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Letter to the Editor

The new binary millisecond pulsar PSR 0021–72A: a laboratory for gravitational physics

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Summary. The recently discovered binary millisecond pulsar PSR 0021–72A in the globular cluster 47 Tuc has some remarkable properties. The orbit is viewed almost exactly face-on. The measured rate of precession of periastron and the predicted rate of geodetic precession are greater by nearly 2 orders of magnitude than in the classical binary pulsar PSR 1913+16, and tidally induced apsidal motion may play a role. The observability of pulses in directions nearly perpendicular to the orbital plane suggests that the system has large angles between the pulsar spin axis and the normal to the orbit. This, together with other considerations, implies that the system was probably formed by interaction of a third body with a low-mass X-ray binary in the cluster core. Accurate position measurements may well find it to be outside the cluster core. Its future lifetime is not likely to be more than 4 Myr.

Key words: gravitation — relativity — pulsars: individual — stars: binaries: close — stars: collapsed

1. Introduction

Recently, two binary millisecond pulsars (0021–72A&B) were discovered in the globular cluster 47 Tucanae (Ables et al., 1988). One of them (A) turns out to have most remarkable parameters. These are: $P_{orb} = 1924.3 \pm 0.3$ s, $e = 0.33$, $P_{pulse} = 4.478953$ ms, $f(M) = 1.61 \times 10^{-8}$ $M_\odot$, $a_1 \sin i = 585$ km. During a colloquium in May, Ables reported a measured value of 0.6 deg/day for the periastron advance (Dr. D. Backer, private communication).

In view of the short orbital period, the companion must be a white dwarf or a neutron star. In the case of a white dwarf companion, there may be a considerable tidal contribution to the periastron advance. I discuss this in section 2. In section 3, possible formation scenarios for the system are discusssed. Subsequently (sect. 4 and 5), I discuss globally some complications not included in the model.

2. The model

We assume the secondary to be either a white dwarf or a neutron star. The orbit is Keplerian with two perturbations: a periastron advance due to general relativity (Shapiro and Teukolsky, 1983, sect. 16.5) and one given by (Newtonian) tidal apsidal motion (Schwarzschild, 1958, sect. 18). The latter depends on the internal structure of the binary members through their so-called 'apsidal motion constant' k. The pulsar's radius is too small for it to contribute to $\dot\omega_{tid}$. To be specific, we take white dwarf companions to be ideal $n = 3/2, \mu_e = 2$ polytropes, with

$$k_2 = 0.14660 \qquad \text{(Motz, 1952)} \tag{1}$$

$$R_2 = 0.0128\, m_2^{-1/3} \qquad \text{(Shapiro and Teukolsky, 1983)} \tag{2}$$

Making use of the observed quantities and the relation

$$m_2 \sin i = f(M)^{1/3} m^{2/3} \tag{3}$$

we can write the two contributions to the periastron advance as :

$$\dot\omega_{GR} = 126\, m^{2/3} \qquad \text{deg/yr} \tag{4}$$

$$\dot\omega_{tid} = 2.20\, m_1 m_2^{-8/3} m^{-5/3} \qquad \text{deg/yr} \tag{5}$$

(masses and radii are in solar units). The labels "1" and "2" refer to the pulsar and the companion, respectively, and $m = m_1 + m_2$. The condition that the sum of $\dot\omega_{GR}$ and $\dot\omega_{tid}$ must equal the observed 220 deg/yr defines a curve in the (m_1, m_2) plane (Fig. 1).

From the approximate relation for the Roche lobe radius

$$\frac{R_L}{a} = 0.46\, q^{1/3} \qquad \left(q = \frac{m_2}{m_1}\right) \tag{6}$$

and the requirement that the companion not overfill its Roche lobe at periastron we obtain a constraint on m_2 :

$$m_2 > 0.044 \left(\frac{m_1}{m}\right)^{1/2} \tag{7}$$

In reality, the radii for objects less massive than about 0.1 $M_\odot$ are significantly smaller than the ones predicted by eq. 2. If one uses a better mass-radius relationship in this regime (Zapolsky and Salpeter, 1969), one finds the lower limit to the companion mass to be about 0.02 $M_\odot$, nearly independent of the pulsar mass. For canonical neutron star masses (1.2–2.0 $M_\odot$), the companion mass implied by the observed periastron advance (Fig. 1) is much greater than this limit.

