

Discovery of a second-generation planet candidate accreting onto a white dwarf

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Supplementary Information

Interpretation of photometric period

The photometric variability detected within the *TESS* data must have an origin that is either intrinsic to the white dwarf, or external, i.e. related to a companion.

Variability in white dwarfs can be caused by pulsations or the combination of rotation and inhomogeneous surface brightness distributions. The latter may be related to the presence of magnetic fields[1], or variations in atmospheric abundances across their surface[2], or a combination of both. Given that helium abundance variations have been reported for HS 0209+0832[3], associating the photometric variability with inhomogeneities in the surface composition seems a plausible explanation. However, the period of the photometric variability in HS 0209+0832 of $\simeq 4.4$ days is much longer than those of the other white dwarfs exhibiting surface variations in their helium abundance, ranging from tens of minutes[2, 4] to at most $\simeq 10$ h[5, 6]. In fact, this period is much longer than the typical spin period of white dwarfs of $\simeq 30$ hours, which is well-established from *Kepler* asteroseismology[7]. Only one out of 20 stars in the *Kepler* sample had a rotation period above four days. Moreover, a number of white dwarfs showing surface inhomogeneities of helium are extremely massive ($> 1M_{\odot}$) and strongly magnetic ($B \gtrsim 1$ MG), so could be the result of binary mergers, whereas HS 0209+0832 has an average mass ($0.61M_{\odot}$) and no evidence of magnetism ($B \lesssim 30$ kG).

We now turn to the possibility that the photometric variability is extrinsic to the white dwarf, noting that the photometric period falls in between those of the two known close-in giant planets orbiting white dwarfs: WD 1856+534 ($P = 1.4$ days[8]) and WD J0914+1914 ($P \simeq 10$ days[9]). No transits are detected in the *TESS* data, which places an upper limit on the orbital inclination of the planet of $i \lesssim 88^{\circ}$. A period of 4.40 ± 0.02 days is equivalent to a planet orbiting at $d = 0.044$ AU, calculated using Kepler’s third law. The maximum equilibrium temperature T_p of the planetary dayside would roughly be:

$$T_p = \left(\frac{2}{3} \frac{R_{WD}^2}{a^2} T_{WD}^4 \right)^{1/4} \approx 1260 \text{ K}, \quad (1)$$

assuming zero albedo and no heat redistribution and using values for white dwarf temperature T_{WD} and radius R_{WD} from Extended Data Table 1. This planetary temperature is on the low end for hot or ultra-hot Jupiters, which cover $T_p \approx 1,400 - 2,000$ K[10]. Even taking this optimistic T_p estimate, a possible planet would need to have a radius of approximately $8 R_{Jup}$ to match the observed variability amplitude due to thermal re-emission of the incoming stellar irradiation. Alternately, if we assume an albedo of $A_g = 1$, then the possible planet would need to have a radius of $4 R_{Jup}$ to match the observed photometric variability amplitude. Both of these radii values are (i) well beyond observed radii of even the most extended hot Jupiters [11], (ii) exceeds theoretical radii for cooling sequences of young Jovians [12], and (iii) is

close to filling the Hill sphere ($\approx 10R_J$) of a Jovian at 0.044 AU. While it is possible such a large effective surface could be produced by an outflowing, highly reflective thermal wind, our default interpretation of the observed phase variability is different.

The short cooling age of the WD (≈ 5 Myr) means that any second-generation planets will still possess large internal reservoirs of heat, and their self-luminosity may create substantial surface temperatures. For example, using the Sonora Diamondback substellar evolution models[12], we estimate that an approximately $10 M_J$ would have an effective temperature of $T_{\text{eff}} \approx 1700$ K and a radius of $R_p \sim 1.75 M_J$ at $t = 5$ Myr, which in principle is hot and large enough for thermal emission from this possible planet to explain the observed amplitude of phase variability.

