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THE ORIGIN OF THE PLANET AROUND PSR 1829−10

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ABSTRACT

We consider various scenarios for formation of a planet around a neutron star, as observed in PSR 1829−10. We show that matter, ablated from a companion 1.5 $M_\odot$ star which was orbiting around the neutron star progenitor at a distance of $\approx 3 \times 10^{12}$ cm, would be captured by the neutron star and form a disk around it. The companion star escaped from the system during the supernova event, and the observed planet was eventually formed from this disk.

Subject headings: planets: formation — pulsars — stars: neutron

The recent discovery of a planet in a circular orbit around PSR 1289−10 (Bailes, Lyne, & Shemar 1991) raises an immediate question: what is the origin of this system? We consider several possible scenarios. We show that only one, formation of the planet from matter ablated from a companion star which escaped from the system during the supernova, seems to be plausible. It follows from this scenario that PSR 1829−10 will have a peculiar velocity of the order of 100 km s^{-1} which might be detectable in the future. It also follows from this scenario that a possible second planet, which was proposed as an explanation for the unusually large $\ddot{P}$ of this pulsar, should have a mass larger than $\geq 8.8 \times 10^{-5}$ $M_\odot$ and should be at a distance of more than 3 AU.

We begin with a brief review of the essential features of the system. The pulsar is young; the period $P = 330$ ms and its first time derivative $\dot{P} = 5.2 \times 10^{-15}$ correspond to a lifetime $T = P/2\dot{P} \approx 1.25 \times 10^6$ yr. The current luminosity of the pulsar is 4.6×10^{33} ergs s^{-1}. Its strong magnetic field of 2.4×10^{12} G indicates that the pulsar is not of a "recycled" type. The sinusoidal variations of the time of arrival of the pulses correspond to a Keplerian motion due to the presence of a planet with a mass of $m_p = 3.0 \times 10^{-5}$ $M_\odot/\sin i$ (i is an unknown inclination angle), at an orbital radius $a = 0.71$ AU and a very small eccentricity, $e \leq 0.1$. The second time derivative of the pulsar's period, $\ddot{P} = 0.36 \times 10^{-24}$ s^{-1}, is larger by four orders of magnitude than the expected $\ddot{P}$ due to the dipole radiation, $-\dot{P}^2/P = -5.3 \times 10^{-29}$ s^{-1}. This unusually large second derivative could be due to the presence of a second planet with a mass M_2 at a distance a_2 from the pulsar:

$$M_2 = 5.6 \times 10^{-5}\, M_\odot \left(\frac{a_2}{5\ \mathrm{AU}}\right)^{7/2} \frac{1}{\sin i}\, \frac{1}{\sin \phi}\,, \qquad (1)$$

where ϕ is an unknown orbital phase of the second planet.

In the discovery paper, Bailes et al. (1991) considered several possible scenarios for the origin of the system. We turn now to a discussion of these and other possibilities. We assume that the neutron star has formed in a supernova (most likely of Type II) which took place about 10^6 yr ago. We divide the scenarios for formation of the planet into those in which the planet existed before the supernova event and those in which it was formed or captured after it. We consider the former group first.

The simplest scenario, in which the planet has existed before the supernova, can be easily ruled out. Such a planet would most likely become unbound during the supernova, when more than half the system's mass was ejected abruptly (Blaauw 1961). Disruption of the system can be prevented only if the mass ejection is asymmetric (Flannery & van den Heuvel 1975). Specifically for an initially circular orbit the system will not be disrupted if

$$\cos\theta > \cos\theta_c = \frac{(v_a/v_\mathrm{K})}{2} + \frac{2\,\Delta m/m - 1}{2(v_a/v_\mathrm{K})}\,, \qquad (2)$$

where m is the total mass of the system before the supernova event, Δm is the ejected mass, v_K is the Keplerian orbital velocity of the planet, v_a is the kick velocity that the neutron star gets from the asymmetric explosion, and θ is the angle between the two velocities (Sutantyo 1978). With $\Delta m \approx 0.9m$, $0.65 v_\mathrm{K} < v_a < 1.45 v_\mathrm{K}$ and $\theta < \theta_c$ ($\cos\theta_c \approx 0.9$ for $v_a = v_\mathrm{K}$ and $\cos\theta_c \approx 1$ for $v_a = 1.45 v_\mathrm{K}$) are needed to prevent disruption. The condition on v_a corresponds to an asymmetry of the order of 10^{-3} in the supernova explosion that should be aligned along the direction of motion of the companion. However, the magnitude of asymmetry is close to that which is required to give the high velocity of pulsars. The solid angle of the required direction of the asymmetry becomes $\approx (1/4\pi)\sin^2\theta_c \approx 0.03$ for $v_a = v_\mathrm{K}$ and becomes smaller for larger v_a. This is small but not prohibitively so. The increase in nondisruption probability if the star loses a large fraction of its envelope prior to the supernova event is insignificant.

