

Transformation of a Star into a Planet in a Millisecond Pulsar Binary.

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**Millisecond pulsars are thought to be neutron stars that have been spun-up by
accretion of matter from a binary companion. Although most are in binary**

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systems, some 30% are solitary, and their origin is therefore mysterious. PSR J1719–1438, a 5.7 ms pulsar, was detected in a recent survey with the Parkes 64 m radio telescope. We show that it is in a binary system with an orbital period of 2.2 h. Its companion’s mass is near that of Jupiter, but its minimum density of 23 g cm^{-3} suggests that it may be an ultra-low mass carbon white dwarf. This system may thus have once been an Ultra Compact Low-Mass X-ray Binary, where the companion narrowly avoided complete destruction.

Radio pulsars are commonly accepted to be neutron stars that are produced in the supernova explosions of their progenitor stars. They are thought to be born with rapid rotation speeds ($\sim 50 \text{ Hz}$) but within a few 100,000 yr slow to longer periods because of the braking torque induced by their high magnetic field strengths ($\sim 10^{12} \text{ G}$). By the time their rotation periods have reached a few seconds the majority have ceased to radiate at radio wavelengths. The overwhelming majority ($\sim 99\%$) of slow radio pulsars are solitary objects. In contrast $\sim 70\%$ of the millisecond pulsars (MSPs) are members of binary systems and possess spin frequencies of up to 716 Hz (1). This is consistent with the standard model for their origin in which an otherwise dead pulsar is spun-up by the accretion of matter from a companion star as it expands at the end of its life (2). Through some process yet to be fully understood, the recycling not only spins up the neutron star but leads to a large reduction of the star’s magnetic field strength to $B \sim 10^8 \text{ G}$ and usually leaves behind a white dwarf companion of typically $0.2\text{--}0.5 M_{\odot}$. The lack of a compelling model for this reduction of the magnetic field strength with continuing mass accretion, and issues between the birthrates of MSPs and their putative progenitors, the low-mass X-ray binaries (LMXBs) led to an early suggestion (3) that accretion induced collapse of a white dwarf might form MSPs “directly” in the cores of globular clusters, and possibly in the Galactic disk.

In the standard model, the reason why some MSPs possess white dwarf companions and

others are solitary is unclear. Originally it was proposed that solitary MSPs might be formed from a different channel, in which a massive ($M > 0.7 M_{\odot}$) white dwarf coalesces with a neutron star (4). The binary pulsar-white dwarf system PSR J1141–6545 (5) is destined to merge in < 2 Gyr and thus is a potential progenitor for this scenario. At lower white dwarf masses, the final product is less clear, as the mass transfer can stabilise (6). From an observational point of view, the “black widow” MSPs may give some insights. In these systems an MSP is usually accompanied by a low-mass ~ 0.02 - $0.05 M_{\odot}$ companion in close orbits of a few hours. It was initially believed these systems might evaporate what was left of the donor star (7), but other examples (8) meant that the timescales were too long.

The MSP population was further complicated by the detection of an extra-solar planetary system in orbit around the fifth MSP found in the Galactic disk, PSR B1257+12 (9). This system has two ~ 3 Earth-mass planets in 67- and 98-day orbits, and a smaller body of lunar mass in a 25 d orbit. The planets were probably formed from a disk of material. The origin of this disk is however the subject of much speculation, ranging from some catastrophic event in the binary that may have recycled the pulsar (10) to ablation (11) and supernova fall-back (12). A large number of potential models for the creation of this system have been proposed, and are summarised in the review by Podsiadlowski (13). Although more than another 60 MSPs ($P < 20$ ms) have been detected in the Galactic disk since PSR B1257+12, until now none have possessed planetary-mass companions.