However, intrinsic thermal planetary luminosity will fail to produce phase variability: isotropic thermal emission will simply add a constant offset to the WD light curve. Therefore, we propose the hypothesis that the photometric variability may be caused by a young giant planet that has a heavy atmospheric haze layer on its dayside and a relatively clear nightside. The maximum of the photometric variability would then correspond to when we are seeing the hot intrinsic emission of the planet on its nightside, while the variability minimum would occur when the dayside is visible and we see a minimal reflection signal from the optically thick dayside haze later.

As a consistency check on the haze-covered-dayside, clear-nightside hypothesis, we consider the production and destruction timescales of the haze. The EUV environment of this possible planet is orders of magnitude above that of typical hot Jupiters orbiting FGK stars, where photochemical hazes are already routinely invoked to explain muted transmission features and low geometric albedos[13, 14, 15]. Scaling from those works, even modest conversion efficiencies of incident EUV photons into haze particles[16] can build dayside aerosol columns of $\tau \gtrsim 1$. on timescales much shorter than the day-to-night advective timescale, $\tau_{\text{adv}} \sim R_p/v_{\text{wind}} \sim \text{hours-to-days}$ – assuming $v_{\text{wind}} \sim 1\text{--}10$ km s $^{-1}$ [17, 18]. The dayside can therefore plausibly form and maintain an optically thick haze layer.

On the nightside, the planet’s high intrinsic temperature of 1,700 K is close to the thermal decomposition temperatures of most photochemical haze precursors and aerosol monomers[19, 20], so once the dayside EUV source is removed the hot atmosphere should rapidly destroy the haze layer. The destruction timescale should be at most comparable to τ_{adv} , so that particles advected from the dayside are destroyed on roughly the same timescale on which they are delivered. A self-consistent micro-physical and circulation calculation is beyond the scope of this work. But the dayside EUV-driven production, together with rapid thermochemical destruction on the hot nightside, gives a plausible way to sustain the asymmetric haze distribution our hypothesis requires.

The non-detection of an infrared excess with *Spitzer*[21] suggests that it was observed during the planet’s hazy dayside phase.

We notice that a similar, albeit shorter period (1.1 days) and higher-amplitude (0.1%) modulation is seen in the *TESS* lightcurve of GD 394[22]. That white dwarf has a nearly identical temperature to HS 0209+0832 ($T_{\text{eff}} = 35,700 \pm 1,500$ K)[23], but also displays a large-amplitude (25%) modulation at the same 1.1 days period in the extreme ultraviolet[24]. Magnetic fields and surface inhomogeneities were ruled

out by phase-resolved STIS spectroscopy[23]. A close-in planet would suffer mass loss due to irradiation by the hot white dwarf. This would form a cloud of evaporated material around the planet, and if this cloud transits GD 394, it would result in photo-electric absorption of the extreme ultraviolet flux of the white dwarf[23]. We note that the same hypothesis could explain both the photometric variability of HS 0209+0832, as well as the helium line variability (assuming that the atmosphere of the planet contains and loses helium). Line-of-sight helium might also be the cause of the poor fit of the white dwarf model to the He II 1640 Å line (bottom right panel of Fig. 1), for which no plausible explanation was found[25]. Helium absorption has been detected in evaporating planets around main sequence stars[26, 27], which supports the plausibility of the above scenario.

Abundances incompatible with a first-generation planet

The most unique abundance pattern of HS 0209+0832 is the enhancements in s-process elements. Strontium and barium, both s-process elements, have been previously detected in high resolution spectra of ultra-hot Jupiter (UHJ) atmospheres such as KELT-9 b[28], WASP-121 b[29], and WASP-189 b[30]. Although niobium has not yet been detected in UHJs, it is reasonable to assume it is present given the similar nucleosynthetic origins of s-process elements. However, cross-correlation spectroscopy cannot calculate relative elemental abundances, so we cannot infer abundances of s-process elements in first-generation exoplanets. Using main sequence stars as a proxy for first-generation planet abundances, we identified 100 stars from the Hypatia catalogue with abundances of both calcium and niobium[31]. We found the maximum niobium abundance was $\log(\text{Nb}/\text{Ca}) = -3.3$, much lower than $\log(\text{Nb}/\text{Ca}) = -0.94 \pm 0.33$ for HS 0209+0832. There is no known process to generate such a large niobium enhancement in a first-generation planet compared to its main sequence host star.