In the unlikely case that v_a/v_K and θ are just right and the planet remains bound, its resulting orbit will become very eccentric (Sutantyo 1978):

$$|e| \geq 1 - \left[\left(\frac{v_a}{v_\mathrm{K}}\right)^2 - 2\left(\frac{v_a}{v_\mathrm{K}}\right)\cos\theta + 1\right]\left(\frac{m}{m - \Delta m}\right). \qquad (3)$$

The eccentricity, e, for these parameters will be larger than 0.75. The lifetime of the system is not sufficient for circularization of the orbit via tidal interaction between the pulsar and

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the planet. The energy of the tidal deformation of the planet is $\epsilon^2 G m_p^2/R_p$ where R_p is the planet's radius and $\epsilon = (M/m_p)(R_p/a)^3$. This corresponds to a tidal velocity of $v_t \approx 0.2$ cm s^{-1}. Here $(v_t/v_K)^2$ orbital periods, that is, $\approx 10^{16}$ yr, are required for a tidal circularization of the orbit (Fabian, Pringle, & Rees 1975; Press & Teukolsky 1977).

In a second scenario, the observed planet is a remnant of a more massive companion, for example, a 0.1 $M_\odot$ star, which was evaporated, like PSR 1744−24A and PSR 1957+20 (Ruderman, Shaham, & Tavani 1989a; van den Heuvel & van den Paradijs 1988) by the pulsar's emission. Comparison of the gravitational binding energy of the companion, with a mass, m, and a radius, R, with the radiation flux that it absorbs at a distance, a, from a pulsar with a luminosity, L, yields a lower limit for the evaporation lifetime, $t_{\rm evp}$:

$$t_{\rm evp} \geq 2 \times 10^{15} \left(\frac{m}{0.1\ M_\odot}\right)^2 \left(\frac{a}{10^{13}\ {\rm cm}}\right)^2 \times \left(\frac{R}{10^9\ {\rm cm}}\right)^{-3} \left(\frac{L}{4 \times 10^{33}\ {\rm ergs\ s^{-1}}}\right)^{-1}\ {\rm yr}\ . \quad (4)$$

This inequality gives a lower limit since part of the absorbed energy could be radiated away without evaporation, and the ejected matter could have velocity larger than the escape velocity. The lower limit $t_{\rm evp}$ is larger by a factor of $\approx 10^9$ than the lifetime of the system. It will be too long even if the pulsar's luminosity reached the Eddington luminosity, 10^{38} ergs s^{-1}.

One cannot circumvent the problem by proposing that initially the companion was nearer to the pulsar and it moved outward while it evaporated, a phenomenon which is observed today at PSR 1957+20 (Ryba & Taylor 1991; Banit & Shaham 1991). We would expect a remnant that forms in this process to have $t_{\rm evp} \approx T$, while at present $t_{\rm evp} \gg T$. The system could reach the current state via an evaporation process only if a combination of the following things occur: (1) the companion spent a significant fraction of the age of the system at a distance much shorter than the current orbital separation, that is, at 10^{12} cm or less. (2) The pulsar's luminosity at that period was around the maximal possible one, that is, around the Eddington luminosity, 10^{38} ergs s^{-1}. (3) The remnant moved, rapidly, outward relatively recently. (4) The luminosity dropped abruptly at the same stage. These features seem to fit, qualitatively, a bootstrap mechanism (Ruderman et al. 1989b) in which the luminosity of the pulsar at the high stage is determined by an accretion process which is switched off when the companion moves outward. A quantitative estimate shows, however, that the final separation is much too large for this mechanism to work.

Is it possible that the system formed in an accretion-induced collapse of a white dwarf with or without a Type I supernova? Since only about 0.1 $M_\odot$ is ejected from the core in such a case, it is likely that a planet will remain bound. Such scenarios were considered by several authors in the context of planetoid and comet formation around neutron stars in an attempt to explain the observation of γ-ray bursts (Rappaport & Joss 1985; Tremaine & Zytkow 1986; Nakamura 1989). Accretion-induced collapse can occur in cataclysmic variables (MacDonald 1984), in white dwarf–giant binaries (Blandford & De Campli 1981; Helfand, Ruderman, & Shaham 1983; Joss & Rappaport 1983; van den Heuvel & Taam 1984), or in a double white dwarf system (Iben & Tutukov 1984; Webbink 1984; Paczyński 1985). In all cases it is not clear where the remnant of the secondary is today! These scenarios also require the presence of a planet around the white dwarf, a situation which is almost as puzzling as the presence of a planet around a neutron star. This last requirement becomes even more complicated if we recall that it is difficult to form planets in binary systems (Nakano 1987).