PSR J1719–1438 was discovered in the High Time Resolution Universe survey for pulsars and fast transients (14). This $P = 5.7$ ms pulsar was also detected in archival data from the Swinburne intermediate latitude pulsar survey (15). Its mean 20 cm flux density is just 0.2 mJy but at the time of discovery was closer to 0.7 mJy due to the effects of interstellar scintillation. We soon commenced regular timing of the pulsar with the Lovell 76-m telescope that soon revealed that the pulsar was a member of a binary with an orbital period of 2.17 h and a projected

semi-major axis of just $a_p \sin i = 1.82$ ms (Fig 1). Since then we have performed regular timing of the pulsar at the Parkes and Lovell telescopes that have enabled a phase-coherent timing solution over a one year period. There is no evidence for any statistically significant orbital eccentricity with a formal $2\text{-}\sigma$ limit of $e < 0.06$.

With these observations, we can explore the allowed range of companion masses from the binary mass function that relates the companion mass m_c , orbital inclination angle i and pulsar mass m_p to the observed projected pulsar semi-major axis a_p , orbital period P_b and gravitational constant G :

$$f(m_c) = \frac{4\pi^2}{G} \frac{(a_p \sin i)^3}{P_b^2} = \frac{(m_c \sin i)^3}{(m_c + m_p)^2} = 7.85(1) \times 10^{-10} M_\odot \quad (1)$$

Only a few MSPs in the Galactic disk have accurate masses (*16–18*), and these range from $1.4\text{--}2.0 M_\odot$. Assuming an edge-on orbit ($\sin i = 1$) and pulsar mass $m_p = 1.4 M_\odot$ $m_c > 1.15 \times 10^{-3} M_\odot$, ie approximately the mass of Jupiter.

We can accurately determine the component separation ($a = a_p + a_c$) for the PSR J1719–1438 binary given the observed range of MSP masses using Kepler’s third law and because, $m_c \ll m_p$, to a high degree of accuracy,

$$a = 0.95 R_\odot \left(\frac{m_p}{1.4 M_\odot} \right)^{1/3} \quad (2)$$

making it one of the most compact radio pulsar binaries. For large mass ratios, the Roche Lobe radius of the companion (*19*) is well approximated by

$$R_L = 0.462a \left(\frac{m_c}{m_c + m_p} \right)^{1/3} \quad (3)$$

and dictates the maximum dimension of the companion star. For $i = 90^\circ$ and a $1.4 M_\odot$ neutron star, the minimum $R_L = 2.8 \times 10^4$ km, just 40% of that of Jupiter. On the other hand, for a pulsar mass $m_p = 2 M_\odot$, and $i = 18^\circ$ (the chance probability of $i > 18^\circ$ is $\sim 95\%$), then $R_L = 4.2 \times 10^4$ km.

A lower limit on the density ρ (the so-called mean density-orbital period relation (20)) can be derived by combining the above equations.

$$\rho = \frac{3\pi}{0.462^3 G P_b^2} = 23 \text{ g cm}^{-3} \quad (4)$$

This density is independent of the inclination angle and the pulsar mass and far in excess of that of Jupiter or the other gaseous giant planets whose densities are $< 2 \text{ g cm}^{-3}$.

The mass, radius and hence the nature of the companion of PSR J1719–1438 are critically dependent upon the unknown angle of orbital inclination. After PSR J1719–1438, PSR J2241–5236 (22) has the smallest mass function of the other binary pulsars in the Galactic disk, albeit 1000 times larger (Fig 2.). The $\sin^3 i$ -dependence of the mass function could mean that PSR J1719–1438 is a physically similar system, but just viewed face-on. This would require an inclination angle of just $i = 5.7^\circ$, for which the chance probability is 0.5%. The only binary pulsar with a similar orbital and spin period is PSR J2051–0827, but the inclination angle required for mass function equivalence in this case has a chance probability of only 0.1%. Of course, as the known population of black widow systems increases, we will eventually observe examples of face-on binaries that mimic those with planetary-mass companions. The current distribution of mass functions among the known population is such that this is still unlikely.