A first-generation planet could plausibly survive common envelope evolution and its orbit brought close to the white dwarf due to drag forces[32], but for a planet to be brought $\simeq 8 R_{\odot}$ away from the white dwarf, extreme fine tuning is needed[33] or multiple envelope ejection events[34]. Additionally, the timescale where accretion can occur is much longer than the timescale for decay[35]. Therefore, a planet which survived common envelope evolution would not be substantially enhanced in s-process elements, as we see in HS 0209+0832. We can calculate an upper limit on the accretion rate $\dot{M}_{\text{Edd}}$ assuming that the planet accretes material during the common envelope phase at the Eddington limit:

$$\dot{M}_{\text{Edd}} = \frac{4\pi G M_p m_p}{\sigma_T c} \quad (2)$$

where c is the speed of light, G is the gravitational constant, M_p is the mass of the planet, m_p is the proton mass, and σ_T is the Thomson cross section for an electron. For an extremely long common envelope phase of 10,000 yrs, a giant planet would accrete a maximum mass of $2.2 \times 10^{-5} M_{\text{Jup}}$.

Predicted second-generation planet composition

The first intact exoplanets discovered, the pulsar planets [36], are likely of second-generation origin [37, 38]. In contrast to first-generation planets, which form from a standard proto-planetary disc coeval with its main sequence host star, second-generation planets form after the host star has finished its life on the main sequence, and thus in a very different environment. Although the material and mechanisms that formed the pulsar planets are quite different in detail, their example has prompted some theoretical investigation of a different type of second-generation planet: one which forms from AGB wind material that settles into a disk in the vicinity of a newborn white dwarf [39].

The details of second-generation planet formation have only received limited investigation. Most existing theoretical works consider second-generation proto-planetary disks formed when a portion of the AGB wind is captured by a binary companion star [39, 40], although in principle such a disk could form around a single white dwarf if either (i) a progenitor binary system is converted into a single star by a common envelope episode during AGB evolution, leaving behind a white dwarf and a post-common envelope disk[41], or (ii) a small fraction of the AGB wind returns hydrodynamically, as is known to occur in other contexts. For example, in core collapse supernova explosions, a fraction of the initially unbound ejecta can become bound later on and fall back to the centre of the system. A variety of hydrodynamical mechanisms have been proposed to achieve this[42]; one that seems relatively plausible for the white dwarf context is ejecta deceleration by reverse shocks[43]. Specifically, the material ejected in a very late thermal pulse has very high velocities [44] and will overtake the remnants of the slow[45] AGB superwind, launching a reverse shock into the final mass ejection that can decelerate it and may bind a fraction of it to the white dwarf. It should be emphasized that these second-generation disks are not purely theoretical: infrared excesses have been detected around a large number of post-AGB stars, pointing to the existence of post-AGB disks[46] where planets could form[47].

Once present, a second-generation proto-planetary disk can in principle create smaller planets by core accretion or larger ones by Toomre instability, as in first-generation disks. The composition of such second-generation planets will be strongly affected by geochemical and (if present) atmospheric chemical processing, but their bulk compositions will in any case differ dramatically from that of their first-generation counterparts. For example, AGB winds often have inverted C/O ratios, which permits non-standard condensation sequences in which rarer oxygen gets locked up in volatiles while carbon can bind into e.g. carbides[48]. In such an environment, planets formed inside the ice line will be heavily depleted in oxygen, rather than carbon (as is typical for first-generation planets). If this process produces Furthermore, because AGB stars are the Universe’s primary locus of s-process nucleosynthesis [49, 50], objects formed out of AGB wind material will likely be the most s-process enriched planets in the Universe, with corresponding abundance signatures.

