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GENESIS OF A PLANET IN MESSIER 4

STEINN SIGURDSSON
Lick Observatory, University of California, Santa Cruz, CA 95064

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ABSTRACT

The anomalous spin period second derivative of the binary millisecond pulsar PSR 1620−26 in the globular cluster M4 (Backer 1993; Backer, Sallmen, & Foster 1993; Thorsett, Arzoumanian, & Taylor 1993) is best explained by a sub-Jovian mass planet in a moderately eccentric ~7 AU orbit about the pulsar binary (Lyne et al. 1987; McKenna & Lyne 1988; Gross, Kulkarni, & Lyne 1988; Phinney 1993a). We consider formation scenarios for PSR 1620−26. A planet scavenged from a single main-sequence star during an exchange encounter naturally produces systems such as PSR 1620−26. The position of the pulsar just outside the core of M4 is shown to fit naturally with the preferred formation scenario and permit a planet to have survived in the inferred orbit about the binary. It is possible that the orbital eccentricity of the binary was induced by the planet. A confirmation of a planet in eccentric orbit about PSR 1620−26 would strongly suggest that planets form unbiquitously around low-mass main-sequence stars, even stars of low metallicity.

Subject headings: globular clusters: individual: (M4, NGC 6121) — planets and satellites: general — pulsars: individual (1620−26)

1. INTRODUCTION

M4 is a medium-mass ($M \sim 10^5\ M_\odot$) globular cluster, with core density $\rho_0 \approx 3 \times 10^4\ M_\odot\ \mathrm{pc}^{-3}$, located 2 kpc from the Sun. It has a central velocity dispersion, σ, of ~5 km s^{-1} and metallicity of 0.05 solar and formed approximately 15 billion yr ago (Richer & Fahlman 1984; Trager, Djorgovski, & King 1993). The discovery of a period $P = 11$ ms binary pulsar with companion mass $M_c \approx 0.3\ M_\odot$ in a 191 day orbit, of eccentricity $e = 0.025$ (Lyne et al. 1987; McKenna & Lyne 1988; Backer 1993), spurred frequent observations of the system, culminating in the recent discovery of an anomalous second derivative, $\ddot{P} = -2.3 \times 10^{-27}\ \mathrm{s\ s^{-2}}$ of the pulsar spin period (Backer 1993; Backer, Sallmer, & Foster 1993; Thorsett, Arzoumanian, & Taylor 1993). Compared to an observed spin period derivative, $\dot{P}$, of $8.2 \times 10^{-19}\ \mathrm{s\ s^{-1}}$, and expected intrinsic $\ddot{P} = \dot{P}^2/P = 6.1 \times 10^{-35}\ \mathrm{s\ s^{-2}}$, the observed $\ddot{P}$ is seven orders of magnitude too large and, interestingly, of the wrong sign. The pulsar has a characteristic age $\tau_c = P/2\dot{P} = 2.2 \times 10^8$ yr, similar to that of other cluster pulsars, while the timescale for the period derivative to reverse sign, $\tau_p = \dot{P}/\ddot{P}$, is only about 10 yr if $\ddot{P}$ remains constant. With four years of timing data it is unlikely that the anomalous $\ddot{P}$ is due to healing from a "glitch," the fractional change in inertia required for "healing" to continue this long is excessively large. Precession or rapid changes in the pulsar magnetic field cannot account for the observations (Nelson, Finn, & Wasserman 1990). Timing variations due to time-variable plasma delay along the line of sight are ruled out by multifrequency observations (D. Backer, private communication). Alternatively, the $\ddot{P}$ is due to an external cause.

A pulsar moving in a gravitational field with projected acceleration a and jerk $\dot{a}$, will have an observed period derivative

$$\frac{\dot{P}}{P} = \frac{\dot{P}_0}{P_0} + \frac{a}{c}, \qquad (1)$$

where P_0 is the intrinsic pulsar period in the pulsar rest frame and c is the speed of light; other contributions to the $\dot{P}$ are expected to be small (Blandford, Romani, & Applegate 1987; Phinney 1992). Similarly $\ddot{P}$ is dependent on the jerk,

$$\frac{\ddot{P}}{P} = \frac{\ddot{P}_0}{P_0} + \frac{\dot{a}}{c} + \frac{2a}{\tau_c c}, \qquad (2)$$

