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IMPLICATIONS OF THE PSR 1257+12 PLANETARY SYSTEM FOR ISOLATED MILLISECOND PULSARS

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ABSTRACT

The first extrasolar planets were discovered in 1992 around the millisecond pulsar PSR 1257+12. We show that recent developments in the study of accretion onto magnetized stars, plus the existence of the innermost, moon-sized planet in the PSR 1257+12 system, suggest that the pulsar was born with approximately its current rotation frequency and magnetic moment. If so, this has important implications for the formation and evolution of neutron star magnetic fields as well as for the formation of planets around pulsars. In particular, it suggests that some and perhaps all isolated millisecond pulsars may have been born with high spin rates and low magnetic fields instead of having been recycled by accretion.

Subject headings: planetary systems — stars: magnetic fields — stars: neutron — stars: rotation

1. INTRODUCTION

The remarkably stable rotation frequencies of millisecond pulsars (MSPs), with typical period derivatives of 10^{-21}–10^{-19} s s^{-1}, make them extremely sensitive to periodic perturbations such as those produced by orbiting companions. This sensitivity led to the first discovery of extrasolar planets, around the Galactic disk pulsar PSR 1257+12 (Wolszczan & Frail 1992). This pulsar has a period of $P = 6.219 \times 10^{-3}$ s and a period derivative of $\dot{P} = 1.2 \times 10^{-19}$, which in a standard magnetic dipole spin-down model implies a dipole magnetic field of $B = 3 \times 10^{19}(P\dot{P})^{1/2} \approx 8.8 \times 10^{8}$ G and a characteristic age $\tau_c = P/2\dot{P} = 8 \times 10^{8}$ yr. Timing residuals from PSR 1257+12 suggested that there were two Earth-mass planets around this pulsar (Wolszczan & Frail 1992). The planetary origin of the timing residuals was confirmed by observations (Wolszczan 1994) of the expected secular perturbations due to interaction between these planets (Rasio et al. 1993; Malhotra 1993; Peale 1993). These observations also revealed the presence of a third, moon-sized planet closer in (Wolszczan 1994). In order of increasing distance from the pulsar, the masses and semimajor axes of the three planets are $M_1 = 0.015/\sin i_1\ M_\oplus$ at 0.19 AU, $M_2 = 3.4/\sin i_2\ M_\oplus$ at 0.36 AU, and $M_3 = 2.8/\sin i_3\ M_\oplus$ at 0.47 AU, where i_1, i_2, and i_3 are the orbital inclination angles ($i = 0$ is face-on, $i = 90°$ is edge-on). All three planets are in nearly circular orbits, with eccentricities <0.02. There is some evidence for a fourth planet (Wolszczan 1996) which, if it exists, has a mass $M_4 \sim 0.05$–$81\ M_\oplus$ and a semimajor axis $\sim$6–29 AU, where the mass uncertainty is largely due to uncertainty in the fractional contribution of such a planet to the observed spin-down of the pulsar (Wolszczan et al. 2000a). Recently, some doubt was cast on the existence of the innermost planet by Scherer et al. (1997), who pointed out that its 25.3 day orbital period is close to the solar rotation period at the 17° solar latitude of PSR 1257+12, and suggested that the modulation might actually be due to modulation in the electron density of the solar wind in that direction. However, if this effect is important we would also expect to observe it in other millisecond pulsars. More importantly, the oscillation amplitude does not depend on the radio frequency (Wolszczan et al. 2000b), contrary to what is expected for a plasma effect. Hence the 25 day modulation of the frequency from PSR 1257+12 is due to a planet.

The existence of this system has produced much speculation about its origin. As discussed by Phinney & Hansen (1993), the proposed formation mechanisms can be divided into presupernova scenarios, in which the planets existed before there was a neutron star in the system, and post-supernova scenarios, in which the planets formed after the supernova. Podsiadlowski (1993) reviewed a large number of these proposed mechanisms. Presupernova scenarios include those in which planets survive the supernova (Bailes, Lyne, & Shemar 1991) or are captured into orbit around the neutron star by a direct stellar collision (Podsiadlowski, Pringle, & Rees 1991), or are formed in orbit around a massive binary (Wijers et al. 1992). As reviewed by Podsiadlowski (1993), all of these mechanisms are met with serious objections. For example, direct stellar collisions in the Galactic disk are expected to be exceedingly rare, and a supernova explosion in a single-star system would be highly likely to unbind any planets initially in orbit around it, and any remaining planets would have high eccentricities.

For these reasons, more attention has focused on post-supernova scenarios. Some models propose that PSR 1257+12 is a “recycled” pulsar that has been spun up by accretion, in analogy with other millisecond pulsars. In these models the star might have accreted matter from a remnant disk, for example from the disrupted remains of a merger between two white dwarfs or a white dwarf and a neutron star (Podsiadlowski et al. 1991), or from a massive disk left over from a phase of Be binary mass transfer (Fabian & Podsiadlowski 1991), or by deflation of a Thorne-Zytkow object (Podsiadlowski et al. 1991). Alternately, the accretion could have been from a stellar companion, which was then removed or disguised as a planet. One picture, which was motivated by a report of a single planet around PSR 1829−10 that was later retracted (Bailes et al. 1991), is that the companion was evaporated by flux from the neutron star until it had planetary mass (Bailes et al. 1991; Krolik 1991; Rasio, Shapiro, & Teukolsky 1992). A variant of this model is that as the companion is ablated, it expands, eventually being disrupted and forming a $\sim$0.1 $M_\odot$ disk around the neutron star, from which the planets eventually form (Stevens, Rees, & Podsiadlowski 1992). Another possibility is that the ablated matter may not escape the system, instead forming a circumbinary disk from which planets form (Tavani & Brookshaw 1992; Banit et al. 1993). The stellar companion would, in this scenario, be evaporated completely by the neutron star.

