INTERPRETATION OF BINARY PULSAR OBSERVATIONS

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ABSTRACT

The nature, dynamics and evolution of the three known radio pulsar binaries are discussed. The system containing 1913+16 appears to comprise two $\sim 1.4\ M_\odot$ components, and to undergo orbital decay as predicted by general relativity. It is proposed that 1913+16 has a neutron star companion and that 0655+64 and 0820+02 have white dwarf companions which should be observable optically.

INTRODUCTION

There are now three known binary radio pulsars, 1913+16, 0655+64, 0820+02 (Taylor, this volume). All three have companions with mass $\sim 1\ M_\odot$. Of the remainder of the sample of ~ 330 pulsars, roughly 230 have been monitored sufficiently carefully to exclude the presence of companions of mass $\gtrsim 0.01\ M_\odot$ with periods in the range $1\ \mathrm{hr} \lesssim P_b \lesssim 10\ \mathrm{yr}$ (Lamb and Lamb 1976, Manchester et al. 1980). We must wait until the complete sample has been monitored with an arrival time accuracy ~ 1 ms to be sure that there are no more binaries present in it. As they are dissimilar systems, we consider the three known binaries in turn.

1913+16

This source was discovered by Hulse and Taylor (1975) and six years of careful monitoring of the arrival times with r.m.s. accuracy $\sim 80\mu$s have yielded measurements of the five Keplerian orbital elements ($a_1 \sin i$, e, P_b, ω_o, T_o) together with non-zero measurements of $\dot{\omega}$, $\dot{P}_b$, the relativity parameter γ and an independent determination of sin i from the $O(v/c)^3$ terms (Taylor, this volume). There is no detectable orbital variation in either the dispersion measure or the residuals. This supports the hypothesis that the components behave dynamically as point masses. Using general relativity we have, $\dot{\omega} = 6\pi Gm/c^2 P_b a(1 - e^2)$ and $\gamma = 2\pi a_1{}^2 e(2 + m_1/m_2)/c^2 P_b$. Both of these formulae are accurately

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tested in the solar system in the test particle limit $m_1 << m_2$ and we can use them with confidence. Combining them with the mass function, $f_1 = m_2^3 \sin^3 i/m^2$ allows a solution: $m_1 = 1.43 \pm .05\ M_\odot$, $m_2 = 1.40 \pm .05\ M_\odot$, $\sin i = 0.73 \pm .03$. The independent determination of sin i (0.7 ± .3) is dominated by the gravitational time delay (Blandford and Teukolsky 1976, Epstein 1977) which is also tested within the solar system. That these two determinations of sin i agree within error is consistent with the system being dynamically clean. General relativity now allows a novel prediction; that the secular change in the orbit period be due to emission of quadrupole gravitational radiation with $\dot{P}_b = -2.4 \times 10^{-12}$, insensitive to γ and sin i. The measured value is $\dot{P}_b = (-2.1 \pm .4) \times 10^{-12}$ (Taylor, this volume). Gravitational acceleration within the galaxy will not influence this measurement unduly (Shapiro and Terzian 1976).

As well as providing impressive confirmation of a high order, quantitative prediction of general relativity, these measurements can also be used to rule out several alternative theories of gravity (Will 1979). In many alternative theories, such as Brans-Dicke theory, dipole gravitational waves will be radiated if one component possesses a large binding energy (e.g., a neutron star). This does not occur in general relativity. Furthermore, some theories allow the energy of the orbit to increase and this can also lead to acceleration of the barycenter. Dipole radiation will not however be present if both components are sufficiently similar (Eardley 1975). As this is a real possibility, it is worth noting that the quadrupolar contributions in many of these theories are also of opposite sign to those furnished by general relativity and so these theories can definitely be excluded on the basis of the present measurements (Weisberg and Taylor 1980 preprint). There has been some controversy in the literature as to whether or not the slow motion, weak field computation of $\dot{P}_b$ in general relativity is indeed correct (e.g., Ehlers et al. 1976 and references therein). Recently, Walker and Will (1980 preprint) have made further progress toward alleviating these anxieties.

The effect of geodetic precession has apparently not yet been detected. With the above dynamical solution, the observed pulsar colatitude should decrease at a rate $0.87 \cos \eta°\ yr^{-1}$ where η is the position angle of the spin axis or the sky relative to the ascending node (Hari-Dass and Radhakrishnan 1975, Smarr and Blandford 1976). Either the spin and orbital angular momenta are aligned ($\eta = 90°$) or the pulsar has a roughly circular beam of radius $\gtrsim 20°$. In either case, we should have at least 30 yr to observe this pulsar. Other calculable changes in the pulse shape (e.g., aberration, rotation of the plane of polarization) are not presently observable.

