THE ASTROPHYSICAL JOURNAL, 399:L95–L97, 1992 November 1

PLANETS IN GLOBULAR CLUSTERS?

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Received 1992 July 8; accepted 1992 August 11

ABSTRACT

The discovery of planets around PSR 1257+12 suggests that planetary systems may be detected around the recycled pulsars found in globular clusters. Planetary systems in dense clusters have lifetimes to disruption due to perturbations by passing stars comparable to or shorter than the pulsar lifetime, and observations of planets in the cores of clusters may reveal planetary systems formally dynamically unstable on time scales short compared to the characteristic age, τ_c, of the system. Planets formed around cluster pulsars will most likely be restricted to semimajor axes of $\sim$0.1–1.0 AU, while "scavenged" planets may be observed in wider orbits, with no stable systems expected in the densest clusters. Observation is most probable in the rich high-density precore collapse clusters such as 47 Tuc.

Subject headings: globular clusters: general — planetary systems — pulsars: general

1. INTRODUCTION

PSR 1257+12 is a classic "recycled" millisecond pulsar (MSP), with a short ($P = 6.2$ ms) period, low inferred magnetic field ($\sim 10^9$ G), and long characteristic age ($\tau_c = P/2\dot{P} \sim$ few $\times\ 10^8$ yr is the spin-down age of the pulsar, assuming a constant magnetic field, where $\dot{P}$ is the period derivative; Wolszczan 1991; Wolszczan & Frail 1992). It is similar to the recycled pulsars observed in Galactic globular clusters (GCs; Phinney & Kulkarni 1992; van den Heuvel 1991), and mechanisms like those that produced the putative planets around PSR 1257+12 may generate planets around cluster pulsars. Various scenarios have been proposed to account for the presence of planets around pulsars. In clusters formation scenarios involving Type II supernovae (Lin, Woosley, & Bodenheimer 1992) or high-mass X-ray binaries (Wijers et al. 1992; Podsiadlowski, Pringle, & Rees 1991) cannot be at work. Only reaccretion from a disrupted companion or an excretion disk, or, possibly, scavenging of a companion's planetary system during a low-mass X-ray binary phase, can apply (Tavani & Brookshaw 1992; Stevens, Rees, & Podsiadlowski 1992; Krolik 1991). We consider the possibility of planet formation or capture around pulsars in globular clusters, and possible parameters of observable systems, given lifetime constraints.

2. CONSTRAINTS ON FORMATION

Theories of planet formation require planetesimals to aggregate out of a dust disk within the thick accretion disk, by coagulation of small particles due to gas drag and perturbations of the particle orbits (Weidenschilling 1980). In the case of recycled pulsars the disk may be an "excretion" disk from an ablated companion (Krolik 1991; Nakamura & Piran 1991; Tavani & Brookshaw 1992), or the remnant of a wholly disrupted star that merged with the neutron star (or heavy white dwarf; Podsiadlowski et al. 1991; Fabian & Podsiadlowski 1991). Such disks may have considerably higher surface densities in early stages of their evolution than the protoplanetary disks normally considered for planet formation. The presence of PSR 1957+20 in the Galaxy and PSR 1744−24A in the globular cluster Ter 5 (Fruchter, Stinebring, & Taylor 1988; Lyne et al. 1990) suggests that this may be a probable formation scenario. Upon reaching a critical size, the planetesimals undergo runaway growth, reaching masses of order 10 $M_\oplus$, before gas accretion commences, if the ambient temperature is low enough (Cameron 1988). The time scale for planetesimal growth is a function of metallicity, and with cluster metallicities, Z, ranging from 10^{-1} to 10^{-3} solar, the presence of sufficient metals to grow planetesimals is a concern. At $Z = 10^{-3}$, the total mass of ice (rocky material) available for aggregation is only 6 (1.5) $M_\oplus$ per $M_\odot$ of disk matter, insufficient to form even a single large planet if the total mass available in the disk is much less than $M_\odot$.