From Fig. 1, it is seen that — for most neutron star masses — there are two possible companion masses. On the high-mass branch (marked "H" in all figures), the radius of the companion is too small to cause noticeable tidal periastron advance; it could also be a neutron star. On the low-mass branch ("L"), its mass is 0.2–0.3 $M_\odot$ and its radius is large enough to give rise to a significant $\dot\omega_{tid}$. A maximum possible pulsar mass is seen to exist for each measured value of $\dot\omega$. For the reported value of 0.6 deg/day, this mass is 1.7 $M_\odot$.

The large eccentricity suggests that the system is young. This is quantified in Fig. 2a, in which is plotted, as a function of pulsar mass, the system's characteristic time for decay of a due to gravitational radiation, defined by :

$$\frac{1}{a}\frac{da}{dt} \equiv \tau_a^{-1} \tag{8}$$

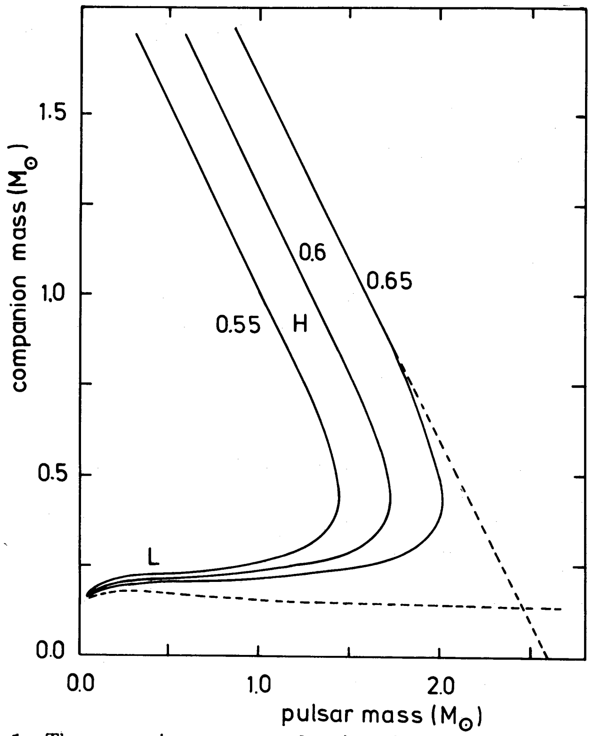

Fig. 1. The companion mass as a function of pulsar mass. The solid curves differ in the value of the observed $\dot{\omega}$, by which they are labelled. The dashed curves are for $\dot{\omega}_{obs} = 0.65$, if only tidal (lower curve) or general relativistic (upper curve) advance were present.