If the pulsar were energetic and the orbit edge-on, we might hope to detect orbital modulation of the companion’s light curve in the optical because the pulsar heats the near-side. Our pulsar timing indicates the pulsar’s observed frequency derivative $\dot{\nu}$ is $-2.2(2) \times 10^{-16} \text{ s}^{-2}$, not atypical of MSPs. However $\dot{\nu}$ is only an upper limit on the intrinsic frequency derivative (23) ($\dot{\nu}_i$), which is related to the pulsar’s distance d and transverse velocity V_T by the Shklovskii relation.

$$\dot{\nu} = \dot{\nu}_i - \nu V_T^2 / (dc) \quad (5)$$

MSPs have relatively high velocities (24) of $50\text{--}200 \text{ km s}^{-1}$. At the nominal distance of the

pulsar from its dispersion measure (25) (1.2 kpc) it would take an MSP transverse velocity of only 100 km s^{-1} for almost all of the observed $\dot{\nu}$ to be caused by the proper motion of the pulsar.

In the case of negligible proper motion, we can derive the most optimistic impact of the pulsar's radiation for optical detectability by assuming isotropic pulsar emission, a companion albedo of unity, that the companion is a blackbody, and that the orbit is edge-on, thus maximising the illuminated region of the companion. The spin-down energy of a pulsar is $\dot{E} = -4\pi^2 I \nu \dot{\nu}$, where I is the moment of inertia of a neutron star and ν is the spin frequency. We find a maximum effective temperature of 4500 K and a peak R -band magnitude of 26–28, depending upon the assumed 1.2(3) kpc distance to the pulsar (25) and the unknown radius of the companion, which we assume is close to the Roche Lobe radius.

We observed the field surrounding PSR J1719–1438 with the Keck 10-m telescope in the g , R and I bands using the LRIS instrument. If the binary was a face-on analogue of PSR J2051–0827 we might expect to see a star at the location of the pulsar because the R -band magnitude of the binary pulsar companion in the PSR J2051–0827 system is $R \sim 22.5$ (26) and it is at a similar distance d from the Sun. The spin-down luminosity of PSR J1719–1438 is however only $0.4 L_{\odot}$ which is about 30% of that of PSR J2051–0827, and a face-on orbit would mean only half of the bright side of the companion was ever visible. This would mean the expected R -band magnitude would be reduced to $R \sim 24.5$, however at the position of the pulsar there is no visible companion down to a 3-sigma limiting magnitude of $R=25.4$ (1250s), $g=24.1$ (1000s) and $I=22.5$ (1000s) at the anticipated maximum light, where the values in parentheses indicate the integration times (Fig 3). The magnitude limit would appear to reduce the probability that PSR J1719–1438 is an extremely face-on analogue of PSR J2051–0827, with the caveat that the assumed spin-down energy of the pulsar is still an upper limit because of equation 5.

We now consider the more statistically likely possibility that the orbit is nearly edge-on. In

this case the relative velocity of the two constituents is $> 500 \text{ km s}^{-1}$ and could potentially lead to a solid-body eclipse for 60 s or so, or if the companion was being ablated we might see excess dispersive delays at orbital phase 0.25 when the pulsar is on the far side of the companion at superior conjunction. Ordinarily the 20 cm mean flux density of 0.2 mJy would make these effects difficult to detect, but a bright scintillation band occurred during one of our long integrations on the source, increasing the flux density sufficiently for us to assert that there are no excess delays or solid-body eclipses occurring in the system (Fig 1). The extremely small dimension of the Roche lobe of the companion only precludes inclination angles of $i > 87^\circ$. Inspection of Fig 2 shows that it is completely impossible to fit a hydrogen-rich planet such as Jupiter into the Roche Lobe of the planetary-mass companion. Although difficult, He white dwarfs might just fit if the computational models (21) are slightly in error ($\sim 10\%$), or the orbit is moderately face on. A carbon white dwarf on the other hand can easily fit inside the Roche Lobe for any assumed inclination angle. We thus conclude that the companion star(planet) is likely to be the remains of the degenerate core of the star that recycled the pulsar, and probably comprised of He or heavier elements such as carbon.