In spite of the impressive agreement between the calculation and the measurement of $\dot{P}_b$, it is strictly still possible for this to be fortuitous and that there be Newtonian contributions to both $\dot{\omega}$ and $\dot{P}_b$. Both helium star and rapidly spinning white dwarf companions could cause this (Roberts et al. 1976, Smarr and Blandford 1976). In fact there is

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an optical object coincident (to within $\sim$0.3") with the position of the binary pulsar ($m_R \sim 21$, $m_V \sim 22.5$) (Kristian et al. 1976, Crane, Nelson and Tyson 1979, but see Elliott et al., this volume). This could be a hot helium star at 5 kpc although if the estimated reddening is $A_V = 3.3^m$ (Davidsen et al. 1975) then it is apparently far too red for its luminosity. (There is no optical pulsation reported from this object to $m_R \gtrsim 26$ (Nather et al. 1977).) However, although we cannot be completely confident of this, it seems unlikely that a helium star could produce so little dispersion or scattering within the orbit (e.g., Ozernoi and Reinhardt 1975) or tidal dissipation (Smarr and Blandford 1976). Furthermore, the limit on a secular change in i indicates that a white dwarf that is spinning rapidly enough to influence $\dot{\omega}$ at the ten percent level through its quadrupole gravitational field must be better aligned with the orbital angular momentum than $\approx 10'$. Dynamical models along these lines now seem even more contrived than they did when they were first proposed.

Evolutionary arguments indicate that the companion is most likely to be a neutron star (e.g., Flannery and van den Heuvel 1975, Webbink 1975) or black hole (e.g., Bisnovatyi-Kogan and Komberg 1976) although white dwarf and He-star companions are not excluded. In favour of the former possibility is the fact that both component masses appear to be close to the Chandrasekhar mass ($\sim 1.4\ M_\odot$) for the degenerate stellar core prior to a supernova explosion. (Indeed, nothing that we know about pulsars and X-ray sources is inconsistent with the notion that most neutron stars are formed with a mass close to this amount (Kelley and Rappaport, this volume).) The low surface magnetic field inferred for the pulsar ($\sim 2 \times 10^{10}$ G) suggests that the pulsar was formed in the first supernova explosion and spun up to its present period of 59 ms during mass accretion in an X-ray binary phase (Smarr and Blandford 1976).

0655-64

As we have just seen (Taylor, this volume) this system is like a twice-enlarged version of 1913+16 except that the eccentricity, $e = 0.0003 \pm .0001$, is extraordinarily small. The inescapable conclusion (e.g., Wheeler, Lecar and McKee 1975) is that the system must have undergone some dynamical evolution since the neutron star was formed. In particular, it is hard to see how the companion can possibly be a neutron star, as we have suggested for 1913+16. (The time scale for orbital decay under gravitational radiation exceeds a Hubble time and so this cannot have evolved the orbit.) The companion could be a black hole formed after the neutron star if the neutrino escape, mass loss and gravitational wave generation during the collapse to the black hole involved a mass loss $\delta m/m \lesssim 3 \times 10^{-4}$. This seems unlikely to be true of a realistic collapse (but see Shapiro and Teukolsky 1980). 0655+64 has a dispersion measure of $\sim$10 cm^{-3} pc which corresponds to a distance estimate d $\sim$ 300 pc and a height above the plane z $\sim$ 120 pc, well within the free electron layer (Manchester and Taylor 1977).

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If we assign a mass $m_1 \sim 1.4\ M_\odot$ to the neutron star, and (indefensibly) exclude cos i > 0.9, then the mass function gives a companion mass in the range 0.7 - 2.3 $M_\odot$. It can be readily confirmed that the orbit is large enough to contain an uneclipsed main-sequence companion, well within its Roche lobe (see Fig. 1). Such a star should be readily observable with $m_V \sim 8 - 14$ (Fig. 2). It is clear, at least empirically

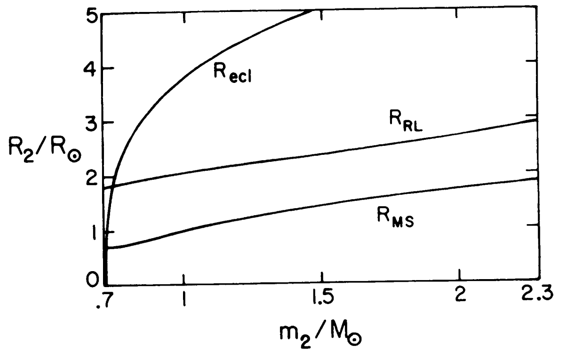

Fig. 1. Constraints on the radius of a companion star to 0655+64, assuming a pulsar mass $m_1 = 1.4\ M_\odot$. If the pulsar is neither eclipsed nor fills its Roche lobe, $R_2 \lesssim R_{ecl}$, R_{RL}. The radii of main-sequence stars R_{MS} are shown for comparison.