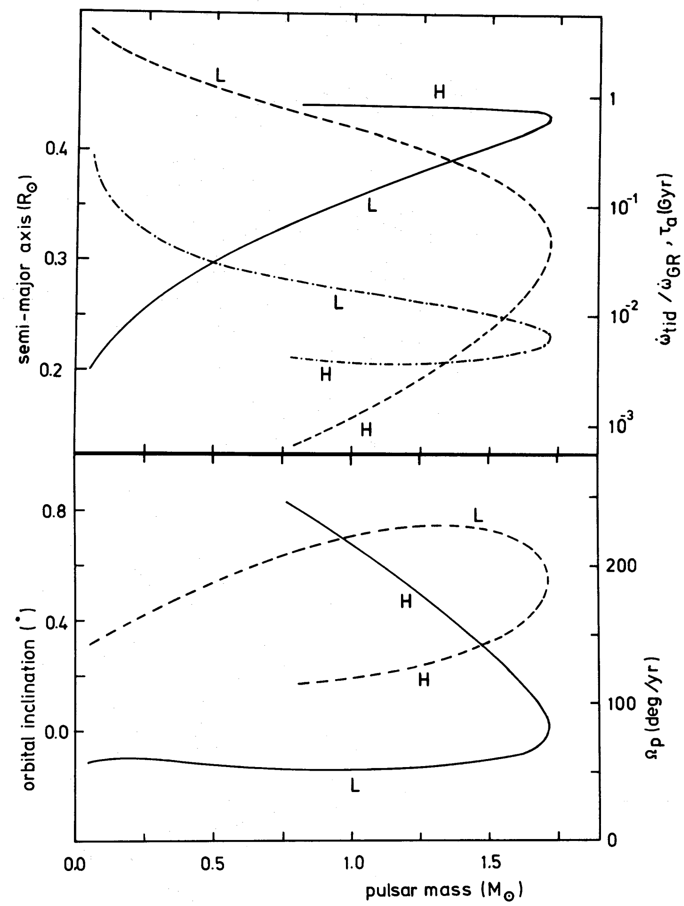

Fig. 2. *upper panel:* The semi-major axis a (solid), the characteristic decay time τ_a (dashed-dotted) and the ratio f of $\dot{\omega}_{tid}$ to $\dot{\omega}_{GR}$ (dashed) for both branches versus pulsar mass. *lower panel:* The geodetic precession (solid) and the inclination (dashed). It is seen that the large Ω_p is a sensitive tool to discriminate between branches.

(see Peters, 1964, sect. 5 for formulae on gravitational radiation and its influence on a binary orbit).

The system's present decay time is not more than about 30 Myr. The semi-major axis is plotted on the same figure. It is independent of the pulsar mass on the high-mass branch, because there the only contribution to the periastron advance is the general relativistic one, which depends on the total mass only (eq. 4). The relative importance of the two advances is shown by the third curve in Fig. 2a, that represents the ratio f of the tidal to the general relativistic advance. In Fig. 2b, the inclination is plotted as a function of pulsar mass. It is always less than 1°, indicating that we see the system in the (a priori unlikely) face-on position.

3. Formation scenarios

The difficult part of finding a formation scenario for the system is its eccentricity, because this makes it unlikely that the system was formed by a spiral-in, following either a common-envelope phase in the evolution of a binary or capture of a white dwarf (or neutron star) by a giant. Although the spiral-in process is not well understood (for recent discussions, see De Kool, 1987 and Livio and Soker, 1988), it seems hard to imagine the system retaining such a large value (0.33 or greater) of the eccentricity.

3.1. Accretion induced collapse

One possible origin for the system, in which an eccentricity is a natural consequence, is the formation of the neutron star by accretion induced collapse of a white dwarf. The primary looses some gravitational mass, equivalent to the neutron star's binding energy, while retaining its orbital velocity. Like in the case of supernova shell ejection at the end of massive star evolution, this introduces an eccentricity given by :

$$e_f = \frac{m_i - m_f}{m_f} \tag{9}$$

where m_i and m_f are the initial and final system mass, respectively. Taking a white dwarf with a baryonic mass of 1.44 $M_\odot$ that collapses to a homogeneous sphere of radius 10 km, we expect the mass-equivalent of the binding energy released to be 0.18 $M_\odot$. The eccentricity thus obtained (using $m_2 = 0.25\ M_\odot$, Fig. 1) is only 0.12. The system has to lose 25% of its total mass to obtain $e = 0.33$. However, borrowing an idea from discussions about supernovae in massive stars, one may think the collapse to be asymmetric and introduce a kick velocity that can increase the eccentricity. Note that the centre-of-mass speed due to this kick cannot be allowed to exceed the escape speed from the core, which is 56.8 km s^{-1} for 47 Tuc (Webbink, 1985).

To see if the formation by accretion induced collapse is possible without kicking the system out of the cluster, one may proceed in the following manner. Given a mass change, one can compute the kick speed needed for each direction to obtain the observed a and e from a circular pre-kick orbit. Next, one can evaluate the resulting system speed relative to the cluster core (assumed zero initially), and investigate the range of kick directions that keeps this speed below the escape speed.

