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Update on Pulsar B1620−26 in M4: Observations, Models, and Implications

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Abstract. Ever more precise radio timing data and serendipitous HST data have confirmed that the outer companion to PSR B1620−26 is a planet. Here we summarize the observational situation, including preliminary new timing solutions and the implications of the measured system parameters. We detail the proposed formation scenarios, discussing the advantages and problems of each for explaining the origin of the triple, and we speculate on some of the implications for planet formation in the early universe. Future data on this system will provide additional constraints on fundamental modes of planet formation. We predict that many more exchanged planets will be discovered orbiting recycled pulsars in globular clusters as the sensitivity and duration of radio timing increases. Strong observational tests of some of the alternative formation models should be possible with additional data.

1. Historical Background

The long series of radio timing data of the triple pulsar PSR B1620−26 (Lyne et al. 1988) has now confirmed that the second companion (Backer et al. 1993), is a $1-3\,M_J$ substellar object—a planet—in a low eccentricity, wide circumbinary orbit about the inner pulsar–white dwarf binary. The outer orbit is significantly inclined to the inner orbital plane, and HST photometric data confirms that the white dwarf is young, and is a proper motion member of the cluster (Thorsett et al. 1999; Sigurdsson et al. 2003).

The mass of the object is very well constrained. The timing data puts a firm *lower* mass limit of about $1\,M_J$; as more data has come in, the *upper bound* on the mass has steadily shrunk. When timing first hinted at the presence of the third object in the system, the mass was only weakly constrained (Michel 1995), although various arguments suggested that a low-mass solution might be preferred (Thorsett et al. 1993; Sigurdsson 1993; Phinney 1993; Rasio 1994; Joshi & Rasio 1997). By 1999 Thorsett et al., using measurements of the precession of the inner orbit produced by the tidal field of the outer object, had effectively excluded stellar-mass companions, and the main issue was whether the object was properly a brown dwarf, formed through star formation processes, or whether it was a planet. When the assumption is made that the pulsar spin-period derivative is negligibly small (which is true if the magnetic field of the pulsar is a typical 3×10^8 G; see Thorsett et al. 1993, 1999), then preliminary analysis of the most recent timing data finds a unique Keplerian solution, with $m_3 \sin i \simeq 1.7\,M_J$, $e \simeq 0.13$, and orbital period $P_b \simeq 68$ yr (a detailed analysis, relaxing the assumption on the spin-period derivative and including orbital perturbation measurements to constrain $\sin i$, is in preparation).

The serendipitous observations of the white dwarf companion in deep multi-epoch HST imaging of M4 (Sigurdsson et al. 2003; Richer et al. 2002, 2003; Bassa et al. 2004) provide constraints on the white-dwarf mass and hence the inner binary inclination. These results, which confirm the prediction from the radio data, strongly favor a $1 - 3\,M_J$ second companion.

We must ask "is it really a planet?" By definition, an object of this mass, orbiting a star, would be a jovian planet if observed in the solar neighbourhood. By inference, it is a gas giant. It seems very unlikely that a rocky or icy planet of such mass could form in M4 in any circumstances. A serious issue raised by the existence of this object is whether it formed through the canonical "bottom-up" core accretion process, or whether it formed through "top-down" collapse of cold gas that had become secularly unstable under its own gravity (Boss 1997, 2002). The former process would imply the existence of lower-mass planets that had failed to grow to the point where nebular gas accretes onto the planet, and hence we would predict the presence or rocky or icy terrestrial planets in M4 specifically and in globular clusters more generally. In view of the observed correlation between the incidence rate of observable "hot" and "warm" jovians and host star metallicity in the solar neighbourhood (Fischer & Valenti 2003), the possible prevalence of "normal" jovians around Pop II stars would be of particular interest, independent of the formation mechanism. Clearly the possibility of low-mass planet formation around Pop II stars has significant anthropic implications, as well as implications for the prospect for extraterrestrial life. Conversely, if the planet formed through top-down collapse, we can further ask whether it formed in a cold protoplanetary disk, or through an independent quasi-spheroidal collapse—essentially as a low-mass or failed brown dwarf. In principle, the different scenarios are testable. The possibility that the difficulty of growing a massive icy core in low-metallicity protoplanetary disks might be partially offset by the onset of gas accretion at a lower core mass is particularly intriguing (Rice & Armitage 2003).