We conclude that the planet must have formed after the supernova event and proceed to discuss the second group of scenarios. A capture of a planet from another stellar system by the neutron star may be possible, but the probability is extremely small. With a density of 1 star per pc^{-3} and a typical pulsar's peculiar velocity of 100 km s^{-1} the probability for such a capture within 10^6 yr is less than 1 in 10^8. The small eccentricity of the orbit is an additional argument against capture, which would have most likely resulted in an eccentric orbit. We have shown earlier that at a separation of 0.7 AU the orbit would not have enough time to circularize.

We are led to scenarios in which the planet formed in the vicinity of the neutron star after the supernova explosion. We are faced with two questions: what is the source of the matter of the planet? and, what is the source of the angular momentum? The simplest matter source is the original star itself: either due to fallback of a small fraction of the ejected envelope or due to a formation of the disk around the neutron star by a piece of matter of the collapsing core (Nakamura 1989).

A small fraction of the ejected supernova envelope may not acquire the needed escape velocity from the supernova. Current calculations (e.g. Shigeyama, Nomoto, & Hashimoto 1988; Shigeyama & Nomoto 1990; Woosley, Pinto, & Martin 1989) are too crude to estimate this amount which is certainly less than 0.1 $M_\odot$. This material will fall back to the vicinity of the core. If the envelope was rotating, the angular momentum is likely to be sufficient to prevent infall of this material onto the neutron star, and we can expect that it will rearrange itself in the form of a thin accretion disk around the equatorial plane of the neutron star.

Formation of a planet around the newborn neutron star was discussed by Nakamura (1989) in relation to the false report on a submillisecond pulsar and a planet in SN 1987A (Kristian et al. 1989). If the angular momentum of the presupernova core is greater than $\sim 6 \times 10^{49}$ g cm^2 s^{-1}, the core may fragment and a binary proto–neutron star may be formed (Nakamura & Fukugita 1989). The larger mass proto–neutron star fragment will accrete the matter of the smaller mass one. When the mass of the smaller fragment becomes $\sim 0.2\ M_\odot$, the disruption occurs to yield a central neutron star and a rotating thin disk of mass $\sim 0.2\ M_\odot$. Nakamura (1989) suggested that a planet formed around the neutron star via a Papaloizou-Pringle (1984) instability.

However, the angular momentum of the planet is too large. The specific angular momentum of the planet, j_p, is $0.4 \times 10^{20} (m_{\rm ns}/1.4\ M_\odot)^{1/2}$ cm^2 s^{-1}, where $m_{\rm ns}$ is the mass of the neutron star. The momentum j_p is larger by one and a half orders of magnitude than the specific angular momentum of the envelope of the presupernova star rotating at a tenth breakup velocity at a radius of 10^{11} cm: $1.4 \times 10^{18} (m_0/15\ M_\odot)^{1/2}$ cm^2 s^{-1}. It (j_p) is larger by three orders of magnitude than the specific angular momentum of material ejected from the core, which could be of the order of $0.4 \times 10^{17} (m_{\rm ns}/1.4\ M_\odot)^{1/2}$ cm^2 s^{-1} if the core had a breakup angular momentum at a radius of 100 km. The specific angular momentum of the disk and, therefore, its size would have been much smaller than the required, 0.7 AU, orbital separation.

Angular momentum can be transferred by viscous stress outward. The required angular momentum could originate at the inner regions of the disk in which case 10^{-2} to 10^{-1} $M_\odot$ would have to transfer their angular momentum to the 10^{-5} $M_\odot$ that eventually forms the planet. Alternatively the origin of the needed angular momentum could be the rotating core itself, from which it could be transferred by magnetic process (e.g., like the one discussed in a different context by Mineshige, Rees, & Fabian 1991). However, the transfer of the required angular momentum, ΔJ, is accompanied by transfer of energy, ΔE, with

$$\Delta E \approx \Delta J \omega_i \,, \tag{5}$$

where $\omega_i = j_i/r_i^2$ is the Keplerian angular velocity at the radius r_i from which the angular momentum is transported. In all the cases mentioned, ΔE is larger than the binding energy of the planet by two or more orders of magnitude. It is difficult to imagine a way to transfer the required angular momentum without transferring enough energy to make the material of the disk unbound. Furthermore, at least $(j_p/j_i)m_p$ will be accreted on the neutron star, whose strong magnetic field indicates that no more than 10^{-4} $M_\odot$ were accreted on it since it was formed.