One must also account for the fact that the system may have evolved after collapse due to gravitational radiation. There exists a unique relationship in closed form between a and e of an orbit decaying due to gravitational radiation (Peters, 1964). Using that relationship, the orbit was evolved back in time, and for each time the range of allowed kick angles was investigated assuming that the orbit at that time was the one immediately after the collapse. The range of allowed directions is greatest if

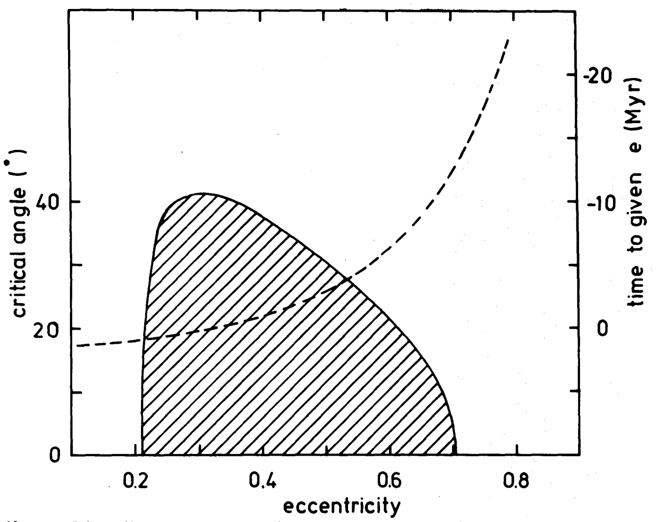

Fig. 3. The allowed range of kick angles as a function of past e for a core escape speed of 56.8 km s^{-1} in the case of a high mass companion and kick perpendicular to the radius vector. The allowed region is hatched. The dashed curve gives the age corresponding to each past e if orbital evolution is by gravitational radiation only.

the kick direction is perpendicular to the radius vector of the relative orbit and such that the point of collapse becomes the new periastron.

The case investigated was that of a 1.26 $M_\odot$ neutron star originating from a 1.44 $M_\odot$ white dwarf both for the low-mass (0.25 $M_\odot$) and the high-mass (1.04 $M_\odot$) companion allowed by the observed $\dot{\omega}$ of 0.6 deg/day. In Fig. 3, the result is shown for the most favorable case (high mass companion). It is seen that the critical angle, at which the binary escapes exactly, does not exceed 41° for any possible past eccentricity. The age of the system (negative in the past) is plotted on the same figure.

The qualitative behaviour of the critical angle as a function of post-kick eccentricity can be understood as follows: from Fig. 4 (dashed curve), we note that the radius of the progenitor orbit hardly increases with increasing eccentricity. The main effect is then that getting a greater post-kick eccentricity requires a greater kick speed. The final velocity of the centre of mass, $\vec{v}_{CM}$, is:

$$\vec{v}_{CM} = \frac{m_{1f}\vec{v}_K - dm\vec{v}}{m_f} \tag{10}$$

in which $\vec{v}_K$ is the kick velocity, $\vec{v}$ the initial orbital velocity and m_{1f}, m_f and dm are the final pulsar mass, final system mass and mass lost from the system, respectively. At low eccentricities, the required kick is so small that it cannot compensate the large recoil speed (i.e. the speed caused by the mass loss alone, second term in eq. 10) for any kick direction and the system escapes; at too large a post-kick eccentricity, the converse is true: the kick dominates and cannot be compensated by the recoil.