In addition to the very precise radio timing measurements of the spin frequency and its various derivatives and the observed time variation of some of the orbital parameters, a number of other observables of the system combine to provide key hints as to its formation and dynamical history. These almost completely constrain its possible past. The data allow us to invert the dynamical history of the system with remarkable confidence to recover the initial conditions with relatively little ambiguity.

Almost as soon as the system was detected, the white-dwarf orbital eccentricity was noted to be anomalously large (McKenna & Lyne 1988). If the pulsar were spun-up through conservative mass transfer from the progenitor of the white dwarf (Rappaport et al. 1995; Phinney & Kulkarni 1994), we would expect the white-dwarf eccentricity to have been several orders of magnitude smaller after the white dwarf detached. It is generally agreed that the current eccentricity was dynamically induced after mass transfer was completed. The process by which this occurred has been somewhat contentious, with a number of less than satisfactory processes proposed. However, the cause of the white-dwarf orbital eccentricity is now almost certainly confirmed to be the Kozai mechanism (Ford et al. 2000), in which angular momentum is exchanged from the inclination of the planet's orbit to the eccentricity of the white dwarf's orbit. The current orbits are known to be significantly non-coplanar (relative inclination of about 40°), and the inclination must have been significantly larger still before angular momentum exchange took place ($70 - 80^\circ$), for the Kozai mechanism to have induced the observed white-dwarf orbital eccentricity. The inferred current and original high relative inclination between the inner binary plane and the orbital plane of the planet is highly significant and a major clue to the possible formation paths for this system.

The planet orbit is now thought to have relatively *low* orbital eccentricity. This is a major constraint on formation scenarios, since most mechanisms that lead to high orbital inclination naturally also lead to high orbital eccentricity. Exchange processes that leave a planet in a stable circumbinary orbit tend to naturally lead to moderate eccentricities and high inclination, since high-eccentricity post-exchange orbits are generally dynamically unstable, and low-eccentricity orbits are improbable due to the small available phase space at low eccentricity.

The current low eccentricity of the planet's orbit may be due to circularization of the initially moderately eccentric planet orbit during adiabatic mass loss of the white-dwarf progenitor envelope, when the system mass went from about $2.3\,M_\odot$ initially to the current $1.8\,M_\odot$. The planet's semi-major axis increased in proportion at that time. This sequence requires the planet be in place before the white-dwarf progenitor evolved off the main sequence. To a good approximation, during the RGB evolution of the white-dwarf progenitor, we can treat the planet as a test particle in a Keplerian orbit about a point mass potential with a central mass equal to the total mass of the neutron star and its companion. The loss of the envelope mass is slow, and the planet's orbital evolution is adiabatic; its energy changes in response to the loss of mass from the center, but the other integrals of motion are invariant. Eccentricity in general is an orbital parameter, not an invariant, however, for a Keplerian orbit, $1 - e_p^2 \propto E_p J_p^2$; the eccentricity is a function of the integrals only, and is invariant to isotropic slow mass loss. The current eccentricity, $e_{\rm fin} = 0.2 \pm 0.1$, from current fits to the timing data, is somewhat lower than expected from exchange models (which predict $e \simeq 0.3 - 0.7$).