The time scales for planet formation have been studied mostly in the context of the presolar nebula. Following Nakano (1987) we estimate a conservative time scale, $t_{\rm pf}$, for planet formation, assuming a surface density profile, $\Sigma(r) = fr^k$, $r \le r_0$, where f is a normalizing constant, canonically $k = -3/2$. For total disk mass m_d, $f = (k+2)m_d/2\pi r_0^{k+2}$, $k \neq -2$. Assuming the planet formation time scale is dominated by the planetesimal aggregation time scale, $t_{\rm pf} \approx 10^3(r/\Sigma_s[r])$, where Σ_s is the surface density of solids. $\Sigma_s(r) \approx 1.8 \times 10^{-2}(4.2 \times 10^{-3})Z\Sigma(r)$ for ice and C-Si-Fe grains, respectively, for r such that the local temperature is low enough for the respective solids to condense out. Defining $M_{-2} = m_d/10^{-2}\ M_\odot$ for convenient scaling of disk mass, we find the planet formation time scale

$$t_{\rm pf} \approx 4(16) \times 10^6 \frac{1}{Z} \frac{1}{(k+2)M_{-2}} r_{\rm AU}^{1-k} \text{ yr} , \qquad (2.1)$$

for nucleation from ice or C-Si-Fe grains, respectively, and $r_{\rm AU}$ is the radius in AU at which planetesimal growth is taking place. Grain formation cannot take place if the ambient temperature is greater than the vaporization temperature of the grains, approximately 2000 K for C-Si-Fe grains, about 200 K for ice grains, providing a lower limit of $r_{\rm min} = 0.02(2.0)(L_{\rm PSR}/L_\odot)^{1/2}$ AU for C-Si-Fe and ice grains, respectively. It is clear that, except possibly for the lowest metallicity clusters, $t_{\rm pf} \lesssim \tau_c$ for $r \gtrsim r_{\rm min}$, for C-Si-Fe nucleated planets, assuming efficient absorption of the pulsar flux, and pulsar luminosities characteristic of recycled pulsars. The effects of metallicity on the surface density profile of solids in disks are not known. It is possible that the low opacity of metal-poor accretion disks increases the time scale for disk evolution by turbulent viscosity, leading to higher Σ_s and enhanced planet formation efficiency. Formation scenarios involving accretion-induced collapse (Grindlay & Bailyn 1988) or white dwarf collisions (with another white dwarf or a neutron star) provide cases in GCs in which the accreting matter may have a very high metallicity and consequently a short time scale for planetesimal aggregation. Simulations suggest that in neutron star–binary interactions up to half the tidal interactions may be with white dwarfs, assuming a reasonable initial mass function and an evolved binary population, with the heavier C-O white dwarfs having a proportionately larger fractional cross section for tidal encounters (Sigurdsson & Phinney 1992). For $L_{\rm PSR} \sim L_{\rm Edd}$ expected during pulsar spin-up, where $L_{\rm Edd} \approx 2 \times 10^{38}$ ergs s^{-1} is the Eddington luminosity, $r_{\rm min} = 6$ AU for C-Si-Fe nucleated planetesimals, so any planetary formation only commences after spin-up. It is possible that any scavenged planets present with semimajor axis $a_p \lesssim 1$ AU will be ablated completely during spin-up. Most of the accretion disk may be ejected during spin-up, but if the metals from order $10^{-2}\ M_\odot$ or greater are retained, in an annulus from $r_{\rm min}$ to $r_0 \lesssim 2$ AU enough matter is present for planet formation to be possible. It is not necessary to retain the bulk of the gas, as long as the metals have the opportunity to condense out into a thin disk. If PSR 1257+12 scavenged its planets from a companion main-sequence star with a normal planetary system, circularizing the orbits during the accretion phase, a similar mechanism may also operate in clusters, with pulsars retaining primordial planets after disrupting the companion. With the time scales assumed here, primordial planetary formation around main-sequence stars is possible in GCs, and although the encounter between a neutron star and a main-sequence primary may disrupt the planetary system, friction in the envelope of the merged remnant would circularize and shrink the orbits of any surviving planets. This scenario permits the presence of planets in eccentric orbits with $a_p \gg 1$ AU around cluster pulsars in low-density clusters, whereas the time scales for reaccretion would predict maximum $a_p \lesssim 1$ AU and small eccentricities.