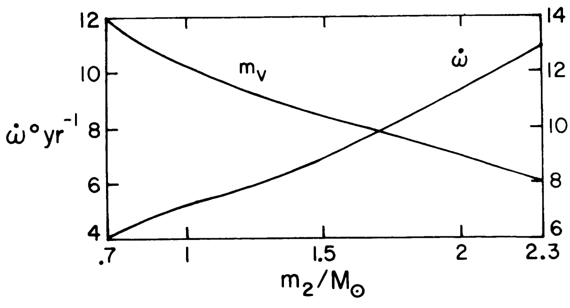

Fig. 2. Visual magnitude m_V and apsidal motion $\dot{\omega}$ for a main-sequence companion to 0655+64 as a function of the companion mass m_2, for a pulsar mass $m_1 = 1.4\ M_\odot$. A distance of 300 pc is assumed. Apsidal motion constants are taken from Cisneros-Parra (1970).

from observations of binary X-ray sources and probably theoretically, that circularization is very efficient in systems like this (e.g., Zahn 1966). The system may then be an X-ray source progenitor.

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Because the orbit is so circular it will be comparatively hard to measure the apsidal motion. The relativistic contribution is $\dot{\omega}$ °yr^{-1} = 0.19 $(m/1\ M_\odot)^{2/3}$. A simple estimate using the method of Blandford and Teukolsky (1976) gives the time for a ten percent measurement of $\dot{\omega}$ as $t \sim 6\varepsilon_{-4}^{2/3}\ \dot{n}_3^{-1/3}\ \dot{\omega}^{-2/3}$ yr where $100\varepsilon_{-4}\mu s$ is the error in an individual arrival time and $\dot{n}_3$ is the arrival time measurement rate in units of 1000 yr^{-1}. It remains to be seen whether or not 0655+64 can be timed as accurately as 1913+16. Even if it is, roughly ten years of careful monitoring would be necessary to measure the relativistic apsidal motion. If the companion is a main-sequence star, then $\dot{\omega}$ will have a larger tidal contribution $\sim 4 - 9$°yr^{-1} (Fig. 2). A shortening of the orbital period should also be detectable in this case.

A more likely possibility is that the companion be a white dwarf formed after the neutron star and after a "double core" phase in which the secondary star (white dwarf progenitor) lost a lot of mass and orbital angular momentum. Unless the dispersion measure distance is a severe underestimate or the system is much older than most pulsars and its height above the plane would indicate, a white dwarf should easily be observable. We must await a timing position to see if this is the case. If the companion is identified optically, the system will be a double-line spectroscopic binary and we will obtain the mass ratio which, in the case of a white dwarf companion, will allow the component masses to be determined if and when $\dot{\omega}$ is measured.

0820+02

Revised elements for this system, discovered by Manchester et al. (1980), are given by Taylor (this volume). If we assume that $m_1 \sim 1.3\ M_\odot$ (see below), and again exclude cos i > 0.9 as improbable, then the companion has a mass in the range $0.2\ M_\odot \lesssim m_2 \lesssim 0.5\ M_\odot$. The small binding energy and eccentricity (e = 0.04) of the orbit suggest dynamical evolution since the neutron star was formed. There is as yet no timing position, but VLA observations by Condon (private communication) have led to a probable pulsar position. Coincident with this position is a faint $\sim 23^m$ optical object (Kristian and Young, private communication). Pulsations are fainter than 25^m. There is no X-ray source near the pulsar (DeCampli and Feigelson, private communication).

From its dispersion measure distance of ~1 kpc, 0820+02 is ~300 pc above the galactic plane, again well within the free electron scale height. If we allow for $\sim 0.8^m$ reddening then the optical object has $m_V \sim 12.5$. This is consistent with a white dwarf companion as long as its effective temperature is less than ~8,000 K. A second possible identification is an M dwarf, in which case $m_2 \lesssim 0.25$. This should be extremely red. If the optical object turns out to be very blue then either its distance is far greater than 1 kpc or there is a strong non-thermal contamination associated with the pulsar. We must await further spectroscopic work.