It is possible that this system had an unusually low initial post-exchange eccentricity, but this then raises the same fine-tuning problems present in other scenarios. Alternatively, we can postulate a post-exchange eccentricity of about 0.5 and ask whether circularization could have taken place without substantial decrease in inclination. Given a current semi-major axis around 20 AU, the post-exchange, pre-RGB phase, semi-major axis must have been about 16 AU, with a corresponding periastron of about 8 AU, assuming a median post-exchange eccentricity of 0.5. As the white-dwarf progenitor evolved, its orbit initially circularized, and then expanded as conservative mass transfer took place, until it reached its current orbit; the timescale for such a mass transfer phase and spin-up is $\gtrsim 10^8$ yr. With a periastron around 8 AU, compared with a white-dwarf progenitor final orbit of 1 AU, we find that substantial tidal circularization of the planet's orbit could have occurred at late stages of the mass transfer phase, yet the timescales are long enough that complete circularization is precluded. Following Verbunt & Phinney (1995), we estimate $\ln \Delta e \sim -1$, or $\delta e \sim 0.3$, consistent with an initial post-exchange orbital eccentricity $\sim 0.3 - 0.5$, in the range predicted and consistent with the currently observed eccentricity. Inclination changes during this phase should have been negligible; unless there was significant planar outflow during mass transfer, in which case coupling of the planet to the excretion ring during plane crossings could in principle be a concern. This system of course is a triple, not a point-mass secondary interacting with an extended massive central star, but the additional lever arm of the giant rotating about the inner system center-of-mass will in general somewhat enhance the tidal torque, making this scenarios more plausible. The inferred eccentricity of the planet's orbit, before the evolution of the pulsar companion to white dwarf, is then about 0.5, exactly in the range predicted for an exchange scenario; and is not sensitive to the exact value of the current eccentricity. Allowing the neutron star to accrete $\sim 0.1\,M_\odot$ during mass transfer, with a correspondingly larger final total central mass, does not significantly change the predicted initial eccentricity; if there was slow isotropic mass loss, some additional circularization due to tidal interaction with the wind is conceivable. Mass accretion by the planet is negligible for all scenarios; mass loss due to LMXB ablation of the planet is also negligible for plausible LMXB phase luminosities.

If the planet's eccentricity was initially low, negligible tidal circularisation took place; if the planet's eccentricity was initially substantial, then there was opportunity for significant tidal circularisation during the mass transfer phase, if the mass transfer phase was extended. Since this is a long-period, low-mass binary pulsar, we expect sub-Eddington mass transfer with mass-transfer timescales $\sim 10^8$ yr or longer, depending on the core mass of the main-sequence progenitor post-exchange and the eccentricity of the main-sequence progenitor orbit before circularization of the inner orbit and onset of mass transfer (Burderi et al. 1996; Webbink et al. 1983).

The HST data reveal that the white dwarf is young. The main-sequence progenitor was presumably as old as the cluster, 12.7 Gyr, but the white dwarf emerged from the mass transfer phase just under 0.5 Gyr ago. This is consistent with a single exchange, where the white-dwarf progenitor was acquired by the neutron star some 1–2 Gyr ago, and the recoil induced by the super-elastic exchange ejected the system to the outer parts of the cluster, where stellar densities are low and interaction timescales are long. Therefore the system has probably been mostly dynamically isolated since the exchange.

The projected pulsar position is somewhat outside the cluster core. The true position of the pulsar is of course probably somewhat further from the core than we see in projection. Since the system is significantly more massive than the main-sequence turnoff, or indeed any likely other stellar component in M4, it tends to sink to the core through dynamical friction. The current characteristic timescale for the orbit of the triple to sink back into the cluster core through dynamical friction is $\sim 1\,\text{Gyr}$, and its current position is consistent with an initial orbit with an apocenter beyond the half-mass radius and total dynamical lifetime of 2–3 Gyr, which is consistent with a single exchange origin, combined with ejection from the core.

Given these various constraints, and the current pulsar kinematics, we can now construct a canonical formation scenario for the system.

2. Canonical Formation Scenario

The pulsar is very unlikely to have formed as a member of the current binary. A small fraction of neutron stars appear to have sub-solar-mass companions. For the white dwarf to be at the current 1 AU orbit, its progenitor must have been in a tighter orbit initially, and for such a system to have survived the supernova that formed the neutron star, there must have been a modest natal kick on the system. However, given a kick that would leave a tight low-mass binary, the system most likely would have been ejected from the cluster by the net kick on the center of mass of the system (Phinney & Kulkarni 1994).

More likely the pulsar was originally a member of a pulsar – heavy white dwarf system, descended from intermediate-mass binaries (Davies & Hansen 1998), which is consistent with retention of the system in the globular cluster at formation. The pulsar would then have started as a normal slow pulsar, and been recycled to millisecond periods by its original companion (most likely a $\sim 0.7\,M_\odot$ white dwarf in an orbit with semi-major axis around 0.3 AU). The system formed with the cluster, and spent most of the subsequent time in the cluster core. M4 presumably has been slowly evolving in density, with the core density increasing somewhat in the last few Gyrs as the cluster evolves towards core collapse (Meylan & Heggie 1997). Then, some 1–2 Gyr ago, the neutron star binary encountered a main-sequence star near the turnoff mass. Given the structure of the cluster, the most likely star to undergo an exchange with a neutron star binary is a turnoff mass star (Sigurdsson 1993b; Sigurdsson & Phinney 1995). That this happened relatively recently in the cluster history is not coincidental, the pulsar is bright and therefore likely relatively recently recycled, and given cluster dynamical evolution, the probability of an exchange taking place has increased with time over the last few Gyrs. In this scenario, *the original white-dwarf member of the binary is ejected from the system.* The main-sequence star, with a mass somewhat higher than the original white dwarf, becomes a member of the binary. The current white dwarf member of the binary is the descendant of this main sequence star.