A third class of postsupernova models, distinct from those involving disks or disrupted companions, suggests that the planets formed from fallback matter from the supernova (Bailes et al. 1991; Lin, Woosley, & Bodenheimer 1991), or from matter that had been ablated from a binary companion prior to the supernova (Nakamura & Piran 1991). The matter from which the planets formed might also have been accreted from the companion if supernova recoil sent the neutron star through the companion (suggested by C. Thompson 1993, private communication; summarized in Phinney & Hansen 1993). In such models the neutron star was born with approximately its current spin rate and magnetic moment, and was therefore not spun up by accretion, in contrast to the standard formation scenario for millisecond pulsars.

Here we argue in favor of this third class of models. We therefore suggest that many or all isolated MSPs may have simply been born as they are now. This alleviates potential problems with the birthrate of MSPs versus the birthrate of low-mass X-ray binaries (LMXBs; these are usually considered the progenitors of all MSPs in the recycling scenario, and in our model are still the progenitors of binary MSPs). This picture also suggests, but does not require, that supernovae may produce a bimodal distribution of neutron star magnetic fields and possibly spin rates.

We begin our argument in § 2 by showing that in most scenarios the planets must have formed in approximately their current location. We then show that models requiring the neutron star to be spun up by accretion subsequent to the supernova typically run into at least one of the following problems: (1) if the planets form before or during the spin-up, they will be evaporated by the accretion luminosity, and (2) if the planets form after spin-up, they must form from some remnant disk, but the particle luminosity from the neutron star is sufficient to disperse a tenuous disk of material faster than it can be supplied by, e.g., evaporated material from a companion. We also argue that the lack of planetary bodies with masses greater than Ceres around other isolated millisecond pulsars (Wolszczan 1999) strongly constrains the formation of this system, and in particular suggests a probabilistic scenario in which isolated MSPs either capture enough mass to form planets or capture virtually no mass, rather than a smooth distribution in between. In § 3 we summarize the allowed formation histories, and we discuss the implications of such a formation scenario for the MSP population in § 4. We present our conclusions in § 5.

2. PHYSICAL CONSTRAINTS ON MODELS

It is useful to consider first the evolutionary path leading to the current high rate of spin of the pulsar. Clearly, it either was born with and has sustained a high spin frequency, or it was spun up by accretion at some point in its evolution. The accretion scenarios can be further subdivided according to whether the planets formed before, during, or after the spin-up phase, and whether they formed at their current locations or formed farther out and later migrated inward. In this section we therefore first consider dynamical migration, then investigate the effects of photon and particle luminosity on gas and planetesimals in a disk.

2.1. *Dynamical Migration*

In the section following this one, we put strong constraints on possible planetary formation mechanisms by assuming that the planets formed at their current distances from the pulsar. Here, we examine the validity of this assumption by considering possible mechanisms by which the planets may have formed farther from the pulsar and subsequently migrated inward to their present positions. In order for such migration to have occurred, the planets must have interacted with an amount of mass roughly comparable to their own. There are three main possibilities: (1) gravitational scattering by other planets or protoplanets; (2) interaction with a disk of planetesimals; and (3) interaction with a gas disk.

Gravitational scattering of protoplanets can be quickly ruled out as a substantial source of radial migration for the pulsar planets under consideration. In this scenario, we model interactions between planets as randomly oriented velocity impulses, and assume that several to several tens of scattering events have happened during the formation of the system. Large stochastic eccentricities and inclinations are expected in systems in which significant gravitational scattering has occurred. For example, if cumulative scattering events are capable of changing planetary semimajor axes by a few tens of percent, they will also be strong enough to induce orbital eccentricities of the order of 0.2 and inclinations above 10°. While large inclinations cannot be ruled out in the PSR 1257+12 system, the near circular orbits of all three planets argue strongly against significant gravitational scattering.

Interactions with a disk of gas or planetesimals are required to attain the nearly circular orbits that are observed. Can these interactions also cause planets to migrate significantly? In the case of planetesimals in the PSR 1257+12 system, the answer is again no. Escape velocities from Earth-sized planets are of the order of 15 km s^{-1}, while the orbital velocity of even the outermost pulsar planet is of the order of 50 km s^{-1}. Since orbital velocities dominate escape velocities, gravitational scattering of planetesimals is relatively weak. Even the outermost planet cannot eject planetesimals from the system unless an unlikely sequence of multiple favorable close approaches occurs; collisions between planets and planetesimals are much more likely. The planets, therefore, absorb the vast majority of the planetesimals while nearly conserving the total angular momentum of the system. The most that can happen is that the inner and outer planets separate somewhat; there is no systematic inward migration. In this scenario, conservation of angular momentum implies that the three planets could not all have formed farther from the pulsar than they are now, thereby avoiding the destructive mechanisms that we discuss below.

Finally, interactions with a gas disk can cause solid objects to move inward toward the pulsar. So that angular momentum is conserved, an equivalent amount of gas must be offset outward. If the composition of the gas is roughly solar, the solids that condense to form the planets account for at most a few percent of the total mass. The rest of the mass remains in gaseous form in an extended thickened disk encircling the pulsar. Planet-sized objects raise waves in the disk, and the gravitational perturbations of these waves put torques back on the planets, which can systematically change their orbits. The details of how this occurs depend most strongly on the mass of the planet and the radial density profile of the disk. Given a large disk mass, planetary migration by this mechanism could be substantial. However, if the pulsar is to be spun up by accretion, the $\sim 10^7$–10^8 yr spin-up timescale is long compared with the expected $\sim 10^6$–10^7 yr survival time of protoplanetary disks (Bachiller 1996). We expect that the lifetime of a protoplanetary disk will be especially short in the high-luminosity environment of the pulsar. Therefore, for most of the spin-up time, the planets must have been unshielded by a disk and close to their present distances.

