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Letter to the Editor

Formation of a "planet" by rapid evaporation of a pulsar's companion

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Abstract. A planet-size object in circular orbit around a pulsar could be formed as the result of rapid evaporation of a more massive binary companion by the pulsar's radiation.

Key words: pulsars – stars: planetary systems

1. Introduction

This work was originally motivated by the report of a planet-size companion in orbit around the pulsar PSR1829-10 (Bailes *et al.* 1991). Even though this first report was later retracted (Lyne and Bailes 1992), it led to a campaign of systematic re-examination of a number of pulsar timing observations, which has already resulted in the discovery of two other planets around the nearby, high-galactic-latitude pulsar PSR1257+12 (Wolszczan and Frail 1992).

In this *Letter*, we show that the formation of a binary pulsar with a planet-size companion, large orbital separation, and small eccentricity could result from the rapid evaporation of a much more massive binary companion by the pulsar's radiation. Such an evaporation process is known to be taking place in at least two other binary pulsars: PSR1957+20 (Fruchter *et al.* 1990, Ryba and Taylor 1991) and PSR1744-24A (Lyne *et al.* 1990). In these systems, binary companions of $\sim 10^{-2}$—$10^{-1}\ M_\odot$ are being evaporated on a timescale $\sim 10^8$yr by the radiation from a low-magnetic-field, millisecond pulsar. We wish to explore the possibility that a young, high-luminosity pulsar could evaporate its binary companion in a timescale comparable to its age, $\sim 10^6$ yr.

Our model, presented in Section 2, is based on simple dynamical equations which express conservation of total energy and angular momentum in the system. This model does not rely on any specific physical mechanism for exciting the evaporative outflow. A variety of such mechanisms have been proposed (see, e.g., Cheng 1989, Krolik and Sincell 1990, Levinson and Eichler 1991, and Ruderman *et al.* 1989), but clearly the problem remains unresolved. In Section 3 we integrate the evolution equations backwards in time, starting from a binary configuration similar to the one originally reported for PSR1829-10. We show that $\sim 10^6$ yr ago, the companion mass and binary separation could have been comparable to those currently observed in the eclipsing binary pulsar PSR1957+20.

2. Basic Equations

For a given mass loss rate from the companion, the orbital evolution of the system is determined by angular momentum conservation. The total orbital angular momentum of the binary is $L = (m_c m_p/M)a^2\Omega_{orb}$, where m_p and m_c are the masses of the pulsar and its companion, $M = m_c + m_p$, a is the binary separation, and $\Omega_{orb} = (GM/a^3)^{1/2}$ is the orbital frequency. Taking time derivatives we get

$$\frac{\dot{a}}{a} = 2\,\frac{\dot{L}}{L} + \frac{\dot{m}_c}{M} - 2\,\frac{\dot{m}_c}{m_c}. \tag{1}$$

For an orbital evolution driven by mass losses only, we can write the rate of change of the angular momentum as

$$\dot{L} = \alpha\, a_c^2\, \Omega_{orb}\, \dot{m}_c, \tag{2}$$

where $a_c = (m_p/M)\,a$ is the distance between the companion and the center of mass of the system. The parameter α is determined by the kinematics of the outflow as

$$\alpha = 1 - \beta\,\frac{v_e}{v_c}, \tag{3}$$

where $v_c = a_c\Omega_{orb}$ is the orbital velocity, v_e is a mean velocity of ejection, and β is a dimensionless measure of the asymmetry in the outflow. For a perfectly collimated outflow at velocity v_e in a direction making an angle θ to the radius vector we have $\beta = \sin\theta$ (both v_e and θ are measured in the frame comoving with the companion, and $\theta > 0$ corresponds to a net positive thrust). Therefore we must have $-1 < \beta < 1$ in general. For a perfectly symmetric outflow, $\beta = 0$ and $\alpha = 1$. As we show below, a small amount of asymmetry, with $\beta > 0$, is necessary for ***significant orbital expansion*** to take place over the lifetime of the pulsar. Such an asymmetry could result from a lack of synchronization between the spin of the companion and the orbital motion. If the companion spins faster than Ω_{orb}, as expected if synchronization was achieved before the evaporation started, advection on the companion's surface will indeed tend to displace the axis of the outflow towards the direction opposite to that of the orbital motion.