In the standard model, this MSP would have been spun-up by the transfer of matter from a nearby companion star to near its current period. The UC LMXBs such as XTE J0929–314 (27) are good potential progenitors of PSR J1719–1438. These systems have orbital periods of tens of minutes and higher ($\sim 10\times$) companion masses. They have also been found to exhibit Ne and O lines in their spectra (28), suggesting that their companions are not He white dwarfs. Importantly, their spin periods are comparable to that of PSR J1719–1438. As matter is transferred from the degenerate companions to the neutron star, the orbits widen and the radius of the white dwarf expands due to the inverse mass-radius relationship for degenerate objects. Deloye and Bildsten (21) predicted how the known UC LMXBs would evolve in the future. They demonstrated that the UC LMXB companions could be comprised of either He or Carbon

white dwarfs and after 5-10 Gyr might be expected to end up as binary pulsars with orbital periods of ~ 1.5 h.

If PSR J1719–1438 was once a UC LMXB, mass transfer would have ceased when the radius of the white dwarf became less than that of the Roche Lobe due to mass loss and out-spiral. In the models by Deloye and Bildsten, the He white dwarfs deviate from the $M^{-1/3}$ law very near to the Roche Lobe radius and approximate mass of our companion star for an edge-on orbit. On the other hand, another mass-radius relationship for Carbon white dwarfs of very low mass (29) suggests that it is Carbon white dwarfs that have $dR/dM \sim 0$ near $M = 0.0025M_{\odot}$ (Fig 2). It thus seems difficult to unambiguously determine the nature of the pulsar companion, but a scenario in which PSR J1719–1438 evolved from a Carbon white dwarf in an UC LMXB has many attractive features. It explains the compact nature of the companion, the spin period of the pulsar and the longer orbital period due to spiral out as a consequence of the mass transfer that spun-up the pulsar. PSR J1719–1438 might therefore be the descendent of an UC LMXB.

However, the question still remains: why are some MSPs solitary while others retain white dwarf companions, and some, like PSR J1719–1438 have exotic companions of planetary mass that are possibly carbon rich? We suggest that the ultimate fate of the binary is determined by the mass and orbital period of the donor star at the time of mass transfer. Giants with evolved cores that feed the neutron star at a safe ($d > \text{few } R_{\odot}$) distance leave behind white dwarfs of varying mass in circular orbits, with a tendency for the heavier white dwarfs to be accompanied by pulsars with longer pulsar spin periods ($P > 10$ ms). Close systems that transfer matter before a substantial core has formed might be responsible for the black-widow MSPs. A subset of the LMXBs are driven by gravitational radiation losses, and form the ultra-compact systems during a second stage of mass transfer. Their fate is determined by their white dwarf mass and chemical composition at the beginning of this phase. High mass white dwarfs do not overflow their Roche Lobes until they are very close to the neutron star with orbital periods of a few

minutes. If the orbit cannot widen fast enough to stop runaway mass transfer we will be left with a solitary MSP or possibly an MSP with a disk that subsequently forms a planetary system. Low mass white dwarf donors transfer matter at longer orbital periods and naturally cease Roche Lobe overflow near the current orbital period and implied mass of the companion of PSR J1719–1438. The rarity of MSPs with planetary-mass companions means that the production of planets is the exception rather than the rule, and requires special circumstances, like some unusual combination of white dwarf mass and chemical composition.

PSR J1719–1438 demonstrates that special circumstances can conspire during binary pulsar evolution that allows neutron star stellar companions to be transformed into exotic planets unlike those likely to be found anywhere else in the Universe. The chemical composition, pressure and dimensions of the companion make it certain to be crystallized (ie diamond).

