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DOI:

[10.3847/2515-5172/acefc5](https://doi.org/10.3847/2515-5172/acefc5)

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Document Version

Publisher's PDF, also known as Version of record

Citation for published version (Harvard):

Baycroft, TA, Badnell, H, Blacker, S & Triaud, AHMJ 2023, 'GJ 9404 b: A Confirmed Eccentric Planet, and not a Candidate', *Research Notes of the AAS*, vol. 7, no. 8, 175. <https://doi.org/10.3847/2515-5172/acefc5>

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GJ 9404 b: a confirmed eccentric planet, and not a candidate

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3 ABSTRACT

4 Eccentric orbits can be decomposed into a series of sine curves which affects how the false alarm
5 probability is computed when using traditional periodograms on radial-velocity data. Here we show
6 that a candidate exoplanet orbiting the M dwarf GJ 9404, identified by the HADES survey using data
7 from the HARPS-N spectrograph, is in fact a bona fide planet on a highly eccentric orbit. Far from a
8 candidate, GJ 9404 b is detected with a high confidence. We reach our conclusion using two methods
9 that assume Keplerian functions rather than sines to compute a detection probability, a Bayes Factor,
10 and the FIP periodogram. We compute these using nested sampling with *kima*.

11 *Keywords:* Exoplanets — Radial velocity method — Nested sampling — Keplerian orbit

12 1. INTRODUCTION

13 Recently, Pinamonti et al. (2022) reported partial results of the HADES survey, where they analyse the radial-
14 velocity monitoring of 56 nearby M dwarfs stars obtained using the HARPS-N spectrograph at TNG (La Palma). The
15 stars range from spectral types M0 to M3, and mass $0.3 M_{\odot} < M_{*} < 0.71 M_{\odot}$. Radial-velocities were extracted using
16 the TERRA template matching algorithm (?). Planets are identified if they exceed a standard False Alarm Probability
17 (FAP) of 0.1%, calculated from a generalized Lomb-Scargle periodogram. Pinamonti et al. (2022) list 11 planets
18 detected by the HADES survey in several publications.

19 In order to compute occurrence rates, Pinamonti et al. (2022) additionally identify five more systems which they
20 call ‘candidates’ mentioning they need additional, more in-depth analysis. To find these, they perform a periodogram
21 analysis along with, in some cases, a Gaussian process (GP) regression in order to model the effects of stellar rotational
22 periods, which are prominent in M dwarfs. Stellar noise correction from activity indexes (as in Gomes da Silva et al.
23 2011) are also used to remove observations affected by flares, and to detrend radial-velocity time series from magnetic
24 cycles. One of these candidates is GJ 9404 b, with an orbital period $P = 13.46^{+0.01}_{-0.51}$ day and mass of $m_p \sin(i) =$
25 $10.3^{+1.8}_{-1.8} M_{\oplus}$. The star has a mass of $M_{*} = 0.62 \pm 0.07 M_{\odot}$. Calculating a FAP requires a periodogram, which is a
26 Fourier decomposition. As such Pinamonti et al. (2022) assume sinusoidal (circular) radial-velocity modulations to
27 assess a planet’s detection, however GJ 9404 b is eccentric.

28 In order to test a new method to compute detection limits (as in Standing et al. 2022) to be used to estimate
29 occurrence rates, we reanalysed the entire HADES sample with the *kima* nested sampling algorithm (Faria et al.
30 2018). As part of that re-analysis we find that GJ 9404 b is not just a candidate, but can be confirmed as a planet.

31 2. KIMA ANALYSIS & RESULTS

32 For the radial velocity analysis we use the package *kima* (Faria et al. 2018). The model includes Keplerian orbits for
33 planets, a systemic velocity, and a jitter added in quadrature to account for any unmodelled variability. A Student’s
34 t-distribution is used for the likelihood evaluations. Compared to a Gaussian distribution, this naturally accounts
35 for any outliers present in the data. The *kima* package uses diffusive nested sampling (Brewer & Foreman-Mackey
36 2018) to explore parameter space and the number of Keplerian orbits is a free parameter. This allows for a Bayesian
37 model comparison between models with different numbers of planets using a Bayes Factor. We take a Bayes Factor,
38 $BF > 150$ as very strong evidence in favour of the more complex model (as in Kass & Raftery 1995). We also use the
39 samples obtained by the nested sampling to compute a False-Inclusion Probability (FIP) periodogram (as described
40 in Hara et al. 2022). We take a $FIP < 0.01$ as a detection threshold. Given a series of detections with $FIP < 0.01$ we
41 would expect $< 1\%$ of them to be false detections (Hara et al. 2022). At first sight this threshold might appear more