If one assumes the kick velocity to be randomly oriented, an upper limit to the probability of accretion induced collapse not causing escape is the fraction of solid angle subtended by all directions less than ϕ_{cr} from the direction of the orbital velocity, and is given by:

$$P_{NE} \doteq \frac{1}{2}(1 - \cos\phi_{cr}) \tag{11}$$

(it is an upper limit because the opening angle of the allowed cone is less in all planes not perpendicular to the radius vector of the relative orbit). The values of P_{NE} are 12% in both optimum cases, but more typical values are nearer 2–3%. The angle between the old and new orbital angular momenta (equal to the angle between the pulsar spin axis and the normal to the new orbit if (i) the white dwarf rotation axis was aligned with

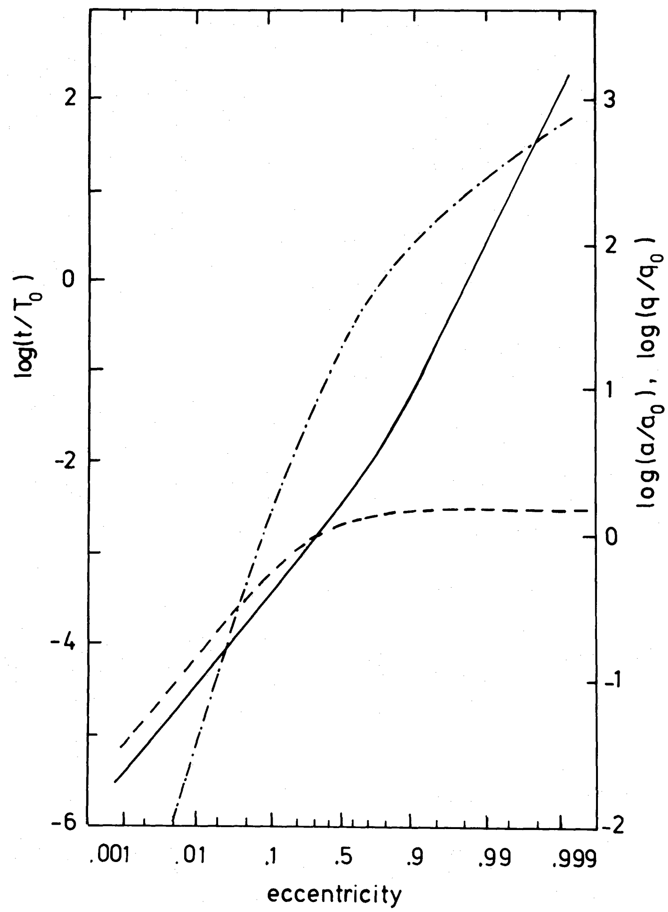

Fig. 4. The relationship between e and a due to gravitational radiation decay (full line). Note the rapid increase of a with e. Dashed curve: periastron distance at the time when the eccentricity was e, divided by its present value (this equals the pre-collapse orbital radius divided by the present periastron distance for the case that the abcissa is the eccentricity immediately after collapse). Note its near constancy for large e. Dashed-dotted: the time, divided by T_0, for the system to decay to $a = 0$. T_0 is 83 and 23 Myr for the high and low mass case, respectively. To emphasize the regions near $e = 0$ and $e = 1$, the abcissa is linear in $\log[e/(1-e)]$.

the normal to the pre-kick orbit due to accretion and (ii) the spin axis was not tilted during the collapse) can in neither case become greater than 5°. In short, it appears that the formation through accetion induced collapse is rather unlikely.

3.2. Alternative scenarios

Since accretion induced collapse and normal spiral-in scenarios are unlikely, we are left with the possibility of forming the system by a three-body interaction between a binary and a normal star. If the neutron star was not formed by accretion induced collapse then it must be primordial. It is spinning with 4.5 ms period, so it must have been spun up and to achieve spin-up to such a short period, it must have a low field. It is hard to imagine the system to be a double neutron star. The progenitor of such a system would have to be a primordial massive binary, and the system would have coalesced by now (unless it was born with an eccentricity greater than 0.999, see Fig. 4).

I therefore propose that the system's progenitor was an ordinary low-mass X-ray binary (LMXB) or a descendant thereof. It encountered either a main-sequence star or a giant (the probability for this to happen to a binary in the core of 47 Tuc within a Hubble time is appreciable, see Verbunt and Meylan, 1988), and the resulting triple system went through one of the following phases:

1. An exchange interaction between the binary and the star in which the former neutron star companion was expelled. In the case of a giant, spiral-in of the LMXB may occur before the old companion is expelled, but a sizeable eccentricity can still be induced. The giant's envelope is ejected during this process or is left behind as both the narrow new binary and the — now single — companion move off.