Parameter	Value
Right Ascension (J2000) (hh:mm:ss)	17:19:10.0730(1)
Declination (J2000) (dd:mm:ss)	−14:38:00.96(2)
ν (s ^{−1})	172.70704459860(3) Hz
$\dot{\nu}$ (s ^{−2})	−2.2(2) × 10 ^{−16}
Period Epoch (MJD)	55411.0
DM (pc cm ^{−3})	36.766(2)
P_b (d)	0.090706293(2)
$a_p \sin i$ (lt-s)	0.001819(1)
T_0 (MJD)	55235.51652439
e	< 0.06
Data Span (MJD)	55236-55586
Weighted RMS residual (μ s)	15
Points in fit	343
Mean 0.73 GHz Flux Density (mJy)	0.8*
Mean 1.4 GHz Flux Density (mJy)	0.2
Derived parameters	
Characteristic Age (Gyr)	>12.5
B (G)	<2 × 10 ⁸
Dispersion Measure Distance (kpc)	1.2 (3)
Spin-down Luminosity L _⊙	<0.40(4)

* Derived from a single observation.

References and Notes

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Note. Differencing of two summed images at the expected maximum and minimum light of the companion also failed to reveal any modulation of flux from any potential candidates near the nominal pulsar position.

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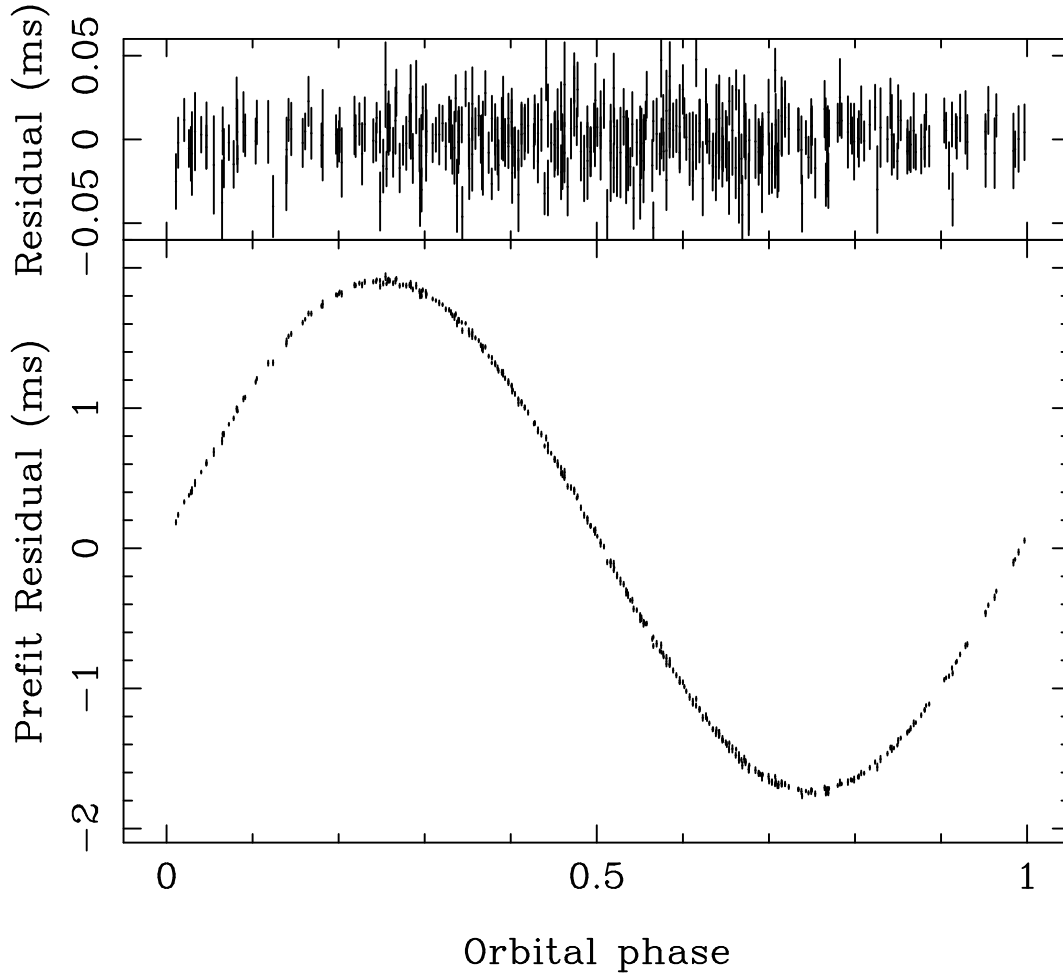