If the cluster formation rate is dominated by neutron star–binary star interactions (Phinney & Kulkarni 1992; Sigurdsson 1991), and planets do not form in main-sequence binaries, then scavenging is less likely in GCs, leaving reaccretion from a remnant as the dominant channel for planetary formation in clusters. Scavenging is still possible in the case where the neutron star is in a binary and encounters a single main-sequence star with a planetary system. If the single star has spent a large fraction of the cluster history outside the cluster core, it may possess an extended planetary system, even in the denser clusters.

If pulsar recycling in GCs is dominated by binary encounters, a companion of mass m_c may remain in an eccentric orbit, semimajor axis a_c, about the accreting system (Sigurdsson 1991). The effects on planet formation of a stellar companion in a highly eccentric orbit about a protoplanetary disk are unknown. Perturbations from the companion may disrupt planet formation or may enhance planetary formation by providing density enhancements in the disk and perturbing planetesimal orbits. Even if a stellar companion enhances planetary formation for wide-orbit companions, close companions will prevent any planet formation, and recycled MSPs with stellar mass companions of periods $\lesssim 1$ yr would not be expected to form planets, excepting, of course, contact binaries as discussed above.

3. STABILITY OF PLANETARY SYSTEMS IN GLOBULAR CLUSTERS

Most cluster pulsars are found in the cores of clusters, where the stellar density, $n_4 = n/10^4$ pc^{-3}, may be as high as 10^2 for post-core-collapse (PCC) clusters. At such densities close stellar encounters are frequent, and it becomes necessary to consider the lifetime of planetary systems to disruption. The disruption mechanism may be usefully considered in two parts, direct disruption of the planets' orbits by encounters with field stars with pericenters $p \lesssim a_p$ (colloquially referred to as "ionization" in the literature, by analogy with comparable processes in atomic physics), and the perturbation of the outer planets of a system by more distant encounters, leading to chaotic disruption of the planetary system through dynamical evolution of the orbits. The cross section for a field star of mass $M_* \sim 0.7\ M_\odot$ to approach to within $p_{\rm AU}$ from a neutron star is $\sigma \approx \pi p_{\rm AU}^2(1 + 36/[p_{\rm AU} v_{10}^2])$AU^2, for a relative velocity at infinity of $v_{10} = v_\infty/10$ km s^{-1}. The mean time between encounters, T, is given by

$$T = \frac{3 \times 10^9}{\langle n_4 \sigma_{\rm AU} v_{10} \rangle}\ \text{yr}\,, \tag{3.1}$$

where $\sigma_{\rm AU} = \sigma/\sigma(p = 1\ \text{AU})$. Thus a system like PSR 1257+12 would be expected to be disrupted on time scales short compared to τ_c in PCC clusters like M15, but would not experience direct disruption encounters in lower density clusters such as M13 or M53. Interestingly, the time scales for direct disruption, in the core of the cluster, of a planet in a ~ 1 AU orbit in a medium density cluster like 47 Tuc are comparable to τ_c. For encounters with a pericenter greater than a_p, the planet's orbit is perturbed by the encounter, with the eccentricity, e, and inclination being sensitive to encounters with pericenters of order $3a_p$. For wider encounters the perturbation is exponentially small and can be neglected.

The effective cross section for direct disruption and strong perturbations was evaluated by direct integration of 25,000 encounters between a 1.4 $M_\odot$ ($M_{\rm PSR}$) primary with a 10 $M_\oplus$ (m_p) secondary in an $a_p = 1$ AU, $e = 0$ orbit, and a 0.7 $M_\odot$ (m_c) field star, with $v_\infty = 5$–10 km s^{-1}. The encounters were drawn from a uniform distribution in phase space. Defining a critical velocity v_c, such that for $v_\infty = v_c$ the total energy of the system is zero in the center-of-mass frame,

$$v_c = \sqrt{G\,\frac{M_{\rm PSR}\, m_p}{m_c}\,\frac{(M_{\rm PSR} + m_p + m_c)}{(M_{\rm PSR} + m_p)}\,\frac{1}{a_p}}\,, \tag{3.2}$$

we find for parameters relevant for cluster encounters that $v_\infty/v_c \sim 16$–32. The induced perturbations in semimajor axis, eccentricity, and inclination are not sensitive to the exact mass ratio or relative velocity. The cross section for direct disruption was dominated by encounters with pericenter $p < a_p$, with approximately one-quarter of those encounters directly disrupting the system. An additional quarter of such close encounters led to an increase in the planetary semimajor axis by a factor of 2 or greater, leaving a system likely to experience a second close encounter on a time scale short compared to the time scale for the initial encounter.