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The major theoretical interest in this system is to understand how it can have such a low specific binding energy. We must address the possibility that the orbit has expanded since the neutron star was formed. One means of achieving this involves asymmetric pulsar radiation from a pulsar formed spinning rapidly (Harrison and Tademaru 1975). However, as this does not change the semi-major axis, we require two coincidences: (i) that the original explosion in a close binary was just sufficient to give it a very large eccentricity (large a) but not unbind the system, and (ii) that the net impulse was just sufficient to reduce the eccentricity back to zero. This seems rather improbable. A potentially more efficient use of the pulsar radiation is in the ablation of gas from the near side of the companion, perhaps when it started to expand through a red giant phase. In particular, if the companion rotates faster than corotation, which is to be expected with an expanding orbit, then a wind from the companion will not be symmetric about the line of centers and will tend to increase the orbital angular momentum and energy of the binary. As the companion is driven away, the solid angle it subtends will decrease and the efficiency of this mechanism will be reduced, thus allowing a weakly bound orbit to be produced without requiring any special coincidences. A simple estimate suggests that an initial pulsar spin angular velocity of $\sim$100 rad s^{-1} is adequate to drive the companion away. Note, however, that either mechanism requires the system to be older than $\sim P/2\dot{P} \gtrsim 3 \times 10^7$ yr, which suggests that the velocity perpendicular to the galactic plane has an unusually small value, less than 20 km s^{-1}.

A third and more attractive scheme goes as follows. Suppose the progenitor was a wide binary (a $\sim$ 3AU) in which the more massive companion evolved to form a high mass O-Ne-Mg white dwarf. When the companion, perhaps enlarged by prior mass transfer from the primary, reaches the red giant phase, it can expand to deposit sufficient mass onto the primary to drive it over the Chandrasekhar limit $\sim$1.4 $M_\odot$ (cf. Whelan and Iben 1973). The minimum mass that need be lost is of order the binding energy of a neutron star. For a hard equation of state, this is $\sim$0.1 $M_\odot$ (e.g., Arnett and Bowers 1977), so provided that the mass (mostly neutrinos) is lost symmetrically and there is negligible blow-off from the outer parts of the white dwarf and the companion the eccentricity induced can be as low as 0.04 without appealing to additional tidal circularization. The secondary now evolves, perhaps influenced by the presence of the neutron star, loses its envelope and leaves behind a $\lesssim$0.5 $M_\odot$ white dwarf remnant in an enlarged orbit. (Slow, spherically symmetric mass loss leaves e unchanged; a increases $\propto m^{-1}$.) If the companion is a white dwarf then the relativistic apsidal motion is $\dot{\omega} = 1.6 \times 10^{-6} m^{2/3}$, much larger than any likely Newtonian term. This will be virtually impossible to measure, requiring $t \gtrsim 100\epsilon_{-4}{}^{2/3}\dot{n}_3{}^{-1/3}$ yr.

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DISCUSSION

KUNDT: Could you repeat the reasoning why the binary pulsar PSR 1913+16 is the older of the two neutron stars? In Kundt (1980) I published an alternative interpretation.

BLANDFORD: The argument is not strong. It relies on the observation that the surface field (2×10^{10} Gauss) is the lowest known for a pulsar and perhaps indicates that the neutron star is quite old. The spin period (60 ms) is just about what you would expect from spinning up a low field neutron star in an X-ray binary.

TAYLOR: It is perhaps worth pointing out that at the provisional timing position for PSR 0655+64 there is no star brighter than $m \approx 20$. Can you make a white dwarf as faint as that?

BLANDFORD: Yes, if you make it cool enough or put it further away than its dispersion measure distance.

FERGUSON: Is it possible to create a large number of neutron stars by accretion onto white dwarfs without an accompanying supernova? Might this be a common method of neutron star formation?

BLANDFORD: Yes, it might be and would yield a neutron star birth rate in excess of the supernova and supernova remnant rate. Unfortunately, most of these remnants should remain bound (unless they are in very wide binaries) and this will not necessarily increase the single pulsar birth rate.

VAN DEN HEUVEL: May I just comment on making a supernova by pushing a white dwarf over the Chandrasekhar limit? Recent work by Miyaji et al. (1980) and Nomoto (1980) has shown that if the white dwarf has a suitable composition, i.e. O-Ne-Mg, one can rather easily push it over the Chandrasekhar limit by accretion. In this case the core collapses to a neutron star, presumably in a supernova explosion. As such white dwarfs are formed in main-sequence stars over a fairly wide mass range (about 8 - 10 $M_\odot$ or perhaps even 8 - 12 $M_\odot$) this may in fact be a fairly common type of supernova.

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