2.2. *Accretion Luminosity and Ablation*

If the planets formed at approximately their current locations, they could be affected by the photon or particle luminosity from the neutron star, either during accretion or after. Here we consider ablation of the planets by the photon luminosity produced by accretion, and in the next section we discuss ablation of a protoplanetary disk and planetesimals by high-energy particles produced by pulsar spin-down.

Higher luminosity during accretion means more rapid and effective ablation of the planets, so in order to be conservative we calculate the minimum luminosity required for spin-up. The luminosity, in turn, is related to the accretion rate, which can be estimated by magnetic torque balance arguments (e.g., Ghosh & Lamb 1979). These arguments show that if the star is spun up entirely by accretion (the standard assumption in LMXB recycling scenarios), then the equilibrium spin frequency, at which the net torque vanishes, can be characterized by the orbital frequency at some radius r_t. The required accretion rate increases rapidly with decreasing r_t and hence with increasing stellar spin frequency, so the most conservative assumption is that the neutron star is currently spinning at the highest frequency it has ever had. In reality, substantial spin-down via magnetic dipole braking has likely taken place.

To calculate the luminosity required for a given r_t, we write $r_t = \omega_c r_A$, where ω_c is the "fastness parameter" and r_A, the Alfvén radius, is (see, e.g., Shapiro & Teukolsky 1983, p. 451)

$$r_A = 3.5 \times 10^8 L_{37}^{-2/7} \mu_{30}^{4/7} \left(\frac{M}{M_\odot}\right)^{1/7} R_6^{-2/7}\ \mathrm{cm}\ . \quad (1)$$

Several recent analyses (e.g., Li & Wang 1999; Psaltis et al. 1999) have concluded that $\omega_c > 0.8$. Therefore,

$$r_t = 2.8 \times 10^8 (\omega_c/0.8) L_{37}^{-2/7} \mu_{30}^{4/7} \left(\frac{M}{M_\odot}\right)^{1/7} R_6^{-2/7}\ \mathrm{cm}\ . \quad (2)$$

Here $L = 10^{37} L_{37}$ ergs s^{-1}, $\mu = 10^{30}\mu_{30}$ G cm^3, and $R = 10^6 R_6$ cm. From this equation we see that higher ω_c means larger r_t for a given luminosity, implying a lower stellar spin frequency. Therefore, the required luminosity increases with increasing ω_c. The equilibrium period is then $P_{\rm eq} = 2\pi(r_t^3/GM)^{1/2}$ (valid in Schwarzschild spacetime). This period cannot exceed the current rotational period of PSR 1257+12, $P = 6.2 \times 10^{-3}$ s. Moreover, models and observations of neutron star low-mass X-ray binaries suggest that accretion may cause the field to decay (see, e.g., Bhattacharya et al. 1992), so the field strength during accretion was at least as large as it is now. Therefore, we can solve for the minimum luminosity during accretion by setting $P_{\rm eq} = P$ and substituting in $\mu = 8.8 \times 10^{26}$ G cm^3 and $R_6 = 1$. The result is $L_{37} > 0.9(M/M_\odot)^{-2/3}(\omega_c/0.8)^{7/2}$. Even for a relatively massive neutron star with $M = 2\ M_\odot$, this is 5×10^{36} ergs s^{-1} $\approx 10^3\ L_\odot$.

At the distance of the inner planet, $r = 3 \times 10^{12}$ cm, the equivalent blackbody temperature for a perfectly absorbing surface is $T = [L/(\sigma 4\pi r^2)]^{1/4} = 5300$ K even for $M = 2\ M_\odot$. At the $\sim$keV energies typical of accretion emission from a neutron star surface, the absorption cross section is much greater than the scattering cross section, especially if heavy elements are present, so the assumption of nearly perfect absorption is likely to be good. Furthermore, the dependence on albedo is very weak (only the 1/4 power), so the temperature estimate above is robust. This temperature is sufficient to boil any element likely to be in abundance around the star. Therefore, either direct evaporation or ablation due to the impinging X-rays can proceed efficiently.

Consider evaporation first, assuming that the innermost planet is formed of an element of atomic weight A. We also conservatively assume a density $\rho \approx 10$ g cm^{-3}; a more realistic, less dense planet would be more easily evaporated. The radius of the planet is then 1.3×10^8 cm, so the scale height of the atmosphere created is $h = kT/mg = 1.2 \times 10^9 A^{-1}$ cm. If the planet is composed of elements significantly lighter than iron ($A = 56$), then the scale height is comparable to R, so the illumination will cause the planet to swell up and disperse on about a sound crossing time. Even for iron, $h \approx 0.15R$. The weakening of gravity with increasing radius means that a substantial fraction of the gaseous iron will be at large enough distances to escape; for example, a calculation including the r^{-2} dependence of gravitational acceleration shows that $\approx 1\%$ of the planet will be at radii $> 4R$, and $> 0.1\%$ will be unbound. Therefore, even if the innermost planet is pure iron, it will be evaporated in a few hundred sound crossing times, a matter of only days. Note that even if there is an optically thick disk present, the blackbody temperature at the orbital radius of the planet is unchanged, so evaporation will proceed efficiently.