with $\ddot{P}$ dominated by the second term in the scenarios considered (Blandford et al. 1987; Phinney 1992; Phinney 1993b). It is a priori unlikely that $\dot{P}_0$ (and thus $P_0/\dot{P}_0$) is very different from the observed $\dot{P}$ ($P/\dot{P}$), the P–$\dot{P}$ is consistent with theory of pulsar spin-up (Manchester 1992; Phinney & Kulkarni 1993). Given the fit of PSR 1620−26 on the canonical P–$\dot{P}$ diagram, and ordinary characteristic age, we assume initially that $\dot{P}_0 \lesssim \dot{P}$.

The density of M4 is two orders of magnitude too small for the $\ddot{P}$ to be due to the jerk of the cluster core on the pulsar (Phinney 1993b). It is conceivable that the jerk may be due to an unusually close encounter with a passing field star, but the timescale for such encounters is $O(10^4)$ yr $\gg \tau_p$ and requires that we observe the encounter at an a priori improbable stage (Phinney 1993b). Alternatively, the jerk is due to a planetary mass body close to the binary (Blandford et al. 1987). Solving for a and $\dot{a}$, assuming $\dot{P}_0 \sim \dot{P}$, we find a sub-Jovian mass object in a orbit with a semimajor axis, r_p, of about 7 AU is sufficient to account for the observed $\ddot{P}$ and provides small enough an acceleration to permit the observed $\dot{P}$ (Phinney 1993a). With an orbital period of $24(r_p/10\ \mathrm{AU})^{3/2}$ yr, the low τ_p arises naturally and $\ddot{P}$ may be observed at its current value with reasonable prior probability. Simulations of $\boldsymbol{a} \cdot \boldsymbol{n}$ and $\dot{\boldsymbol{a}} \cdot \boldsymbol{n}$ for planets of different masses in orbits of varying r_p and e with orbital axis at varying angles to the lines of sight $\boldsymbol{n}$ show $r_p \sim 7$ AU and $0 \le e \le 0.7$ fit the current observations for planet masses of order 50 $M_\oplus$.

2. EVOLUTION

The current 0.3 $M_\odot$ companion of PSR 1620−26 is most likely a white dwarf remnant of a ~0.8 $M_\odot$ main-sequence star that was previously in a tighter orbit about the neutron star, the pulsar being spun up to its current period when the star evolved off the main-sequence and transferred mass onto the neutron star as the stellar envelope expanded beyond its Roche lobe, τ_c yr ago. As it evolved, the orbit of the companion expanded and circularized leaving the system observed (Lyne et al. 1987; Rappaport, Putney, & Verbunt 1990; Sigurdsson 1991). The timescale for the disruption of a planet in a $r_p/10$ AU orbit in M4, by encounters with field stars of density $\rho(r)$, is

$$\tau_d[\rho(r)] \sim \frac{5 \times 10^7}{(r_p/10\ \mathrm{AU})[\rho(r)/\rho_0]}\ \mathrm{yr} \tag{3}$$

(Sigurdsson 1992), much less than the age of the cluster (for orbit eccentricity e, $r_p \times (1 + e)$ gives the effective semimajor axis for encounters].

It is very unlikely that any planet could have survived in the current orbit through the evolution of the binary from its formation 15×10^9 yr ago. Assuming the current system started as a main-sequence binary, the original secondary must have initially been in an orbit wide enough to avoid mass transfer as the neutron star progenitor evolved off the main-sequence, in order for its mass to remain low enough to survive for the lifetime of the cluster. Yet for mass transfer to take place, the original secondary must finish in a tight orbit about the newly formed neutron star. This is possible if the supernova in which the neutron star forms provides a kick of just the right magnitude and direction, leaving the secondary in a short-period eccentric orbit. Ignoring the difficulty of forming a planet in such a system, the probability of the planet surviving the kick is vanishingly small and a planet could not remain in this wide an orbit for a cluster lifetime, as passing stars disrupt the weakly bound planet.