Since the evaporation of the companion is driven by the pulsar radiation, we write the mass loss rate as

$$\dot{m}_c = \frac{-\eta\, R_c^2}{2\, v_e^2\, a^2}\, L_p, \tag{4}$$

where L_p is the pulsar luminosity and R_c is the radius of the companion. The parameter η measures the efficiency of

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conversion of the intercepted radiation power into kinetic energy of the outflow. If the pulsar emission is isotropic, then conservation of energy requires $\eta < 1$ in eqn. (4). We assume that the radius of the companion R_c =const, which is appropriate for cold, degenerate matter. Indeed, for a mass in the range 10^{-5}—$10^{-1} M_\odot$, the radius of a degenerate carbon dwarf (Salpeter and Zapolsky 1967) varies only between $0.02 R_\odot$ and $0.04 R_\odot$ (for pure hydrogen this radius would be about 3 times larger). The ejection velocity v_e must always remain larger than the escape velocity from the surface of the companion. Therefore we write

$$v_e = \nu \left(\frac{2\,G\,m_c}{R_c}\right)^{1/2}, \tag{5}$$

where ν is a constant > 1.

We model the evolution of the pulsar itself by assuming a constant braking index n (so that $\dot{\Omega} \propto \Omega^n$ where Ω is the angular velocity of the pulsar) and a luminosity $L_p \propto \Omega^4$, valid for all models with no magnetic field decay (Shapiro and Teukolsky 1983). This gives

$$L_p(t) = L_{po} \left(\frac{\Omega_i}{\Omega_o}\right)^4 \left[1 + (n-1)\left(\frac{\Omega_i}{\Omega_o}\right)^{n-1} \frac{t}{T}\right]^{-4/(n-1)}. \tag{6}$$

Here $T \equiv -(\Omega/\dot{\Omega})_o$, $L_{po} = I\,(\Omega\dot{\Omega})_o$, where I is the moment of inertia, and we have chosen $t_i = 0$ so that the age of the pulsar $t_o = [1-(\Omega_o/\Omega_i)^{n-1}]T/(n-1)$. The standard magnetic dipole model is recovered when $n = 3$ in eqn. (6).

Equations (1)—(6) can be combined to give the following dimensionless evolution equations,

$$\frac{d\tilde{a}}{d\tilde{t}} = -\left[\frac{\Lambda \tilde{a}^{1/2}(1+\tilde{m}_c)^{1/2}}{\tilde{m}_c^{1/2}} + 1\right] \left(\frac{\tilde{a}}{1+\tilde{m}_c}\right) \frac{d\tilde{m}_c}{d\tilde{t}},$$
$$\frac{d\tilde{m}_c}{d\tilde{t}} = \frac{-\mathcal{E}}{\tilde{a}^2\,\tilde{m}_c} \left[\frac{A^{n-1}}{1+(n-1)A^{n-1}\tilde{t}}\right]^{4/(n-1)}. \tag{7}$$

Here we have defined dimensionless variables $\tilde{t} \equiv t/T$, $\tilde{a} \equiv a(t)/a_o$, and $\tilde{m}_c \equiv m_c(t)/m_p$, as well as three dimensionless parameters: an energy parameter,

$$\mathcal{E} \equiv \frac{\eta\,R_c^3\,L_{po}\,T}{4\,\nu^2\,G\,m_p^2\,a_o^2} = 1.5 \times 10^{-11}\,\eta\,\nu^{-2} \left(\frac{R_c}{0.03 R_\odot}\right)^3$$
$$\times \left(\frac{L_{po}}{1.2 L_\odot}\right) \left(\frac{T}{2.5 Myr}\right) \left(\frac{m_p}{1.4 M_\odot}\right)^{-2} \left(\frac{a_o}{10^8\,\mathrm{km}}\right)^{-2}, \tag{8}$$

an angular momentum parameter,

$$\Lambda \equiv \beta\,\nu \left(\frac{8\,a_o}{R_c}\right)^{1/2}$$
$$= 1.9 \times 10^2\,\beta\,\nu \left(\frac{R_c}{0.03 R_\odot}\right)^{-1/2} \left(\frac{a_o}{10^8\,\mathrm{km}}\right)^{1/2}, \tag{9}$$

and a pulsar parameter, $A \equiv \Omega_i/\Omega_o \sim 10^2$, if the pulsar was born with millisecond period.