The issue of angular momentum becomes more severe if the system contains, as $\ddot{P}$ indicates, a second, Jupiter-like, planet. The orbital angular momentum would be 1.2×10^{49} g cm^2 s^{-1}. That is, it will be almost the same as the total angular momentum of a core rotating at a breakup velocity!

Both problems of origin of the planet's matter and angular momentum can be solved if the supernova occurred in a binary system in which a second main-sequence star, with a mass, $m_{\rm com} \approx 1.4$ $M_\odot$ and a radius, $R_{\rm com} \approx 10^{11}$ cm, was circulating the supernova progenitor (the primary) at a distance, $a_{\rm com} \approx 3 \times 10^{12}$ cm. This companion star would have been in the outer region of the envelope of the primary if it was a red giant. It is more likely that it would have been outside the primary which was a blue giant like the progenitor of SN 1987A. In either case the binary system would have been disrupted during the supernova event in which more than 10 $M_\odot$ was lost from the system. The supernova ejecta would cause a small, but important in this case, mass loss from the companion star (Sofia 1967; Colgate 1970; McClusky & Kondo 1971; Sutantyo 1974a, b; Wheeler, Lecar, & McKee 1975; Fryxell & Arnett 1981; Taam & Fryxell 1984). The mass loss is due to two processes: stripping and ablation. Stripping first takes place mostly in the outer layers that are tangential to the motion of the supernova ejecta. The stripped matter is dragged by the supernova ejecta, and it acquires a velocity of a few thousand km s^{-1} relative to the neutron star. Therefore it is unbound. Ablation takes place at the outer layer of the secondary star that are facing the ejecta. It results in roughly spherical ejection of matter at an escape velocity, that is, several hundred km s^{-1} from the secondary. It is the ablated matter which is of interest to us since only it can be captured by the neutron star.

The amount of ablated material is given, roughly, by $m_{\rm com}\Psi$ with the parameter Ψ being defined as (Wheeler et al. 1975):

$$\Psi \equiv 0.25 \frac{M_{\rm sn}}{M_{\rm com}} \left(\frac{R_{\rm com}}{a_{\rm com}}\right)^2 \left(\frac{v_{\rm sn}}{v_{\rm esc}} - 1\right) , \tag{6}$$

where $v_{\rm sn} \approx 10^4$ km s^{-1} is the velocity of the supernova ejecta and $v_{\rm esc} \approx 600$ km s^{-1} is the escape velocity from the companion. With the above parameters $\Psi \approx 0.04$, which corresponds to ablation of about 0.06 $M_\odot$ from the companion (Wheeler et al. 1975). This matter comes from the region that faces the supernova, and it is heavily enriched by metals since a large fraction of it is made of the $(R_{\rm com}/a_{\rm com})^2 m_{\rm sn} \approx 0.02$ $M_\odot$ supernova material that collides with the star.

The matter is ejected from the secondary with an escape velocity, $v_{\rm esc}$. The secondary itself is moving at $v_{\rm com} = 200$ km s^{-1} relative to the neutron star. The velocity $v_{\rm com}$ is larger by a factor of $(m_{\rm sn}/m_{\rm ns})^{1/2} \approx 4$ than the orbital velocity around the neutron star at this distance. The secondary, as well as most of the matter ejected from it, escapes from the system. However, a small fraction of the ejected material will be captured by the neutron star. To estimate this fraction we have solved ballistic trajectories of matter ejected from a 1.5 $M_\odot$ star with $v_{\rm com} = 200$ km s^{-1} at a distance of 3×10^{12} cm from a 1.4 $M_\odot$ neutron star. The matter was ejected spherically with $v_{\rm esc}$. We find that about 1% of the matter is captured by the neutron star. Since the ablated matter velocity is here assumed constant, the capture problem is the inverse of equation (2), and this capture probability is essentially $(1/4\pi) \sin^2 \theta_c^2$. This assumes that the matter ablated from the companion has a constant velocity $v_{\rm esc}$. However, a velocity distribution will be ejected, and the slower matter will be captured more easily and significantly increase this value. The captured matter has enough angular momentum to form a disk at $\approx 10^{13}$ cm around the neutron star. The total amount of mass captured is $\approx 6 \times 10^{-4}$ $M_\odot$, roughly of the order of magnitude required to form the observed planet and sufficient for a "Jupiter" at a larger distance.