An alternative formation mechanism is that a first-generation planet accretes a second-generation envelope, a so-called “born-again” planet. For example, a super-Earth or sub-Neptune planet could be scattered towards the second-generation proto-planetary disk and accrete an atmosphere. This would decrease the time needed

for planet formation given that the core is already present. However, if the process of enriching a first-generation planet with AGB material works, it would likely be more common to observe accretion of second-generation material onto white dwarfs because most progenitors would eject an s-process-rich envelope, but HS 0209+0832 is the only example of this to date. Regardless, it would be impossible to determine whether HS 0209+0832 b has a first- or second-generation core given the difficulty of measuring interior abundances. Future work on planet formation models within a second-generation proto-planetary disk could deduce whether a first-generation core is required for formation of a second-generation giant planet.

In this paper, we use the results of detailed stellar evolution and neutron capture nucleosynthesis modelling to explore the parameter space of AGB wind compositions. Our working hypothesis is that second-generation planets will form out of AGB wind material and that their bulk composition will reflect this. We employ a large grid of stellar evolution models covering a broad range of zero-age main sequence (ZAMS) masses M_{ZAMS} and metallicities Z_{ZAMS} . The models we employ use the Monash stellar evolution code [51] to explore the synthesis of s-process elements in the He-rich intershell region [52]. Specifically, we examine 138 different stellar evolution models, with $1M_{\odot} \leq M_{\text{ZAMS}} \leq 7.5M_{\odot}$. These models cover a discrete set of Z_{ZAMS} values: $Z_{\text{ZAMS}} = 0.0001$ [53], $Z_{\text{ZAMS}} = 0.0006$ [54], $Z_{\text{ZAMS}} = 0.001$ [55], $Z_{\text{ZAMS}} = 0.0028$ [56], and $Z_{\text{ZAMS}} = 0.007$, $Z_{\text{ZAMS}} = 0.014$, and $Z_{\text{ZAMS}} = 0.03$ [52]. We use these models to build a grid of AGB wind compositions in the space of $\{M_{\text{ZAMS}}, Z_{\text{ZAMS}}\}$ and linearly interpolate to fill gaps in this space.

Lower-mass ($1M_{\odot} \lesssim M_{\text{ZAMS}} \lesssim 4M_{\odot}$) stars synthesize s-process elements during the thermally pulsing AGB in a complex way, relying on α -capture onto ^{13}C to provide a neutron source in the intershell. The buildup of a ^{13}C pocket by proton capture is thought to occur during third dredge-up episodes, but is highly sensitive to the details of proton mixing from the envelope, creating a major uncertainty in s-process predictions [57]. In practice, the Monash models put a “partial mixing zone” (PMZ) in by hand with fixed mass [52]. For many $\{M_{\text{ZAMS}}, Z_{\text{ZAMS}}\}$ pairs, we have multiple stellar evolution calculations with different parametrized PMZ masses. When given the choice, we follow the advice of A. Karakas (private communication) and select the closest PMZ mass to $2 \times 10^{-3}M_{\odot}$ for $M_{\text{ZAMS}} \leq 3M_{\odot}$, $1 \times 10^{-3}M_{\odot}$ for $3M_{\odot} < M_{\text{ZAMS}} \leq 4M_{\odot}$, $1 \times 10^{-4}M_{\odot}$ for $4M_{\odot} < M_{\text{ZAMS}} \leq 5M_{\odot}$, and no PMZ for higher mass progenitors. At the highest masses, the details of ^{13}C production become less relevant, as α captures onto ^{22}Ne provide a stronger neutron source.

We show distributions of AGB wind elemental abundances in Fig. 3. In this figure, the y-axis indicates the AGB wind enhancement in a given element relative to the progenitor star’s ZAMS abundance of that element. The width of the distributions comes from mapping our grid of stellar evolution models onto a bivariate probability density function in $\{M_{\text{ZAMS}}, Z_{\text{ZAMS}}\}$, where ZAMS masses are assumed to follow a Kroupa mass function for $1 \leq M_{\text{ZAMS}}/M_{\odot} \leq 8$ and ZAMS metallicities are assumed to follow a log-uniform distribution between $10^{-4} \leq Z_{\text{ZAMS}} \leq 0.03$. Figure 3 shows that white dwarf progenitors experience little change in O, Ca, Si, or Fe abundances during main sequence and post-main sequence evolution. Carbon abundances can be substantially enhanced or depleted, depending on the details of post-main sequence