Such an exchange is super-elastic, and the system recoils from the core of the cluster with a substantial velocity, traveling far from the core (Sigurdsson 1993a, 1995). Mass transfer ensues when the new member of the system evolves off the main sequence, the orbit circularizes and expands, and the system is x-ray luminous. The current pulsar, recycled for the second time, emerges when the white dwarf forms and the system detaches. The white dwarf is under-massive for its progenitor mass, as observed, since the RGB phase was terminated prematurely, and no helium core burning took place (Sigurdsson et al. 2003; Rappaport et al. 1995).

In the particular scenario proposed by Sigurdsson (1993a, 1995) the main-sequence star was a primordial cluster star, formed in the outer part of the cluster, and it spent most of its life in the outskirts of M4, entering the core relatively recently. This is not improbable. Half the stellar mass of the cluster is outside the half-mass radius (which does not vary much during the dynamical evolution of the cluster), and at late times, as the turnoff mass of the cluster approached that of this particular star, the white-dwarf progenitor would have sunk to the core through dynamical friction, because the turnoff mass is higher than the mean stellar mass. The planet was formed around the star at the time the cluster formed; it was possibly one of many planets in the system (most likely the most massive planet), and it exchanged into the current configuration during the same encounter that the white-dwarf progenitor, its parent star, was exchanged into the system (Sigurdsson 1992, 1993a; Ford et al. 2000). The probability of a planet exchanging to be bound to the neutron star at the same time as the main-sequence star is about 10-20% (*ibid*). If there was more than one planet in the system, the exchange probability is increased in proportion, to first order; if more then one planet is exchanged, the final state is generally unstable and there are subsequent ejections or collisions until only one planet remains. Although there is "room" in orbital space for multiple planets, the probability of more than one remaining is low for any given system. As noted above, this scenario predicts a high inclination, and a modest initial eccentricity, $e_{\rm in} \simeq 0.3 - 0.7$, for the planet's orbit, somewhat higher than currently observed (Sigurdsson 1993a).

The system is unstable to subsequent encounters, but while it is outside the cluster core, the probability of another encounter is small, and the expected lifetime of the system is many Gyrs. Once the system returns to the core, the lifetime of the planet to disruption by another encounter is only $\sim 10^8$ yr.

If correct, the proposed scenario has significant implications. *A priori*, observing an exchanged planet around one of the first discovered and longest observed globular cluster pulsars is likely only if planets are prevalent around globular cluster main-sequence stars. Planet formation in dense environments is thought to be inhibited both dynamically and because of the ionizing radiation from hot, young cluster stars, although recent work shows that the inner protoplanetary disk may be robust and generally survive long enough for planet formation in most of the cluster volume (Bally 2003). In this case most stars formed in globular clusters may have had the opportunity for planet formation to proceed in any protoplanetary circumstellar disks.

3. Alternative Scenarios

The most straightforward alternative is a double exchange scenario (Rasio et al. 1995; Joshi & Rasio 1997). In this scenario, the pulsar – white dwarf system forms normally, as above, but the planet is not initially present. Rather the planet is acquired through a second independent exchange encounter outside the cluster core. This scenario is attractive in that it removes constraints on the sequence of timing of events, the pulsar recycling may have occurred at any point, and the tight restrictions on timescales for future disruption are removed since the planet may have been acquired recently. In objection to this scenario, there is the observed fact that the white dwarf formed recently, and precisely on the timescale required to match the single exchange scenario; and, the low orbital eccentricity of the planet suggests strongly that the orbit circularized after exchange, which requires the planet to have been acquired before the white-dwarf progenitor evolved off the main sequence (Bailyn et al. 1994). In either case, the double exchange scenario also implies the presence of jovian planets in wide orbits about cluster main-sequence stars, and that these planets are not rare. Thus the implications for Pop II planet formation hold.