A separate argument, which is also important for the two outer planets, is that the X-ray illumination can ablate the planets directly. Numerical analyses (e.g., Phinney et al. 1988; van den Heuvel & van Paradijs 1988) suggest that a fraction $\sim 10\%$ of the luminosity intercepted by a gaseous companion to a neutron star ablates that companion, and that the material leaving the companion does so at approximately the escape velocity. A rough estimate of the timescale for ablation, therefore, is obtained by dividing the gravitational binding energy of the companion by 0.1 times the X-ray luminosity intercepted by the companion. If an optically thick disk exists at this time it will be able to shield the planets from ablation. However, as we show in the next section, the required mass of such a disk is comparable to the mass of the planets, and hence a disk massive enough to shield the planets will drag them rapidly inward as the disk accretes.

At a distance of 3×10^{12} cm, about 10^{-9} of the total luminosity falls on the surface of a planet of radius $\sim 10^8$ cm, so 10^{-10} of the total energy released by accretion is used for ablation of the innermost planet. This total energy may be estimated from the amount of angular momentum necessary to spin up the star to its current rotation frequency. That frequency is $\omega \approx 10^3$ rad s^{-1}, so for a neutron star with a typical moment of inertia $I \approx 10^{45}$ g cm^2, the angular momentum is 10^{48} g cm^2 s^{-1}. Assuming that the star was rotating much more slowly than this prior to accretion, this is the amount of angular momentum that must be accreted. At the $\sim 5 \times 10^6$ cm radius at which the torque is exerted, the specific angular momentum is close to its Newtonian form $l \approx (GMr)^{1/2}$, or $l \approx 3 \times 10^{16}$ cm^2 s^{-1} for $M = 1.4\ M_\odot$. The neutron star must therefore accrete 3×10^{31} g $\approx 0.01\ M_\odot$ to spin up to its current frequency. Assuming that the accretion efficiency is $L/\dot{M} \sim 0.2c^2$, typical for accretion onto the surface of a neutron star, this will release a total of 6×10^{51} ergs, taking 4×10^7 yr at 5×10^{36} ergs s^{-1}. Multiplying by $\sim 10^{-10}$ yields 6×10^{41} ergs. If we again conservatively assume that the companion is pure iron, the binding energy at a radius 1.3×10^8 cm is about $GM^2/R = 4 \times 10^{36}$ ergs. This is only 10^{-5} of the ablation energy. Therefore, even if evaporation were somehow suppressed, the inner planet would be ablated within a few hundred years, much shorter than the $\sim 10^7$–10^8 yr spent in the luminous LMXB phase.

The outer planets would also be in danger. Their semimajor axes are approximately twice that of the inner planet, so the temperature is down by a factor of $2^{1/2}$, to ~ 3800 K. This will boil any abundant element except pure carbon, so again ablation would be highly efficient unless the outer planets were truly diamonds in the roughest of environments. If the densities of the outer planets are the same as that of the inner planet, their radii scale like $M^{1/3}$, so their binding energies scale as $M^2/R = M^{5/3}$. Their surface area scales as $M^{2/3}$, so the ratio of binding energy to intercepted luminosity, assuming the same radiation flux, scales as M. At twice the distance and ~ 200 times the mass of the inner planet, the ratio of binding energy to intercepted luminosity is a factor ~ 1000 larger for the outer planets, which means that they will be evaporated in a time $\sim 10^5$ yr, still a factor ~ 100 shorter than the accretion time. Therefore, all three planets would be destroyed if they were in their current positions and the pulsar was spun up by accretion. This shows that if the pulsar was spun up by accretion, that accretion had to take place before planets existed in the system.

These constraints are summarized in Figure 1. Here we plot contours of constant destruction time (from the combined effects of evaporation and ablation) against the mass of the object and the photon flux received, from 10^0 yr (*leftmost contour*) to 10^7 yr (*bottom right contour*). To give a conservative upper limit to the destruction time we assume planets made of pure iron with densities of 10 g cm^{-3}. The locations in this plot of the three planets in the PSR 1257+12 system are indicated with filled circles. For high fluxes, direct evaporation destroys the planet quickly, but for lower fluxes ablation becomes more important, hence the change in the slopes of the lines around a destruction time of $\sim 10^5$ yr. At a flux less than $F \approx 5 \times 10^9$ ergs cm^{-2} s^{-1}, so that iron remains liquid, destruction by either evaporation or ablation is highly inefficient.