3. Results and Discussion

For definiteness we adopt a neutron star mass $m_p = 1.4 M_\odot$ and a companion mass $m_c(t_o) = 3 \times 10^{-5} M_\odot$ and binary separation $a_o = 10^8$ km today. Numerical integration of the evolution equations (7) backwards in time reveals (cf. figs. 1 and 2) that for plausible values of the parameters, *a significant orbital evolution and a substantial change in the companion mass can take place over the lifetime of the pulsar*. In particular, a combination of companion mass $m_c(t_i) \approx 10^{-2} M_\odot$ and binary separation $a(t_i) \approx 10^6$ km can be reached. This is comparable to the currently observed parameters of the eclipsing binary PSR1957+20. In this system, the radio observations (Fruchter *et al.* 1990, Ryba and Taylor 1991) indicate that the companion is indeed being evaporated by the $\sim 40 L_\odot$ radiation power from the pulsar, on a timescale $t_{evap} \sim 10^7$ yr. In the case of a young pulsar, however, the much larger magnetic field implies $L_p(t_i) \sim 10^8 L_\odot$ and a very short evaporation timescale $t_{evap} \sim 10^4$ yr. For $t >> t_{evap}$, the evaporation becomes inefficient and the system stabilizes in its presently observed state (cf. fig. 1). The orbital period derivative should still be positive today, however, with $P_{orb}/\dot{P}_{orb} \sim 10^7\,\mathrm{yr}\,\nu\,\eta^{-1}\beta^{-1}$.

Our integrations show that companion stars of initial mass $> 10^{-2} M_\odot$ can also be evaporated down to planet-size objects. However, this requires an extremely small initial binary separation, with $a(t_i)$ becoming comparable to R_c, and seems therefore rather improbable. However, it is possible that a more massive, *nondegenerate* companion could be more easily evaporated. Indeed, our assumption of degeneracy is consistent with the energetics of the system *today*: even if the intercepted radiation power were entirely used to heat the interior of the planet-size companion, its temperature in thermal equilibrium today would be only ≈ 300 K, negligible compared to the ~ 1 eV Fermi energy. Here we have made the

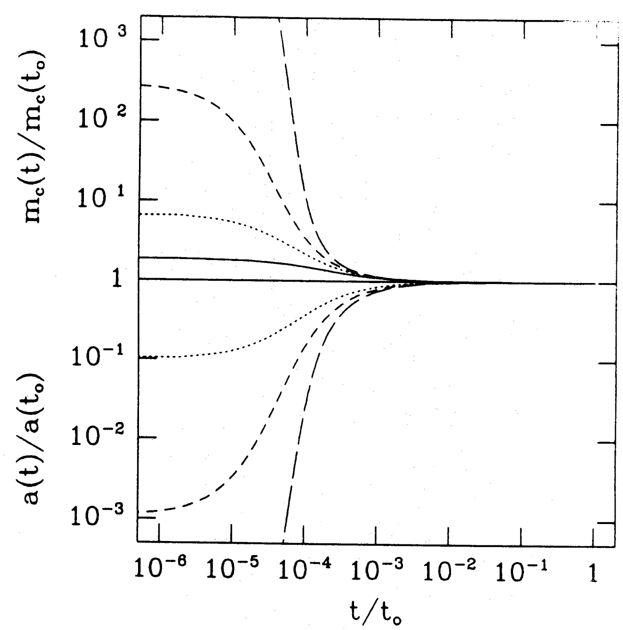

Fig. 1. Evolution of the binary separation a (lower curves) and the companion mass m_c (upper curves) for a pulsar model with braking index $n = 3$ and $\Omega_i/\Omega_o = 10^2$ (giving $t_o = 1.3 \times 10^6$ yr). The energy efficiency parameter $\mathcal{E} = 10^{-13}$. The solid lines are for $\Lambda = 0$, the dotted lines for $\Lambda = 3 \times 10^2$, the short-dashed lines for $\Lambda = 4 \times 10^2$, and the long-dashed lines for $\Lambda = 5 \times 10^2$. Significant changes occur when $\Lambda \gtrsim 10^2$. In all cases, the evaporation of the companion is completed in about 10^4 yr, after which the system stabilizes in its presently observable state.

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further assumption that the companion has remained degenerate and inside its Roche lobe throughout the evolution of the system. This is the most conservative assumption one can make. Indeed, if Roche lobe overflow has occurred at early times, then one could have $v_e \approx 0$ during that phase (or $\nu << 1$ in eqn. [5]). Moreover, the cross-section of a nondegenerate companion would be somewhat bigger. Both effects would clearly tend to accelerate the evaporation process. Such a rapid evaporation of a nondegenerate companion has been discussed in a recent paper by Krolik (1991). He showed that the orbital evolution in that case can also be accelerated since, for sufficiently large R_c/a, the material ablated from the heated side has a significantly smaller specific angular momentum than the companion star as a whole.