We conjecture that the pulsar was originally a member of a massive binary, and that the current 0.3 $M_\odot$ white dwarf companion was not originally a member of this binary but was exchanged into a binary containing the neutron star and a medium-mass white dwarf. The exchange took place *before* the progenitor of the current pulsar companion evolved off the main-sequence. We further conjecture that the planet was originally in a tight ($r_p \lesssim 1$ AU) orbit about this main-sequence star. In this scenario the neutron star originated in a high-mass binary containing a main-sequence star of mass much greater than the current turnoff mass in the cluster (0.8 $M_\odot$). Mass transfer is then unstable, and the neutron star-white dwarf binary would have been a short-period binary, comparable to PSR 0655+64 (Phinney 1992). The then-companion white dwarf would have been $\sim$0.7 $M_\odot$ (Iben & Renzini 1983), more massive than the current companion. Spin-up likely occurred during the evolution of the erstwhile companion, making this a second-generation recycled pulsar.

Such a massive binary would tend to sink to the cluster core through dynamical friction, where the chance of it undergoing close encounters with other stars is highest. The core of M4 is dominated by the most massive single main-sequence stars, assuming the binary fraction is not too large. As the most massive stars evolve off the main-sequence and become less massive white dwarfs, it becomes dynamically favorable for slightly less massive stars to sink into the core. Calculation of the relative encounter probabilities for a massive binary in the cluster core shows that the encounter rate is dominated by turnoff mass stars (see Fig. 1). We can ignore encounters with degenerate stars, as such encounters cannot produce binary pulsars such as PSR 1620−26. An encounter with a main-sequence star at or just below the turnoff mass has a high probability of leading to an exchange of the main-sequence star and the original companion, leaving a hard neutron star–main-sequence binary (Phinney & Sigurdsson 1991). For a neutron star–white dwarf binary with a semimajor axis of order 0.3 AU, the timescale for exchange is of the order 10^{11} yr; thus, if tens of such binaries exist in the cluster, the presence of PSR 1620−26 is not improbable, nor is M4 unique among globular clusters—a similar binary pulsar is observed in the cluster M53, namely, PSR 1310−18 (Kulkarni et al. 1991).

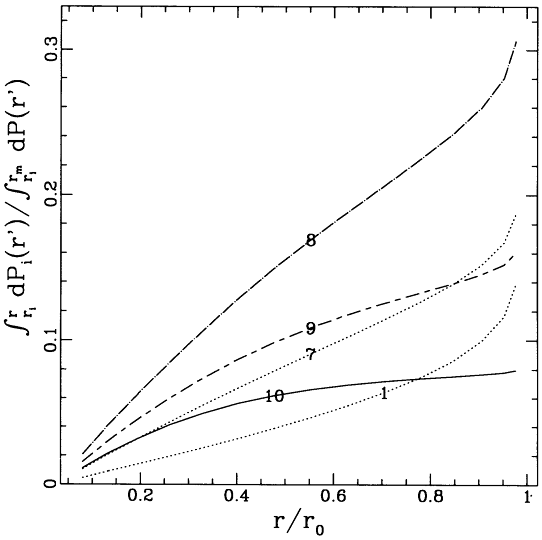

FIG. 1.—Fractional, orbit-averaged, integrated encounter probabilities, P_i, for different mass groups drawn from a Salpeter initial mass function. Mass group 10 is neutron stars, 9 is massive white dwarfs, 8 is turnoff mass stars, (sub)giants, and white dwarfs; lower mass groups are lower-mass main-sequence stars and white dwarfs, covering the range of masses 0.1–0.63 $M_\odot$ in near equal increments. Curves for mass groups 2–6 are omitted to avoid cluttering; the probabilities for those are all less than those shown. Integrated encounter probability is 4.5×10^{-6}. The binary, radius 1 AU, mass 2.1 $M_\odot$, moved in the core of the King model, with core radius r_0, dispersion σ, chosen to fit M4. Velocity at periapsis, r_i, was 1.4 σ, and the half-period to apapsis, r_m, is 1.7×10^6 yr.