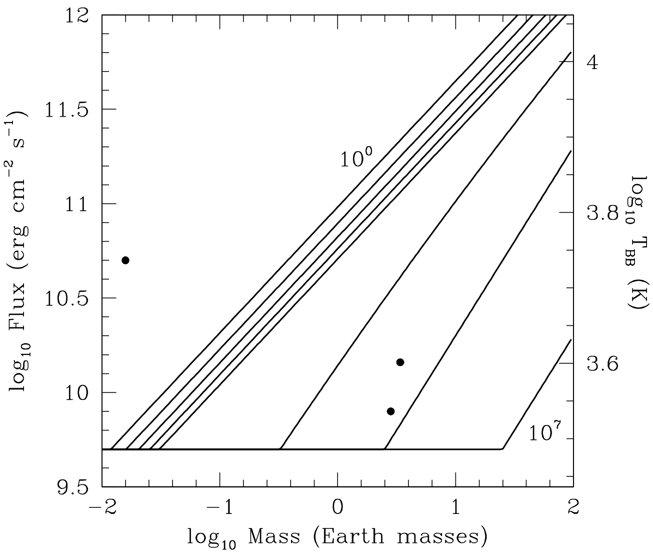

FIG. 1.—Destruction time as a function of planetary mass and photon flux. The equivalent blackbody temperature is plotted on the right-hand axis. As discussed in § 2.2, if the illuminating flux due to accretion luminosity is high enough to make a planet gaseous, either evaporation or ablation can destroy the planet efficiently. This figure shows the destruction time from the sum of these two processes, vs. log flux and log mass of the planet. For comparison, the solar flux at Earth is $\approx 1.3 \times 10^6$ ergs cm^{-2} s^{-1}. The time contours are spaced by 1 order of magnitude each in years, from 10^0 (*far left*) to 10^7 (*far right*). We assume conservatively that the planets are pure iron, with a density of 10 g cm^{-3}. More realistic compositions would be less dense, and hence easier to destroy. Below a flux of 5×10^9 ergs cm^{-2} s^{-1} ($T_{BB} = 3000$K) iron is molten, not gaseous, so evaporation and ablation are negligible. At very high fluxes the scale height of the atmosphere is significant compared to the planetary radius, so evaporation proceeds rapidly. This is the case for the contours from 10^0 to 10^4 yr. At lower fluxes, evaporation is inefficient and ablation takes over, hence the different slopes of the 10^6 yr and 10^7 yr contours. The slight change in slope in the 10^5 yr contour results from the transition between the evaporation and ablation regimes. The current locations of the three planets in the PSR 1257+12 system are shown by filled circles, assuming inclinations of $\sin i = 1$. Clearly, the innermost planet is well into the evaporation regime, whereas the two outer planets are in the ablation regime.

2.3. *Effect of Pulsar Particle Luminosity*

The previous section concentrated on the effect of photon luminosity on already existing planets. Now consider the effect of particle luminosity on a protoplanetary disk. This is of relevance to models of the PSR 1257+12 system such as that of Banit et al. (1993), in which planets form from matter ablated from a companion star. It is also important in projecting whether any millisecond pulsars are expected to have planetary systems consisting solely of small, asteroid-sized objects. We show that the particle luminosity is great enough that if there is a time in the evolution of the system when a massive disk does not exist, then a massive disk cannot form because it would be ablated efficiently by the particle luminosity.

The spin-down energy of isolated pulsars is thought to be released primarily in the form of highly relativistic particles. These particles interact with matter in a fundamentally different way than do X-rays. X-rays interact with electrons, and are not energetic enough to eject nuclei in one collision. In contrast, the relativistic particles are typically nuclei that interact with other nuclei. Their energy is enormous compared with any relevant binding energy (gravitational or chemical), and hence can eject a particle in a single collision. Therefore, whereas X-ray ablation has a threshold in intensity, ablation by relativistic particles always occurs, albeit at negligible rates in some cases.

If the disk is optically thin to these particles, then only a small fraction of the spin-down energy is imparted to the disk. Any impacts will deposit far more than the specific binding energy, and hence any nucleus in the disk hit by a high-energy particle will be sent to infinity, but the energy per particle will be so high that the resulting mass flux from the disk will be small. If we now imagine that the optical depth of the disk is increased, then a larger and larger fraction of the spin-down energy is transferred to the disk. If the disk is still optically thin to the high-energy particles, then each high-energy particle only interacts with one disk nucleus, and the mass flux will scale roughly with the optical depth of the disk. However, when the optical depth to the high-energy particles exceeds unity, then each high-energy particle from the neutron star will interact with more than one target nucleus, and the collisions will spawn further high-energy particles that interact in turn. The energy imparted per particle is therefore diminished, meaning that the mass flux from the disk (which depends on the total energy deposited in the disk divided by the average energy per ejected particle) is increased more rapidly than the optical depth. If, however, the optical depth is very large, then the average energy per particle drops below the gravitational binding energy, and the mass flux drops quickly. The maximum mass flux therefore occurs when the average energy per particle is comparable to the binding energy.

Similar considerations apply to the formation of a planet from grains in such an environment, assuming that the grains are unshielded from the pulsar particles. Small grains are affected little, because they are optically thin. By contrast, larger rocks (with optical depth slightly larger than unity) are exposed to the full flux of the particles, and again the mass flux produced by the particles peaks when the average energy per particle is comparable to the binding energy, although here the binding energy is chemical instead of gravitational.

If there is a supply of matter to a nascent disk (as in the picture of Banit et al. 1993, in which the supply comes from the ablation of the stellar companion), then the mass of the disk depends on whether the supply rate $\dot{M}_{\rm supply}$ is greater than or less than the maximum rate $\dot{M}_{\rm max}$ at which ablation can remove mass. If $\dot{M}_{\rm supply} > \dot{M}_{\rm max}$ then the disk increases steadily in mass, in principle indefinitely. If $\dot{M}_{\rm supply} < \dot{M}_{\rm max}$ then the disk will reach an equilibrium mass when ablation balances supply.

Let us now quantify this picture. Ultrarelativistic particles interacting with protons have a stopping column depth of about $\sigma_p = 100$ g cm^{-2} (e.g., Slane & Fry 1989). At the distance $R = 3 \times 10^{12}$ cm of the inner planet in the PSR 1257+12 system, the gravitational binding energy is about $U = 10^{14}$ ergs g^{-1}, and the area of a sphere at radius R is $A \approx 10^{26}$ cm^2. The current spin-down luminosity of the pulsar is $\dot{E} \approx 10^{34}$ ergs s^{-1}. If the disk subtends a solid angle that is $\epsilon = 0.1$ of the whole sphere, this means that the maximum mass flux in the wind is $\dot{M}_{\rm max} = \epsilon \dot{E}/U = 10^{19}$ g s^{-1}. To estimate $\dot{M}_{\rm supply}$ we assume a supply of matter due to evaporation of a stellar companion (as in the "black widow" pulsar PSR 1957+20). We also make the generous assumption that the evaporation rate is equal to that in the black widow pulsar even though the spin-down luminosity of PSR 1957+12 is 10 times less than that of PSR 1957+20. Then $\dot{M}_{\rm supply} = 10^{17}$ g s^{-1}. This is less than $\dot{M}_{\rm max}$ by 2 orders of magnitude, and hence an equilibrium disk mass will be reached. Assuming that equilibrium occurs at an optical depth of a few, the total mass in equilibrium is about 10^{27} g. In addition, since the mass is coming from the companion, about 97% of this mass is expected to be in hydrogen or helium, leaving no more than 10^{26} g and probably a factor of a few less in metals, compared with the $\sim 4 \times 10^{28}$ g in the two largest planets in the system. Moreover, relativistic particles would shatter complex nuclei and reduce the metal fraction even more. The remaining mass in metals would be far less than needed to form the current planets.