We now turn to the question of how to make planets from the trapped matter. The key problem is whether the planets have enough time to form. Nakano (1987) discussed the formation time of the planet from a disk with a surface density distribution, σ, of the form:

$$\sigma = 1.7 \times 10^3 f_\sigma a_{\rm AU}^{-1.5} \text{ g cm}^{-2} \,, \tag{7}$$

parametrized by f_σ. By varying f_σ we can apply Nakano's theory to our case. Since the central luminosity of the pulsar is high enough we expect that hydrogen and helium will be blown off from the disk, and only metals will be left. As we pointed out earlier, the ablated mass is mostly metal, so this will not affect by much the mass of the disk. The formation time of the planet at $a_{\rm AU}$ from a ring of width $\delta r = c_m a_{\rm AU}$ of a metallic disk is given by Nakano (1987) as

$$t_{\rm pf} = 3.2 \times 10^4 \frac{c_m}{0.2} f_\sigma^{-1} a_{\rm AU}^{2.5} \text{ yr} \,. \tag{8}$$

A disk of mass 3×10^{-5} $M_\odot$ at $a_{\rm AU} = 0.7$ with $c_m = 0.2$ is characterized by $f_\sigma = 0.125$. The corresponding formation time is 2.6×10^5 yr given by equation (8), which is sufficiently shorter than the life of the pulsar, 1.25×10^6 yr.

The second possible planet is further away and takes more time to form. Assuming that $\sin i \approx 0.5$, $\sin \phi \approx 0.5$, and $c_m = 0.1$, equations (1) and (7) give $f_\sigma = 7.2 \times 10^{-3} a_{2,\rm AU}^3$. The formation time of the second planet, $t_{2,\rm pf}$, given by equation (8) is

$$t_{2,\rm pf} = 2.2 \times 10^6 a_{2,\rm AU}^{-0.5} \text{ yr} \,. \tag{9}$$

The condition that this is shorter than the lifetime of the pulsar, $t_{2,\rm pf} < 1.25 \times 10^6$ yr, yields

$$a_{2,\rm AU} \geq 3 \,, \tag{10}$$

and

$$M_2 \geq 8.8 \times 10^{-5} M_\odot \,, \tag{11}$$

which provide a prediction on the mass and orbital separation of the second planet, if it exists.

The requirement that the metals could condensate at the 0.7 AU yields another limit on the system. Under the central luminosity L of the pulsar, the temperature T at the distance of $a_{\rm AU}$ is given as

$$T = 2000\ {\rm K}(a_{\rm AU}^{-0.5})\left(\frac{L}{10^{37}\ {\rm ergs\ s^{-1}}}\right)^{0.25}\ . \qquad (12)$$

Metallic carbon can condensate at the distance of $a_{\rm AU} = 0.7$ if L is smaller than 5×10^{37} ergs $\rm s^{-1}$. Thus, the initial period of the pulsar should be larger than 32 ms, which is not a severe restriction.

The distance of the companion from the supernova progenitor should be "fine tuned" to form the planets. If it is further out, say at $\approx 10^{13}$ cm, Ψ will be smaller by one order of magnitude, and the amount of matter released will be quite small, $\approx 10^{-3}\ M_{\odot}$. Even a smaller fraction of this will be captured, and the resulting disk will not be sufficient to form a planet. If the companion is too near to the supernova progenitor (say around 10^{12} cm), more matter will be ejected from it. But this matter will be moving so fast relative to the neutron star that only a tiny fraction of it will be captured. This narrow range of initial separations in which the conditions of planet formation are satisfied explains why we observe only one planetary system among the several hundred pulsars observed so far, as otherwise the existence of a binary companion in the prepulsar systems is not a unique phenomenon at all.

While this "fine tuned" distance might exist only in this system, other systems in which companions exist will also eject mass during the supernova event, and some fraction of it will be captured and form a disk around the pulsar. While the amount of the mass in the disk will be much smaller and will not be sufficient for planet formation, it will be sufficient for formation of planetoids with a typical mass of 10^{21}–10^{22} gn (Nakarno 1987). Thus the mechanism that we have outlined here could be an additional way to produce planetoids around neutron star (Tremain & Zytkow 1986; Nakamura 1989) as needed to produce gamma-ray bursts from such objects.

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