Parameters	Units	Values
M_{\star}	M_{\odot}	0.62 ± 0.07
P	days	$13.4586^{+0.0044}_{-0.0067}$
K_{\star}	m s^{-1}	$5.13^{+1.04}_{-0.85}$
e		$0.49^{+0.11}_{-0.13}$
T_{per}	BJD	$2\,457\,095.30^{+0.59}_{-0.38}$
ω	rad	1.90 ± 0.33
$m_{\text{p}} \sin i_{\text{p}}$	M_{\oplus}	11.9 ± 1.9
a_{p}	AU	0.0943 ± 0.0036
σ_{jit}	m s^{-1}	$2.27^{+0.40}_{-0.42}$

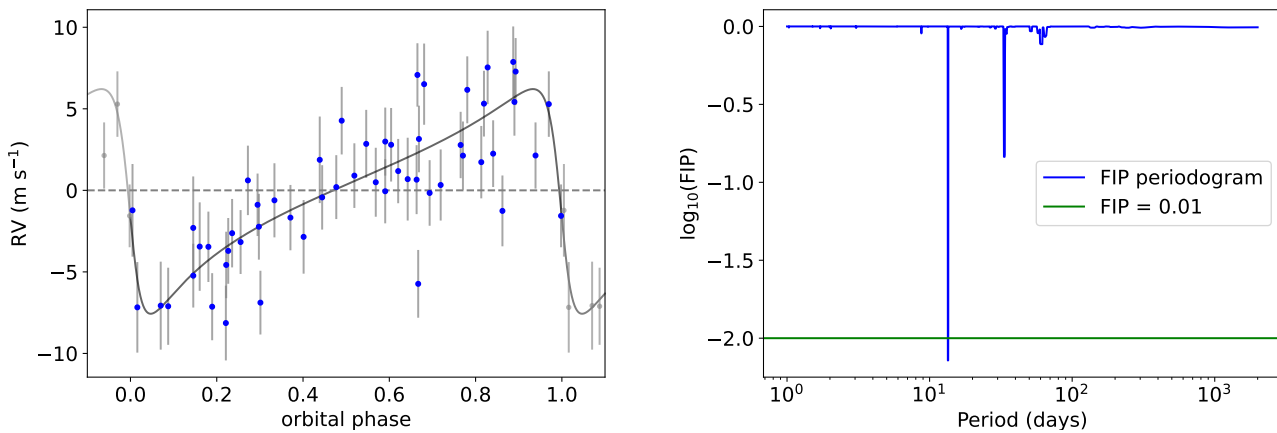


Figure 1. Top: Median values and 1σ uncertainties for the parameters of GJ9404b from `kima`. Bottom left: phase plot of best-fitting planetary solution. Bottom right: in blue the false-inclusion probability (FIP) periodogram, in green the threshold at which the false-inclusion probability is 0.01.

42 permitting than the FAP, but FAPs are sensitive to false positives, whereas the FIP is a more reliable metric (Hara
43 et al. 2022).

44 We reanalyse with `kima` the radial velocity data for GJ 9404 which we obtained from Pinamonti et al. (2022). This
45 analysis results in $\text{BF} = 782$ for a 1-planet model vs a 0-planet model, and $\text{BF} = 7$ in favour of a 2-planet model vs
46 a 1-planet model. This means that there is conclusive evidence for one Keplerian signal and moderate evidence for
47 a second. The best-fitting solution is shown on the bottom left of Figure 1. In contrast to the analysis used in the
48 Pinamonti et al. (2022), the use of Keplerian orbits within `kima` allows for eccentric orbits.

49 The false-inclusion probability periodogram is shown on the bottom right of Figure 1. This shows two periodicities,
50 one of which passes the detection threshold. The more prominent signal in the FIP periodogram corresponds to the
51 best-fitting solution and the posterior distributions for the parameters are shown in the table in Figure 1. We note that
52 this planet was claimed as a candidate in Pinamonti et al. (2022) and that our period and mass values are compatible
53 to the parameters presented in that publication. The rotation period of the star is 23.2 ± 0.1 days (Pinamonti et al.
54 2022), so the signal we confirm is likely not stellar activity, and thus of planetary origin.

55 3. CONCLUSION

56 The example of GJ 9404 highlights the limitations of traditional periodograms to identify exoplanetary signals in
57 radial-velocity data and measure the robustness of their detections. Our re-analysis of the HADES data (Pinamonti
58 et al. 2022) using `kima` (Faria et al. 2018; Baycroft et al. 2023) reveals that GJ 9404 hosts at least one exoplanet with a
59 very high degree of confidence from the Bayes Factor. We confirm this by performing a FIP periodogram (Hara et al.
60 2022), which assume Keplerian functions rather than sines. Fig. 1 shows the FIP periodogram confirming the Bayes

61 Factor estimated by `kima`. This research note should be seen a reminder of the limitation of traditional periodograms
 62 to assess detection confidence, and a reminder that more powerful and accurate statistical tools now exist.

63 This research received funding from the European Research Council (ERC) under the European Union's Horizon 2020
 64 research and innovation programme (grant agreement n° 803193/BEBOP).

65 *Facilities:* TNG(HARPS-N)

66 *Software:* `kima` (Faria et al. 2018), DNEST4 (Brewer & Foreman-Mackey 2018)

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