In a variant of this scenario, the exchange proceeded as above, but the parent star of the planet was a galactic field interloper, a disk star either passing through the cluster, or, more likely, captured by the cluster during disk passage (Bica et al. 1997). Exchange with a transient disk star is unlikely, because of the high relative velocity and short timescale for passage on an unbound disk star. A disk star captured by the globular during disk passage is more likely to have had an opportunity for exchange. In this case the planet formed around a metal rich Pop I star and implications for planet formation are less interesting. Arguing against this scenario is that, although some models suggest some globulars may be significantly contaminated by disk interlopers, the M4 stellar population is well studied, known to be homogeneous and coeval, and proper motion membership of stars has been established (Richer et al. 2002; Ivans et al. 2003). Thus interlopers cannot be common in M4, and the *a priori* probability of a rare interloper undergoing an exchange encounter with the one pulsar is very low.

A commonly raised concern is whether the planet in this system could have formed in situ after the supernova that presumably led to the neutron star formation, by analogy with the well-known PSR B1257+12 planet system (Wolszczan & Frail 1992). This is not possible. The planet is in a high angular momentum orbit. To transport it there from a close, low angular momentum orbit without disrupting the system is very unlikely; to transport it to a high-inclination, low-eccentricity orbit is a negligible probability process.

Livio et al. (1992) proposed that planet formation might be efficient in the post-merger debris of a white-dwarf–white-dwarf merger. One might speculate that the PSR B1620−26 system is a descendant of such a merger. The primary objection here is the same as for post-supernova formation: such a process would be expected to lead to compact, low angular momentum systems.

A somewhat intriguing possibility is that the pulsar formed from accretion induced collapse (AIC; Bailyn & Grindlay 1990). In this scenario, the system formed from a high-mass white dwarf which presumably collapsed due to mass transfer from the progenitor of the young white dwarf (although one can imagine combining an AIC scenario with an exchange process). Then the planet would either be exchanged from another cluster star, as before; or formed in situ. If it formed at the same time as the stars, then its survival in a circumbinary orbit is remarkable and the system must have formed in the far outskirts of the cluster and not yet reached the cluster core. An attractive aspect of the scenario is that the planet would have formed in a circular orbit much closer to the binary, with the current orbit coming from adiabatic expansion during mass loss, and the planet's eccentricity induced by the sudden loss in rest mass due to neutrino flux at AIC. A strong counterargument to this scenario is that the planet is in a high-inclination orbit, and the white dwarf's orbital eccentricity is too low for an AIC scenario: it ought to be comparable to the planet's eccentricity. The eccentricity discrepancy can be overcome if there was mass transfer after AIC, which terminated before re-circularization was complete, but this may require some fine tuning of timescales.

Another alternative is formation during the post-main-sequence evolution of the white-dwarf progenitor (Livio & Pringle 2003). In this scenario, metal rich outflow through the outer Lagrange point forms an excretion disk around the neutron star – giant system, where the material can cool and planet formation may proceed, in principle. We note that this particular system never underwent an AGB phase, since core evolution was terminated during RGB ascent. Outflows also occur during the early stages of RGB evolution, but the material will not be significantly enriched in metals, since no helium core burning has taken place. Since one motivation for alternative planet formation scenarios is to avoid the difficulty of planet formation in cool, metal-poor protoplanetary disks, it is presumably harder to form the same planet in a hot, metal-poor, thick excretion disk. Note also that the planet then has to form around a low-mass x-ray binary with strong ambient ionizing radiation, and the formation must take place in the outer disk, unlike the case of PSR B1257+12, where planet formation took place in the optically thick inner disk (Miller & Hamilton 2001; Hansen 2002).

Independent of theoretical arguments, the alternative scenario where the planet formed in a hot RGB envelope post-main-sequence is testable. Exchanged planets will only be found around pulsars in dense, low-dispersion environments, such as globular clusters. Planets formed in RGB envelopes must also presumably form around metal rich RGB companions of disk pulsars which are members of low-mass binaries. Therefore this alternative scenario predicts that low-mass binary pulsars in the Galactic disk should have circumbinary jovian planets, a possibility which is not allowed by the exchange scenarios.