If there are several planets in the system, perturbations in e or i of the outer planets greater than order 10^{-2} may induce instability in the planetary system, with time scales of order $10^3 P$ or greater, where P is the period of the outermost planet (Quinlan 1992). As Figure 1 shows, encounters with $p/a_p \lesssim 3$

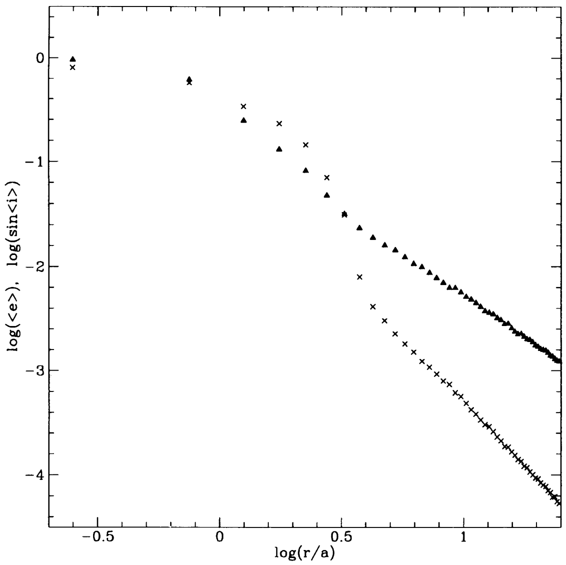

FIG. 1.—Distribution of mean induced eccentricity (*crosses*), and inclination (*triangles*) relative to an original binary axis, for 25,000 encounters, as a function of the ratio of pericenter, r, to planet semimajor axis, a. For r/a greater than those shown, perturbations in e and sin i are exponentially small.

are effective in inducing perturbations of that order, with the inclination more sensitive to distant perturbations (see Phinney 1992 for discussion of analytic approximations to eccentricity perturbations). More effort is needed to understand the effect of perturbations of the inclination of outer planets on planetary system stability. (Recent simulations of solar-type planetary systems suggest that, in fact, inclination perturbations are *not* important in inducing dynamical instabilities in planetary systems; G. Quinlan 1992, personal communication). The transition to chaotic internal dynamics may then lead to ejections of planets or collisions between planets on time scales short compared to τ_c. Colliding planets may remain in a (high e) orbit, or may disintegrate. In case of disintegration, the debris may reaccrete into a planet in a near-circular orbit on time scales short compared to τ_c.

The probability of finding planets around recycled pulsars in PCC clusters such as M15 is small. In low-density clusters such as M13, planets may be found with a semimajor axis as large as 10 AU, with e increasing with a_p. A metal-rich, medium-density cluster, such as 47 Tuc or Ter 5, offers the most interesting prospect for planet detection, with $a_p \lesssim 1$ AU possible, and e increasing with a_p. Observations of planets about pulsars in 47 Tuc–type clusters could constrain planet formation mechanisms and determine the presence of primordial planets in GCs. It is possible that formally dynamically unstable planetary systems may be observed, allowing direct comparison with numerical models. With 10 MSPs now reported in 47 Tuc (Manchester et al. 1991), detection of planets is highly probable, *if* planet formation or scavening mechanisms operate in GCs. Failure to detect planets around any MSPs in low- or medium-density GCs would strongly suggest that the formation mechanisms possible in GCs are not at work, and that low metallicity inhibits planetary formation in disks around pulsars and pre–main-sequence stars.

I would like to thank E. S. Phinney, D. Lin, P. Bodenheimer, P. Artymowicz, N. Murray, and an anonymous referee for helpful discussion and comments.

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