If the neutron star was formed in a recent supernova explosion, a significant orbital eccentricity could be present initially. However, the evaporation of the companion can also rapidly circularize the orbit. Indeed, using secular perturbation theory (Danby 1962) we find that the eccentricity evolves according to

$$\frac{\dot{e}}{e} = \frac{3}{2}\beta\sqrt{1-e^2}\left(\frac{v_e}{v_c}\right)\left(\frac{m_p}{M}\right)\frac{\dot{m}_c}{m_c}, \qquad (10)$$

where $\dot{m}_c$ is still given by eqn. (4). We see that $\dot{e} < 0$ when $\beta > 0$, i.e., ***if the evaporation causes the orbit to expand, it will also circularize it.*** Moreover, the circularization timescale $t_{circ} = e/\dot{e} \sim t_{evap}$ for $\beta \lesssim 1$ and $v_e/v_c \gtrsim 1$.

It is possible that the model presented here could also explain the orbital evolution of the eclipsing binary pulsar PSR1957+20. In that system, however, the orbit is now observed to be decaying ($\dot{P}_{orb} < 0$), rather than expanding (Ryba and Taylor 1991). An asymmetric outflow with $\beta < 0$, i.e., one in which material *gains* specific angular momentum as it is evaporated, would be necessary. We do not know how the direction of the asymmetry is actually determined. Note, however, that any given sign of β is "self-stabilizing" in the sense that desynchronization of the orbital motion with respect to the spin of the companion will create advective flows on its surface which tend to maintain the direction of the asymmetry. One problem is that $\beta < 0$ would also excite eccentricity (cf. eqn.[10]), which seems incompatible with the very nearly circular orbit of PSR1957+20. It is likely, however, that tidal effects are dominant on the $\gtrsim 10^7$ yr orbital evolution timescale, and that they can maintain the orbit nearly circular in spite of the effect of mass losses. It is also possible that the orbital evolution is not dominated by mass losses, but rather by an entirely different mechanism such as tidal effects or resonant coupling to an outer disk (Ryba and Taylor 1991). Whether or not evaporation is relevant to the orbital evolution of PSR1957+20, it is clear that a young, high-luminosity pulsar can indeed evaporate its companion on a very short timescale.

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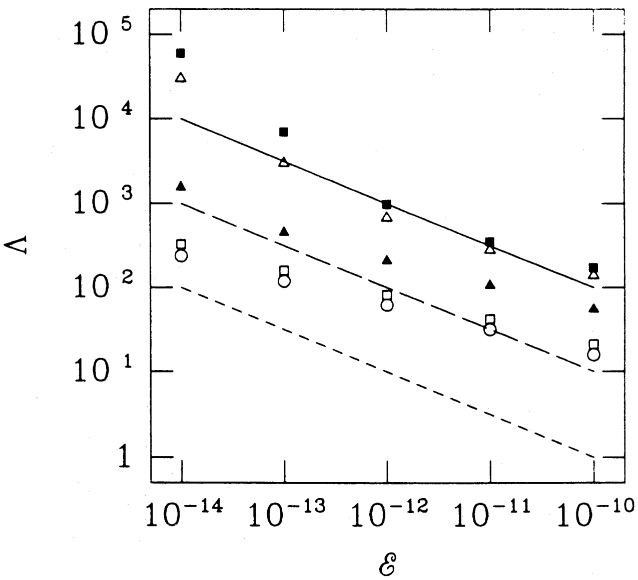

Fig. 2. Influence of various parameters on the evolution of the system. Each dot shows the values of $\mathcal{E}$ and Λ which are required to obtain $m_c(t_i) \sim 0.1M_\odot$ [Note that these values are very insensitive to the exact choice of $m_c(t_i)$, as long as $m_c(t_i) >> m_c(t_o)$]. The solid triangles correspond to $n = 3$ and $A = 10^2$, the solid squares to $n = 4$ and $A = 10^2$, the open triangles to $n = 3$ and $A = 0.2 \times 10^2$, the open circles to $n = 2$ and $A = 10^2$, and the open squares to $n = 3$ and $A = 5 \times 10^2$. The 3 lines correspond to constant values of the product $\eta\beta^2$ (obtained by eliminating ν between eqns. [8] and [9]). The solid line is for $\eta\beta^2 = 1$, the long-dashed line for $\eta\beta^2 = 10^{-2}$, and the short-dashed line for $\eta\beta^2 = 10^{-4}$.

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