evolution. Trans-iron elements are generally enhanced relative to ZAMS abundances. Nickel is enhanced by a factor ≈ 2 ; zinc by a factor of $\approx 3-5$; copper by a broad range of factors, up to an order of magnitude. Actual s-process elements, such as strontium (the center of the first “s-process peak,” where neutron absorption cross-sections are minimized) and niobium, can be enhanced by up to two orders of magnitude relative to ZAMS abundances. The progenitor mass of HS 0209+0832 is $M_{\text{prog}} = 1.34^{+0.36}_{-0.26} M_{\odot}$, and the extreme niobium enhancement suggests that the progenitor had a low absolute metallicity, $\log Z \leq -2.75$ compared to absolute solar metallicity of $\log Z_{\odot} \approx 1.9$ [58], shown in Extended Data Fig. 3. The abundance of heavier s-process elements such as barium or lead is inversely proportional to the metallicity of the progenitor star, i.e. lead will be most enhanced for metal-poor progenitors. A detection of lead using a higher quality spectrum with improved atomic data would further constrain the progenitor metallicity.

HS 0209+0832 is remarkably enhanced in the s-process element niobium, with atmospheric abundances ($\log(\text{Nb}/\text{H}) = -6.33$) that exceed even the maximum values ($\log(\text{Nb}/\text{H}) \sim -7.5$) seen in our model grid, as can be seen in Extended Data Fig. 3. Beyond the raw level of niobium, the detailed abundance patterns of HS 0209+0832 do not match theoretical predictions from AGB winds. In particular, niobium abundances are tightly correlated with strontium abundances in all theoretical calculations of s-process nucleosynthesis. Although we include ≈ 100 strong strontium lines in our synthetic far-ultraviolet spectrum, strontium is not detected in the observed spectrum of HS 0209+0832, and our upper limit on its abundance ($\log(\text{Sr}/\text{H}) < -8.86$) is more than two orders of magnitude below the detected niobium abundance. This is in contrast to AGB nucleosynthesis predictions, which essentially always find strontium enhancements above those of niobium: in our set of nucleosynthetic models, AGB wind compositions have $1.2 < \log(\text{Sr}/\text{Nb}) < 1.7$. However, an analogous discrepancy is observed in several barium stars, which were enriched in AGB material from their binary companion [59]. A sample of barium stars have higher niobium abundances compared to strontium, which may be linked to a late neutron flux moving the first s-process peak to heavier elements such as niobium [59]. The existence of these barium stars points to a nucleosynthetic pathway not captured by present-day s-process models which may also be able to explain our observed Sr/Nb ratio in HS 0209+0832.

Other abundance anomalies appear present in HS 0209+0832 as well. One, discussed earlier, is the apparent enhancement in carbon, which is indeed expected for a large subset of AGB stellar winds. Large portions of AGB parameter space produce C/O ratios greater than unity, potentially setting the stage for non-standard condensation sequences that result in strong oxygen depletion and carbon enhancement, the latter of which we have observed. Other anomalies are harder to explain, for example the unusual discovery of a Ni/Fe ratio greater than unity. It is important to note that no theoretical work has been performed on the atmospheres of second-generation planets. Therefore, we do not know the typical cloud-forming species of s-process elements.

We only measure upper limits for the s-process elements Y, Zr, Ba, and Pb. However, we note that the atomic data is not complete for these elements due to the lack of transition strengths ($\log gf$) for several lines and ionisation states, and hence the

upper limits are not very constraining. Y, Ba, and Pb only have data for their first ionisation state and Zr only for its second ionisation state. The upper limits are not strict enough to constrain their presence in the accreted material, but future observations or atomic data of higher ionisation states may detect more s-process elements. There are several additional unidentified lines which do not match any other known metal feature, and so improvements in atomic data are required to investigate the presence of additional s-process elements.

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