duration of mass transfer necessary to spin up the neutron star to millisecond periods demands that the mass-donating companion be a slowly evolving low-mass star ($\leqslant 1\,M_\odot$). At the end of the mass transfer such a star is expected to leave a 0.2–0.4 $M_\odot$ white dwarf in a nearly circular orbit around the neutron star[6]. Since the neutron star is spun up at the expense of the orbital angular momentum, one also expects the spin axis of the pulsar to coincide with the normal to the orbital plane. In those cases where the initial binary system is very compact, the outcome would probably be an isolated millisecond pulsar, the radiation from which would have evaporated[7] the companion star.

None of these expectations, however, fits the properties of the millisecond pulsar PSR 0021−72A. Its white dwarf companion is too heavy to be the end product of the evolution described above. The fact that we are looking at the orbit face-on, and yet see narrow pulses from the pulsar, suggests that the spin axis of the neutron star must be inclined at a fairly large angle to the orbit normal. Further, the observed eccentricity of 0.32 would be completely unexpected after a mass transfer evolution. All this points to the inescapable conclusion[1,8] that the pulsar did not get spun up in the present binary system.

How, then, did this system originate? The only possibility seems to be[1,8] a close encounter of a $\sim 0.8\, M_\odot$ white dwarf (the present companion of the neutron star) with the binary system in which the pulsar was spun up. Given suitable circumstances, such an encounter would lead to the formation of a temporary triple system from which the least massive member (presumably a low-mass white dwarf left after the mass-transfer evolution) would be eventually ejected, leaving an entirely new binary system, which we now observe. Given the extremely high number density of stars in the core of a globular cluster, the formation of a few such systems over the $\sim 10^{10}$ yr lifetime of the cluster is not unlikely.

Though this appears to be a reasonable scenario for the origin of the present system, one still has reasons to worry. The orbit of such a tight binary will decay very rapidly owing to gravitational radiation, and this would lead to a coalescence of the components in only $\sim 10^6$ yr from now. Similar arguments[1,8] regarding the past evolution of the system imply that it could not have formed more than 10^8 years before present. Thus, for the origin of the present system, one needs a rare event (with an average rate of occurrence of once in $\sim 10^{10}$ years) to have taken place very recently ($\lesssim 10^8$ years ago) and, further, that we observe the system during the final $\sim 1\%$ of its lifetime. Remarkable and rather uncomfortable coincidences!

Bothered by the improbability of this system, Lyne[9] has proposed some alternative interpretations of the observed modulation of pulse arrival times, such as that arising from a precession or a torsional oscillation of the neutron star, or perhaps a binary system with a much larger angle of inclination i and a correspondingly small companion mass ($\sim 4 \times 10^{-3}\, M_\odot$). A closer inspection shows, however, that none of these is really viable. Indeed, the possibility of a much larger angle of inclination has in fact been considered and ruled out by Ables *et al.*[1] and Wijers[8]. A planetary-mass companion as suggested by Lyne[9] would be much larger than the size of the Roche lobe—the critical size beyond which the neutron star will tidally strip matter from the object—unless it is made up entirely of heavy elements like plutonium(!); and even then the tidal distortion of the body would be so large as to produce a much higher rate of periastron advance ($\dot{\omega}$) than observed. As shown by Wijers[8], the measured rate of periastron advance already restricts the inclination angle i to well within a degree and constrains the companion mass to be larger than 0.2–0.3 $M_\odot$.

There are also major difficulties surrounding the other possibilities suggested by Lyne[9]. If the observed modulation of pulse arrival times arises owing to a phase modulation rather than a binary motion, then the required semi-amplitude of such a phase modulation would be larger than π, while the maximum semi-amplitude of phase modulation that can be obtained from precession is only $\pi/2$ (beyond this the apparent spin frequency gets redefined, but the modulation stays within $\pi/2$). Thus the observed behaviour of the pulse arrival times cannot be explained by a precession of the neutron star. A torsional oscillation of the crust with respect to the core can, of course, produce phase modulation of arbitrarily large amplitudes[10], but it is very difficult to imagine how such a process could mimic the effects of periastron advance or the Einstein delay in a binary orbit. Moreover, even if such a scenario *could* explain the observations, it would still make this pulsar very special, since no other known radio pulsar exhibits a similar behaviour.

Thus, with no viable alternatives at present, one has to accept the interpretation of Ables *et al.*[1] despite its improbability. If we do so, then there may be another important lesson to be learnt from this pulsar. The small probability of our being able to observe such a system perhaps suggests that the number of millisecond pulsars produced in globular clusters is more than what is commonly believed. But a serious problem arises in comparing the number of millisecond pulsars inferred in globular clusters with the number of low-mass X-ray binaries (LMXBs), the progenitors of these objects. If one adopts the conventional lifetimes for low-mass X-ray binaries then it appears that the number of millisecond pulsars are far too many to be descendents of LMXBs[11,12]. A similar problem also exists in the galactic disc[13]. This problem may not arise if the lifetimes of low-mass X-ray binaries have been overestimated, and this is likely if the mass accretion onto the neutron star terminates much earlier than one thought. A mechanism for this has in fact been suggested by Ruderman *et al.*[7], in which the radiation and wind from the spun-up pulsar prevents further accretion. One consequence of such an evolution would be that the neutron star would accrete only $\sim 0.1\, M_\odot$ and end up with a total mass of ~ 1.4–$1.5\, M_\odot$, as opposed to the standard models in which the matter accreted amounts to $\gtrsim 0.6\, M_\odot$, and the final mass of the spun-up pulsar is close to $\sim 2\, M_\odot$. Interestingly, the derived mass of the pulsar PSR 0021 − 72A is only $\sim 1.4\, M_\odot$. This, for the first time, provides a direct observational support for an early termination of mass transfer and a reduced lifetime of low-mass X-ray binaries[11].

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