2. The passage of the third star at close distance, inducing the eccentricity and shrinking the orbit. Since the probability of shrinking the orbit by a large amount is small in this case, the progenitor binary must have been a close LMXB, i.e. one with a main-sequence companion.

In all cases of three-body interaction, one expects (*i*) the neutron star's spin axis to be non-aligned with the orbital angular momentum axis, as is suggested by the observations, and (*ii*) a low mass of the companion (like that of the core of a typical incompletely evolved star in 47 Tuc) to be most probable.

The exact probabilities of any of the above occurring have not been computed and it is not certain that they are much greater than P_{NE} of the previous section.

4. Distinguishing high-mass and low-mass companions

It has been argued above, that the neutron star's spin axis and the orbital angular momentum are probably not aligned; we may therefore use the geodetic precession of the neutron star's spin axis to learn more about the system. The rate of precession is given by:

$$\Omega_p = 63\,\frac{m_2(4m_1 + 3m_2)}{m^{4/3}} \qquad \mathrm{deg/yr} \tag{12}$$

(see Smarr and Blandford, 1976, eq. 2.10). As displayed in Fig. 2b, the spin precession is nearly independent of m_1 on the low-mass branch, whereas it varies strongly on the high-mass one. In case the neutron star mass is not very near 1.7 $M_\odot$, even a crude measurement of the (always substantial) precession decides between branches.

5. Other complicating effects

In the above discussion, many complicating effects have been neglected; a brief list of some them is given here.

1. A misalignment of the pulsar and orbital angular momenta will imply precession of both around the total angular momentum. The observed '$\dot{\omega}$' is then really a combination of regression of the nodes (caused, e.g. by fast rotation of the companion) and precession of the longitude of periastron ω.

2. Orbital energy may be dissipated in the companion.

3. Companion evaporation due to the pulsar flux, as observed in PSR 1957+20 (Fruchter et al., 1988; for a theoretical dicussion see Ruderman et al., 1988a,b, Phinney et al., 1988 and Van den Heuvel and Van Paradijs, 1988) will cause an increase of a and e, thus opposing the effects of gravitational radiation.

4. Near $e = 0.33$, the ratio of periastron to mean angular velocity is 2:1. A tidal wave in the secondary, returning with the same phase at each peristron passage, may cause a resonant locking of the system in this orbit, like in the case of Mercury (3:2 resonance, Hut, 1981). The effect will be less here because the companion is not a rigid body, but some halting of the evolution may occur.

The effects in (1) and (2) are treated in detail by Smarr and Blandford (1976).

6. Conclusion

The binary system containing the pulsar PSR 0021–72A was most likely formed by a collision between a low-mass X-ray binary and a (main-sequence or giant) star. This mechanism accounts for the large angle between the pulsar spin axis and the orbital angular momentum, that is inferred from the fact that the pulsar beam swipes the earth despite the fact that we observe the orbit nearly face-on. By implication, the angle between the pulsar spin and field axes might be large as well (this may be seen in the details of the pulse shape). As a result of the narrow three-body encounter that formed the system, its velocity relative to its place of birth, the cluster core, is expected to be large. An accurate position measurement will have to show whether it is indeed found outside the cluster core, as this scenario predicts.

Finally, all relativistic effects are so much greater in this system than in the classical binary pulsar PSR 1913+16 (Hulse and Taylor, 1975; Taylor and Stinebring, 1986 and references therein), that one may hope to measure higher-order relativistic effects and, if the companion is on the low-mass branch, interesting Newtonian perturbations, although it will then be hard to discriminate between the various effects.

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Note added: After completion of this manuscript we received a telex from Dr. Ables indicating that several of the above conclusions have been drawn independently by his group.

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