Fig. 1: Upper panel: Pulse timing residuals for PSR J1719–1438 as a function of orbital phase using the ephemeris in Table 1. Lower panel: Residuals after setting the semi-major axis to zero to demonstrate the effect of the binary motion. There is no significant orbital eccentricity. At superior conjunction (orbital phase 0.25) there is no evidence for solid-body eclipses or excess dispersive delays. The arrival times and ephemeris are provided in the supporting online material.

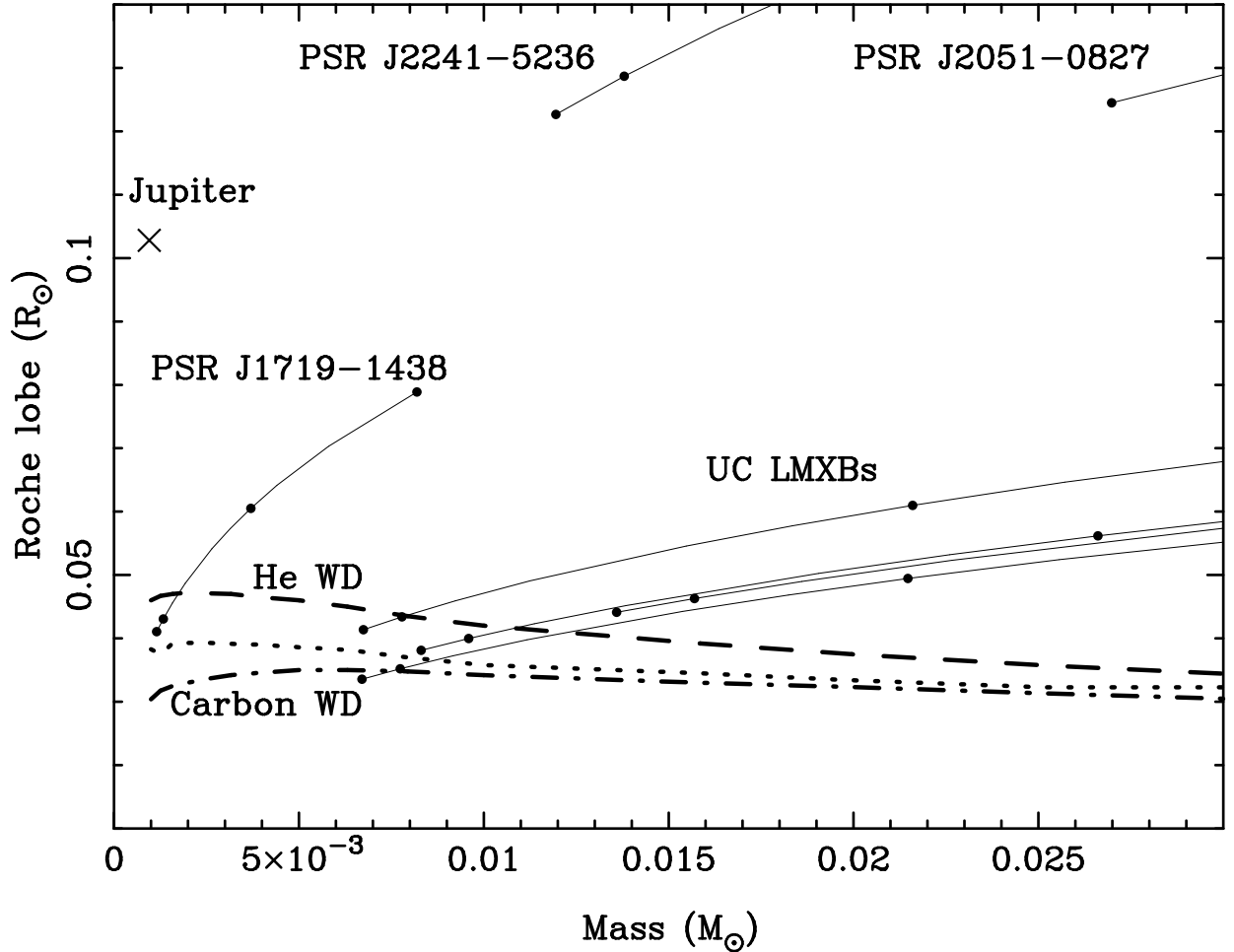


Fig. 2: The locus of the companion mass and Roche Lobe radii for PSR J1719–1438, selected ultra-compact LMXBs and black widow millisecond pulsars for different assumed orbital inclinations. The minimum companion mass and Roche Lobe radii correspond to $i = 90^\circ$ and a pulsar mass of $1.4 M_\odot$. As the unknown angle of inclination decreases, the companion mass and