We now consider whether planets can form in this environment from small grains, if the grains are not shielded from the pulsar radiation. The relevant binding energy U is molecular, which we assume is ~ 1 eV per molecule or about 10^{11} ergs g^{-1}. The particle flux at the distance of the innermost planet is $F \approx 10^{34}$ ergs s^{-1}/10^{26} cm^2 = 10^8 ergs cm^{-2} s^{-1}. The mass-loss rate from the rock due to radiation therefore has a maximum $\dot{m}_{\rm max} = FA/U$, where $A = \pi a^2$ is the cross-sectional area of the rock. For a stopping column depth of 100 g cm^{-2}, the radius of a grain with optical depth $\tau \sim 10$ (so that the average energy per particle is close to the molecular binding energy) is $a \sim 100$ cm. The timescale for evaporation of a particle of mass $m = 4/3\pi a^3 \rho$, where ρ is the density, is then $t_{\rm evap} = m/\dot{m} = 4/3 \rho a U F^{-1}$. This is $< 10^6$ s for $a < 100$ cm and any reasonable density. Therefore, in this environment rocks cannot grow from small grains to radii greater than a few tens of centimeters. If larger planetesimals are present in the system prior to exposure to the particle radiation, then the radiation will tend to ablate the planetesimals. We can estimate the rate of ablation by computing the area strongly affected by the high-energy particles. This area is the region with a path length through the planetesimal such that the energy per particle at exit exceeds the chemical binding energy. Calling this distance d and the planetesimal radius R, the cross-sectional area with a path length less than d turns out to be simply $\frac{1}{4}\pi d^2$, independent of R if $R > d/2$. The mass-loss rate $\dot{m}$ is therefore also independent of R, and hence the evaporation time scales as $m \sim R^3$. Hence, within 10^7-10^8 yr all planetesimals of radius less than ~ 1 km will be evaporated by the 10^{34} ergs s^{-1} flux from PSR 1257+12. The lower limit to the survival radius may be even larger, because the main face of a planetesimal with radius 1 km has an area a factor of a million larger than πd^2, with $d \approx 100$ cm. A small fraction of this incident radiation may ablate additional matter. The lower limit to planetesimal radius is thus probably $\sim$1–10 km.

Particle radiation therefore prevents the formation of planets when the disk is not very optically thick to the high-energy particles. Thus, for planets to form around a pulsar, the disk must have sufficient mass to shield itself from the radiation. That is, the energy of the relativistic particles must be degraded sufficiently that their average energy is less than the binding energy. In a single collision, the most efficient reduction of energy occurs when both the primary nucleus and the target nucleus receive half of the original energy. One can therefore conservatively assume that in each interaction, the maximum energy per particle is reduced by a factor of 2, so that after n scatterings the typical energy after propagation through the medium is reduced by a factor $\sim 2^n$. As long as the particles are relativistic, forward beaming means that the number of scatterings after traversing an optical depth τ is $n \sim \tau$. When the particles are nonrelativistic, the beaming is minor, and thus the number of scatterings increases more rapidly, as $n \sim \tau^2$. Assuming an initial Lorentz factor of $\sim 10^3$–10^5, the minimum optical depth required to reduce the particles to nonrelativistic energies is therefore conservatively $\tau \sim 10$–

20. Assuming a disk covering fraction of $\epsilon \sim 10\%$, the required disk mass is then at least $M_{\rm tot} = \epsilon \pi r^2 \tau \sigma_p$, or about 1–2 × 10^{28} g at a radius $r = 3 \times 10^{12}$ cm. If the initial disk mass is less than this, we expect no planets to form. Given that this is already greater than one Earth mass, this may mean that isolated millisecond pulsars either have planetary-mass objects around them or nothing, and thus that we should not expect systems with just asteroids. If so, it suggests that microsecond timing noise in millisecond pulsars is not dominated by asteroids, as was discussed as a concern by Wolszczan (1999).

2.4. *Constraints from the Lack of Planets around Other Isolated MSPs*

In addition to the constraints just listed, formation mechanisms for planets around millisecond pulsars have another constraint, common to scenarios proposed for any rare object: the mechanism cannot be *too* good, or else more examples would be seen. In this case, why are there no other planets around isolated MSPs, given the extreme sensitivity of MSP timing to such perturbations? Of course, it could be that the PSR 1257+12 system had a unique history, but here we make the Occam's razor assumption that all isolated millisecond pulsars are formed in the same way.