3. PLANET SCAVENGING

We have conducted simulations of encounters between neutron star–white dwarf binaries with semimajor axis r_c = 0.1–0.3 AU and turnoff mass main-sequence stars with a 10 $M_\oplus$ planet with semimajor axis $r_{\rm pl} \sim (1.5–9) \times r_c$, with a total of 8000 encounters. The cross section for exchange leaving the main-sequence star bound to the neutron star was $2/3\sigma_0$, where σ_0 is the cross section for encounters with pericenter of r_c or less, consistent with previous results (Hut & Bahcall 1983; Sigurdsson 1991). Approximately 15% of the exchanges left the planet in a wide orbit about the new binary, this fraction being insensitive to the exact mass or initial semimajor axis of the planet. The encounters were integrated until the system was resolved or a predetermined number of integration steps was reached (5×10^5 in this instance). Approximately a third of the nominal exchanges were not resolved and are not included in the fraction for which the planet was bound (the probability of the planet being ejected increases sharply for long-lived resonances, so the cross-section for forming bound planets is probably no larger than that quoted).

Solving for the orbital parameters of the planet after exchange, for those cases in which the planet became bound to the binary, the majority was found to have a semimajor axis of order 10–100r_c and eccentricities of 0.3–0.7, with a small fraction having semimajor axis $\gg 10^2 r_c$ and eccentricities of 0.9 or

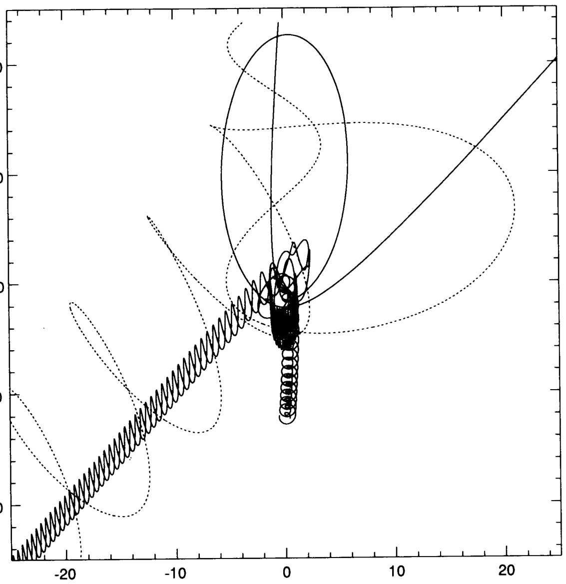

FIG. 2.—Mildly resonant four-body encounter. The original neutron star binary, semimajor axis $r_c = 1$ on this scale, enters from the bottom. The lighter member (white dwarf) of the original neutron star binary is ejected to the upper right, leaving a new eccentric neutron star—main-sequence binary. The planet (*dotted* trajectory) was originally in a $4.5r_c$ circular orbit about the main-sequence star and finishes in a $16.5r_c$, $0.35e$ stable hierarchical orbit about the new binary.

more. Figure 2 shows a typical exchange (weakly resonant) in which the planet remained bound. With the semimajor axis of the neutron star–main-sequence star binary typically $\lesssim r_c$ after exchange, the orbit of the planet is stable to internal perturbations (Harrington 1975) for about two-thirds of the derived orbits. The orbit of the planet is typically highly inclined to that of the inner binary. If the main-sequence star had a planetary companion, the probability of the planet remaining bound to the binary, in a stable orbit, after exchange is approximately 0.1. If the star had more than one planetary companion, the probability of one remaining bound to the binary increases in proportion, the survival probability being independent of the presence of other planets to first order.

If planets form around binary main-sequence stars, the inferred exchange may have been between a single neutron star and a main-sequence binary with planetary companions; further simulations are necessary to determine the cross section for planets to enter stable hierarchical orbits during such exchanges. Single neutron stars in the core of M4 are most likely to undergo exchanges with main-sequence–main-sequence binaries with semimajor axis of order 0.5 AU, and there is little margin for planetary orbits stable to both internal and external perturbations in such a system.

Exchanging the neutron star's companion requires the resulting triple system to have survived for the time for the star to evolve off the main-sequence and mass transfer to take place, $\tau_{\rm ev}$, and for the lifetime of the pulsar, $\tau_{\rm ev} + \tau_c \gtrsim 10^9$ yr $\gg \tau_d(\rho_0)$. In the process of exchange the resulting binary recoils with velocity $\sim 15/\sqrt{(r_c/0.3\ {\rm AU})}$ km s^{-1} in the binary's center-of-mass frame (Phinney 1992; Phinney & Sigurdsson 1991), the net recoil in the cluster frame is slightly higher on average. The recoil places the binary on a wide radial orbit from the cluster core. The orbit in the cluster evolves via dynamical friction and orbit diffusion (due to the inhomogeneities of the potential) (Sigurdsson 1991), returning to the core on a timescale of 10^9 yr. As $\rho(r)$ decreases sharply with r for $r > r_0$, $\tau_d(r \gg r_0) \gtrsim \tau_{\rm ev} + \tau_c$, allowing the planet to survive while the secondary evolves and spins up the neutron star.