radius increase, becoming increasingly improbable. The bullets from lowest to highest mass represent the minimum ($i = 90^\circ$), median ($i = 60^\circ$), 5% and 1% a priori probabilities that a randomly-oriented inclination would result in the mass and radii at least as high as that indicated. The zero-temperature mass-radius relations from Deloye and Bildsten (2003) (21) are also shown for low-mass He and Carbon white dwarfs. The dotted line represents the mass-radius relation for low-mass Carbon white dwarfs computed by Lai, Abrahams & Shapiro (1991) (29). For reference the mass and radius of Jupiter is shown with an X.

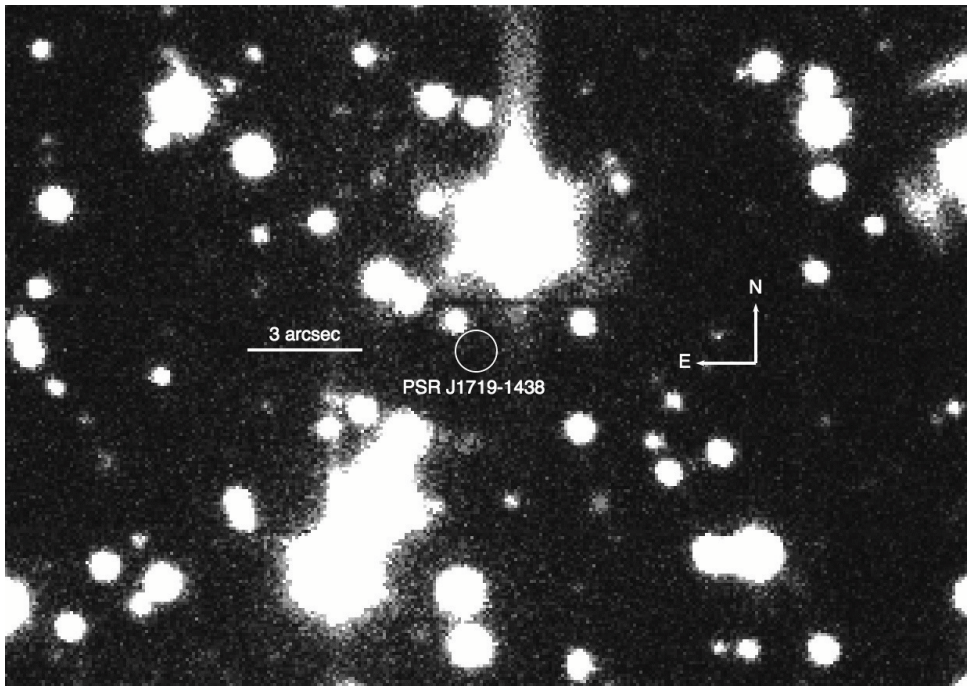


Fig. 3: Keck/LRIS 20 minute *R*-band image centred on the location of PSR J1719–1438. The image was constructed from 5 exposures taken during the expected maximum luminosity of the companion in a total integration time of 1200s.