Of the nine isolated MSPs in the Galactic disk, only PSR 1257+12 has confirmed planets around it, even though asteroid-sized objects with orbital periods of a few years or less could be detected with current techniques (Wolszczan 1999). The gap of at least 3 orders of magnitude between these mass upper limits and the mass of the planets around PSR 1257+12 suggests that the pulsar planetary system is not simply in the high-mass tail of a distribution, but is instead the result of a rare event. This argues against disrupted companion scenarios (Podsiadlowski et al. 1991; Fabian & Podsiadlowski 1991), in which there is always 0.01–0.1 $M_\odot$ in the disk after disruption. Such a high disk mass is expected to be extremely favorable for the formation of planets, because the column depth is high enough to shield the matter from the pulsar flux (see above). It would therefore be surprising that only one MSP has planetary-mass objects around it. Instead, an idea such as one in which supernova recoil kicks the neutron star through the companion (Phinney & Hansen 1993) has many desirable properties. In this picture, only if the neutron star intersects the companion will it accrete mass and potentially form planets. Otherwise, virtually no mass is accreted and the star simply spins down in isolation. We explore this idea further in the next section.

3. ALLOWED FORMATION HISTORIES

The physical constraints in § 2 can be summarized as follows. (1) If PSR 1257+12 was spun up by accretion from a companion, then ablation makes formation of the planets before or during this accretion highly implausible. (2) Particle radiation from the pulsar will destroy a disk if the disk has too low a mass. It will also prevent large grains from forming in an unshielded environment. Therefore, either the supply of mass to the disk must exceed the mass-loss rate, or the disk mass must initially be well in excess of $\sim 10^{28}$ g. (3) The formation mechanism cannot be inevitable for isolated millisecond pulsars, or other examples would be seen.

The most plausible mechanisms are, therefore, those in which an isolated neutron star sometimes (in $\sim 10\%$ of cases) obtains a disk of mass $> 10^{28}$ g from which planets form, but in most cases does not acquire significant mass. This favors ideas such as the supernova recoil scenario (Phinney & Hansen 1993). Given that 1 out of 9 isolated MSPs have planets, then prior to the supernova the stellar companion must subtend a few percent to a few tens of percent of the sky, assuming that the direction of the kick delivered to the neutron star is not correlated with the direction to the companion. This would require a separation of a few times the radius of the presupernova star, if the stellar companion is also a massive star, implying a separation of $\sim 10^{12}$–10^{13} cm. The observed distribution of initial orbital separations $a_{\rm init}$ of massive stars is $\sim 1/a_{\rm init}$ (e.g., Kraicheva et al. 1979), so tens of percent of massive binaries are expected to be in this range of separations.

If the neutron star receives a kick in the direction of the companion, then in order to eventually form planets it needs to capture at least 10^{28} g from the companion. We can make a very rough estimate of the mass captured by making a Bondi-Hoyle type assumption that the matter captured from the companion star has an impact parameter b relative to the neutron star that is less than $b_{\rm max}$, where $b_{\rm max}$ is defined such that the effective orbital velocity $v_{\rm orb} = (GM_{\rm NS}/b_{\rm max})^{1/2}$ is equal to the kick velocity $v_{\rm kick}$ of the neutron star. The proper motion of PSR 1257+12 is measured at 300 km $\rm s^{-1}$ (Wolszczan 1999); identifying this as the kick velocity yields $b_{\rm max} \approx 10^{11}$ cm. If this matter is captured with an efficiency $\epsilon \approx 10^{-3}$–10^{-1}, then the amount of matter captured from the companion is typically $M_{\rm cap} \sim \epsilon b_{\rm max}^2 R_c \bar{\rho}_c$, where R_c and $\bar{\rho}_c$ are the radius and average density of the companion, respectively. For a companion of mass 10 $M_\odot$, radius $R_c = 10^{12}$ cm, and average density $\rho_c = 10^{-2}$ g $\rm cm^{-3}$, the captured mass is $\approx 10^{29}$–10^{31} g, which is in the needed range. Although the initial scale of the disk, $b_{\rm max} \approx 10^{11}$ cm, is 2 orders of magnitude smaller than the current planetary system, conservation of angular momentum implies that the disk will spread significantly as it evolves. Planets will form only after the outermost portions of the disk have spread and cooled enough to allow efficient condensation of solids (Lissauer 1993). Thus, planetary systems formed by this mechanism should consist of terrestrial mass planets confined within a few AU of the central pulsar.

Such a disk mass would effectively shield the protoplanets from the radiation of the neutron star. In addition, when particle radiation dominates the emission from the pulsar (as opposed to accretion radiation), the luminosity of $\sim 10^{34}$ ergs $\rm s^{-1}$ would produce a blackbody temperature of only a few hundred Kelvin at the distances of the planets. At such temperatures, ionization is low and molecule and grain formation is thought to proceed efficiently (Lissauer 1993). This is therefore an environment supportive of planet formation, particularly given that the characteristic age $\tau_c \sim 10^9$ yr of the pulsar is much longer than the $\sim 10^7$ yr required for planet formation. The allowed mass range of the disk would also accommodate a fourth planet with a mass $\lesssim 100 M_\oplus$ if the existence of this planet is confirmed by a long baseline of observations.

This scenario implies that many isolated neutron stars may have planets in orbit around them. Why, then, are there no other known planets around isolated pulsars, millisecond or otherwise? There is a reported detection of a planet in the PSR B1620-26 system, but this is a triple system in a globular cluster and probably formed by a different mechanism, such as an exchange interaction (Sigurdsson 1993; Ford et al. 2000). We attribute the paucity of detected pulsar planets to the stringent conditions for such planets to be observable. Young radio pulsars such as the Crab or Vela are extremely powerful emitters of particle radiation. For example, the spin-down luminosity of the Crab pulsar, which is thought to emerge primarily as high-energy particles, is $\sim 5 \times 10^{38}$ ergs s^{-1}. This will prevent planetary formation within several AU, and will continue to do so until the spin-down luminosity drops by more than an order of magnitude. In addition, the formation of planetary-mass objects is thought to require $\sim 10^7$ yr, by which point any pulsar with a magnetic field $\sim 10^{12}$ G or higher will have spun down past the death line, and will therefore not be detectable as a pulsar. As a consequence, planets would not be detectable around the neutron star. Finally, even if planets are present around a young, high-field pulsar, the timing noise makes the detection of sub–Earth-mass planets difficult (Wolszczan 1999).