The projected position of the pulsar at the edge of the cluster core (Goss, Kulkarni, & Lyne 1988) implies a most probable current position of about 1.5 core radii, and the pulsar may still be returning to the core. Monte Carlo simulations of binaries on radial orbits suggest, in fact, that orbit diffusion will keep the binary outside the core until dynamical friction brings it back to the core for timescales comparable to $\tau_c + \tau_{\rm ev}$ (see Fig. 3). While orbit diffusion permits excursions out of the core, the binary spends most of its time in the core, once it reaches the core. During the mass-transfer phase, approximately one-fourth of the system mass is lost on a timescale that is long, compared to the planet's orbital period, leading to a gradual expansion of the original orbit. Hence r_p and the timescale for disruption were originally 25% less than currently inferred.

Tidal circularization forces the inner binary to have $e \sim 10^{-4}$ at the end of the mass-transfer period, τ_c years ago (Phinney 1992). Secular perturbation theory suggests that the planet will induce an eccentricity one order of magnitude smaller than that observed. The $e = 0.025$ of PSR 1620−26 suggests that the system may have undergone a close encounter, having been induced by a star passing within a few r_c of the binary after mass transfer was completed, or several stars passing at a somewhat larger distance (Rappaport 1990; Sigurdsson 1992). Encounters of order r_p have a probability of approximately $\frac{1}{2}$ of stripping the planet from the binary (Sigurdsson 1992), the orbit of the planet being only weakly perturbed if it is in opposition to the field star during the encounter. The eccentricity of the orbit of the planet is likely to

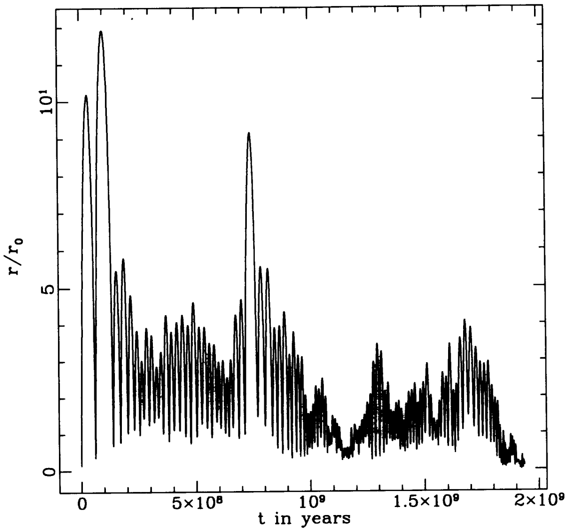

FIG. 3.—Typical radial trajectory for a 2.1 $M_\odot$ binary ejected from the core of an M4 model cluster with speed of 3.1 σ, typical of the range expected for exchanges that could lead to PSR 1620−26. Recoils of $\sim 3\ \sigma$ place the binary on a radial orbit with apapsis beyond the half-mass radius; orbit diffusion then circularizes the orbit at approximately the half-mass radius, where $\rho \sim \rho_0/200$ (and τ_d is proportionally greater than in the core), and dynamical friction slowly shrinks the orbit back to the core. The trajectory shows the orbit evolution through a multimass King model of M4, with dynamical friction and second-order orbit diffusion due to the inhomogeneities of the potential modeled explicitly (Sigurdsson 1991). On radial orbits penetrating the core, the binary spends most of the time at large radii. For clarity, each orbit is shown is an average of 30 real orbits.

have been perturbed by 0.1–0.3 by such close encounters. Encounters with field stars too distant to induce a significant eccentricity in the inner binary will produce random phase errors in the orbit of the planet, and secular perturbation theory may not apply. If the resulting eccentricity perturbations by the phase-perturbed planet add incoherently, then the observed e may be induced in $\sim 5 \times 10^8$ yr, and the binary need not have undergone any close encounters with field stars.