As always, when constructing theoretical scenarios for unique observed astronomical systems, one can imagine unique formation paths which cannot be excluded by the present data. Judicious, but not over-exuberant, application of Occam's Razor is then probably the best way of choosing favored scenarios. We note that some of the alternative formation scenarios involve the essential point of dynamical exchange of a pre-formed planet, which was a member of a main-sequence star system with a primary star that was solar-like but from the metal-poor Pop II.

4. Future Implications

In the immediate future, further observations of the system will take place: spectroscopy of the white dwarf, using Gemini, to confirm the photometric estimates of mass, composition and cooling age. If additional HST data are taken, then the proper motion of the system will be measured to a high precision compared to the internal cluster dispersion. There is little prospect of system radial velocity measurements with the current generation of instruments and telescopes, and obtaining the true radial position of the pulsar in the cluster is not currently possible (although measurements of the apparent orbital period derivative may eventually set useful constraints on the acceleration of the system in the mean cluster potential, which, when coupled with a cluster model, could yield the 3-D pulsar position relative to the center). However, the orbit of the system in the cluster potential will be significantly constrained by proper motion studies and will test the formation scenario.

More importantly, PSR B1620−26 is proof of concept that precision timing of pulsars can find diverse planetary companions, and complements the breakthrough discovery of the first planetary system around PSR B1257+12 (Blandford et al. 1987; Wolszczan & Frail 1992). We need to find more pulsar planetary systems, and we should expect to do so as more data become available. This pulsar is bright, nearby and has been monitored for a long time, which maximizes the prospect for detecting a planet in the system. The planet is also quite massive, which makes it easier to detect. This technique could find terrestrial planets if they exist, and, as discussed in Sigurdsson (1992), it should be possible to distinguish natively formed planets like those in PSR B1257+12 from planets formed around main-sequence stars and exchanged into a pulsar orbit by the kinematics. Any further detection would place important constraints on planet formation. Detection of low-mass planets in Pop II systems would show that core accretion formation is efficient even at low metallicities. Absence of low-mass planets and a preponderance of super-jovians (modulo the selection bias towards detection of high-mass planets) would provide strong support for formation through disk instabilities. It is of course also possible that both mechanisms operate (Haghighipour & Boss 2003; Durisen et al. 2004).

If planet formation is prevalent around metal-poor Pop II stars, which is implied but not absolutely proven by the observation of a single example, then there are significant anthropic implications, for the prospects for origin and evolution of extraterrestrial life and SETI, and for strategies for future planet searches. In particular, Pop II planets would be a strong test of both the "Rare Earth" hypothesis (Ward & Brownlee 2000), and the conjecture of the "Galactic Habitable Zone" (Gonzalez et al. 2001).

A further test of planet formation theory would come through testing of planet migration scenarios and whether migration is a dominant process in formation of planetary systems, or a fringe process made prominent by the selection biases of early phases of planetary observational searches. In contrast to the positive detection of a planet in M4, is the absence of detection of short orbital period jovians in a transit search of 47 Tuc (Gilliland et al. 2000). A number of explanations for the discrepancy are possible: it could be random chance, either the detection in M4, or the non-detections in 47 Tuc could be small number statistics and moderate luck. Alternatively, globular clusters could be heterogeneous with planets forming in some clusters, but not others (cf. Soker 2003), which is a testable hypothesis if many systems are found. Another intriguing alternative is that migration is metallicity-dependent and the prevalence of observed planets around metal-rich stars in the solar neighbourhood reflects this. Livio & Pringle (2003) find a relatively weak theoretical dependence of the migration process on the disk metallicity, but if migration is rare and not dominant (i.e., if most nearby stars have long-period jovians), then maybe we can infer that migration is a "touch'n'go" process, and a small difference in the physics results in a large difference in the incidence. Alternatively, we can conjecture that migration is sensitive to external perturbations, dynamical or radiative, and therefore inhibited to some extent in dense star forming regions.

In conclusion, the confirmation of the second companion of PSR B1620−26 as a planet is a potential key step in our understanding of planet formation processes and a way-guide for planet detection strategies. As a unique example, our inferences are necessarily weak and conditional, but if further analogous examples are found we can make strong tests of theories of planet formation and scenarios for the origin and evolution of life in the universe.

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