Hence, if an isolated neutron star has planets around it, the only chance for their presence to be detected is for the neutron star to have a weak magnetic field, so that it remains a pulsar long enough for planets to form. For the pulses to be detected, the spin frequency must then be high, otherwise the total spin-down energy is too low. This means that the star is born with a high frequency, and that accretion from any remnant disk does not spin the star down significantly. With these constraints on observability, it is not surprising that there is only one known planetary system around an isolated pulsar.

4. IMPLICATIONS FOR MILLISECOND PULSARS

Our picture requires that the neutron star in PSR 1257+12 was born with approximately its current magnetic field strength of $B \approx 10^9$ G. If it were instead born with a $\sim 10^{12}$ G magnetic field, then it would have spun down rapidly to a period of the order of seconds, either because of magnetic dipole spin-down or because of accretion torques. To be spun-up by accretion to millisecond periods, the accretion would have had to proceed at near-Eddington rates after the field had decayed to $B \sim 10^9$ G. The decay time is at least 10^7–10^8 yr for solitary pulsars (Bhattacharya et al. 1992). Moreover, the existence of neutron stars with $B \sim 10^{12}$–10^{13} G in high-mass X-ray binaries, which often accrete at near-Eddington rates and have accretion lifetimes of millions of years, suggests that even active accretion does not cause the field to decay in less than $\sim 10^6$ yr. Therefore, the accretion rate would have had to be close to Eddingtonian after several million years. Studies of accretion from a remnant disk (Cannizzo, Lee, & Goodman 1990) show that the system becomes self-similar quickly and that the accretion rate drops like a power law in time, $\dot{M} \propto t^{-7/6}$; thus, such a high accretion rate millions of years after the onset of accretion would imply an unrealistically high initial accretion rate.

We also suggest that the initial spin frequency of the neutron star was close to its current value. Otherwise, the star would have to be spun-up by accretion. Even if the initial field was weak, for accretion from the disk to spin the star up to its current rate would again require near-Eddington accretion for several million years, and the low accretion rate tail of the accretion from the disk is likely to slow the star down below its current spin rate. Therefore, we propose that the pulsar in this system, and by extension perhaps all isolated millisecond pulsars, was born with approximately its current spin rate and magnetic field strength. We emphasize that these considerations need not apply to isolated millisecond pulsars in globular clusters, in which there are other possible formation channels for isolated MSPs (e.g., exchange interactions; Sigurdsson 1993).

The link between millisecond pulsars and neutron star low-mass X-ray binaries is well established. Some 80% of millisecond pulsars in the Galactic disk are in binaries, compared with only 1% of slower pulsars (Lorimer 2000). In addition, the recent discovery of 401 Hz pulsations from the LMXB SAX J1808−3658 (Wijnands & van der Klis 1998) is the strongest evidence yet that neutron stars in LMXBs can have spin frequencies comparable to those of MSPs. It was thought a decade ago (Kulkarni & Narayan 1988) that there was a significant discrepancy between the birthrate of short orbital period (<25 day) MSPs and their presumed progenitor LMXBs, in that the pulsar birth rate was 2 orders of magnitude too large. However, better statistics have been collected and the factor is now less than 4 (Lorimer 2000).

Isolated millisecond pulsars may pose a different problem, however. The small number of isolated MSPs makes sample variance a significant concern, but analysis of the current data suggests that isolated MSPs have a lower luminosity than MSPs in binaries, and may have other distinct properties as well (Bailes et al. 1997). In addition, the best estimates of the birthrate of isolated MSPs in the Galaxy, 2×10^{-5} yr^{-1} (Lorimer 2000), are at least 10 times the birthrate estimates for binary MSPs (note, however, that the isolated MSP estimate is strongly influenced by the large weights attached to a few low-luminosity sources). If this rate and these discrepancies are confirmed by future surveys with larger samples, it suggests that isolated millisecond pulsars are formed by a different channel, which does not involve recycling (Bailes et al. 1997).

Our analysis of PSR 1257+12 suggests that the different channel may simply be that some neutron stars are born with fast spins and weak magnetic fields. Birth with rapid spin is compatible with the probable origin of the Crab pulsar and other similar pulsars, which could have been born with millisecond periods. Birth with a weak field is not directly comparable to the known population of young pulsars, although with a birth rate of 2×10^{-5} yr^{-1} in the Galaxy and assuming a supernova remnant lifetime of $\sim 10^5$ yr it is not surprising that no known supernova remnant harbors a millisecond pulsar. It is therefore possible that pulsars born with weak fields are simply at the tail end of a distribution peaked at $B_{\rm init} \sim 10^{12}$ G, and it is equally possible that weak-field isolated pulsars are the product of a completely different set of processes in the supernova, or of rare types of supernovae.

5. CONCLUSIONS

We have argued that the physical constraints on the PSR 1257+12 system, in particular the existence of the small innermost planet, in addition to the lack of planets around other isolated millisecond pulsars, points strongly toward an evolutionary history in which the neutron star had a high initial spin rate and weak initial magnetic field and formed planets from a disk of captured matter. We also predict that in the absence of other planets, objects of asteroid size or smaller will not form around millisecond pulsars, due to ablation by the flux of high-energy particles.

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