The discovery of planets around PSR 1257+12 (Wolszczan & Frail 1992; Wolszczan 1991) has led to a number of scenarios for the formation of planets around pulsars during spin-up. It is conceivable that mass excreted from the pulsar companion during the mass-transfer phase led to the formation of the planet; however, the timescale for a planet to form in such a wide orbit is thought to be much longer than τ_c (Nakano 1987; Sigurdsson 1992), and it is unlikely the planet formed in situ, unless planet formation is more efficient than theory suggests (Aarseth, Lin, & Palmer 1993) or the intrinsic spin-down age $P_0/2\dot{P}_0$ is $\gg \tau_c$. If planets form efficiently in excretion disks from red giants, then we expect to observe planets around galactic pulsars comparable to PSR 1620−26, such as PSR 1953+29.

PSR 1620−26 may have formed by accretion-induced collapse (AIC) (Michel 1987; Grindlay & Bailyn 1988), where a massive white dwarf (MWD) accreted matter from a companion and formed the pulsar after its mass exceeded the Chandrasekhar limit. The secondary could not be primordial in that case, as it must have originally been in a tighter orbit then currently observed in order to transfer mass onto the MWD, in which case the progenitor of the presumptive MWD would have undergone mass transfer onto the erstwhile secondary. The consequent unstable mass transfer would most probably leave the secondary too massive to survive a cluster lifetime, and, again, any planet present would be disrupted by encounters. AIC could follow an exchange, as postulated above, with the MWD playing the same dynamical role as the neutron star and the planet either exchanged, as above, or, conceivably, formed in an excretion disk.

If planets do form around solar-type stars in globular clusters, then a large number of planets would be expected to be stripped from their stellar progenitors and form a population of free planets. It is unlikely that the observed $\ddot{P}$ is due to the capture of such a free planet, as resonant captures of planets by the binary are unstable, and the planet would spend most of its time at apastron with expected separation much greater than r_c, requiring that we observe the planet at an intrinsically improbable stage of its orbit.

In principle, planets formed in situ and captured-field planets are distinguished by having near-circular and very eccentric orbits, respectively, and so can be distinguished by the determination of the planet's orbital parameters. However, induction of the binary's observed e by close encounters with field stars would perturb a circular orbit into the regime expected for orbits of scavenged planets, confusing the issue.

Thorsett et al. (1993) note that the $\ddot{P}$ may be due to a massive companion in a wide orbit. While such a system is "hard" and will not be disrupted, it has a large cross section for interaction in the core of M4. Resonant interaction will lead to stars approaching within 2 AU of the inner neutron star—white dwarf binary, strongly perturbing e on a time scale of less than 10^8 yr (Sigurdsson & Phinney 1993). Such triples are too massive to be ejected to the half-mass radius either on formation or during exchange and should be expected to remain in the core where the encounter rate is high.

Further monitoring of PSR 1620−26 will determine whether the anomalous $\ddot{P}$ is due to a planetary companion. Observations over the next decade should allow the pulsar orbital period derivative to be determined, if its amplitude is comparable to $\dot{P}$, and thus $\dot{P}_0$ may be separated from $\dot{P}$ (D. Backer, private communication). If the $\ddot{P}$ is due to a planet in bound orbit, the $\ddot{P}$ should reverse sign on a timescale of a decade. Limits on the third period derivative, dominated by the jounce, $\ddot{a}/c$, suggest that a $e = 0$ orbit is ruled out by current observations (S. Thorsett, private communication). No primordial planet could have survived in the allowed orbits for the age of the cluster, nor does it seem possible a planet could form in such a wide orbit during the lifetime of the pulsar. We conclude that the planet probably formed around a low-mass main-sequence star and was exchanged into its current orbit. Simulations show that the probability of the planet having been scavenged and surviving for $\tau_c + \tau_{\rm ev}$ is approximately $0.1N_p$, where N_p is the number of planets bound to the presumptive main-sequence star immediately prior to the time of exchange. If further observations confirm that the observed $\ddot{P}$ is due to a planet in a stable orbit about the binary, planet formation should be common about solar-mass main-sequence stars, even those of low metallicity. PSR 1310+18 may provide additional information on the genesis of such systems.

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