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Baycroft, Thomas A.; Badnell, Harry; Blacker, Samuel; Triaud, Amaury H. M. J.

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

Thomas A. Baycroft ,[1] Harry Badnell,[1] Samuel Blacker,[1] and Amaury H.M.J. Triaud [1]

[1]School of Physics & Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom

ABSTRACT

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

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

1. INTRODUCTION

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

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

In order to test a new method to compute detection limits (as in Standing et al. 2022) to be used to estimate occurrence rates, we reanalysed the entire HADES sample with the `kima` nested sampling algorithm (Faria et al. 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.

2. KIMA ANALYSIS & RESULTS

For the radial velocity analysis we use the package `kima` (Faria et al. 2018). The model includes Keplerian orbits for planets, a systemic velocity, and a jitter added in quadrature to account for any unmodelled variability. A Student's t-distribution is used for the likelihood evaluations. Compared to a Gaussian distribution, this naturally accounts for any outliers present in the data. The `kima` package uses diffusive nested sampling (Brewer & Foreman-Mackey 2018) to explore parameter space and the number of Keplerian orbits is a free parameter. This allows for a Bayesian model comparison between models with different numbers of planets using a Bayes Factor. We take a Bayes Factor, BF > 150 as very strong evidence in favour of the more complex model (as in Kass & Raftery 1995). We also use the samples obtained by the nested sampling to compute a False-Inclusion Probability (FIP) periodogram (as described 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 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	$13.4586^{+0.0044}_{-0.0067}$
$K_\star$	$\mathrm{m\,s^{-1}}$	$5.13^{+1.04}_{-0.85}$
e		$0.49^{+0.11}_{-0.13}$
T_{per}	BJD	$2\,457\,095.30^{+0.59}_{-0.38}$
ω	rad	1.90 ± 0.33
$m_{\mathrm{p}} \sin i_{\mathrm{p}}$	$M_\oplus$	11.9 ± 1.9
a_{p}	AU	0.0943 ± 0.0036
σ_{jit}	$\mathrm{m\,s^{-1}}$	$2.27^{+0.40}_{-0.42}$

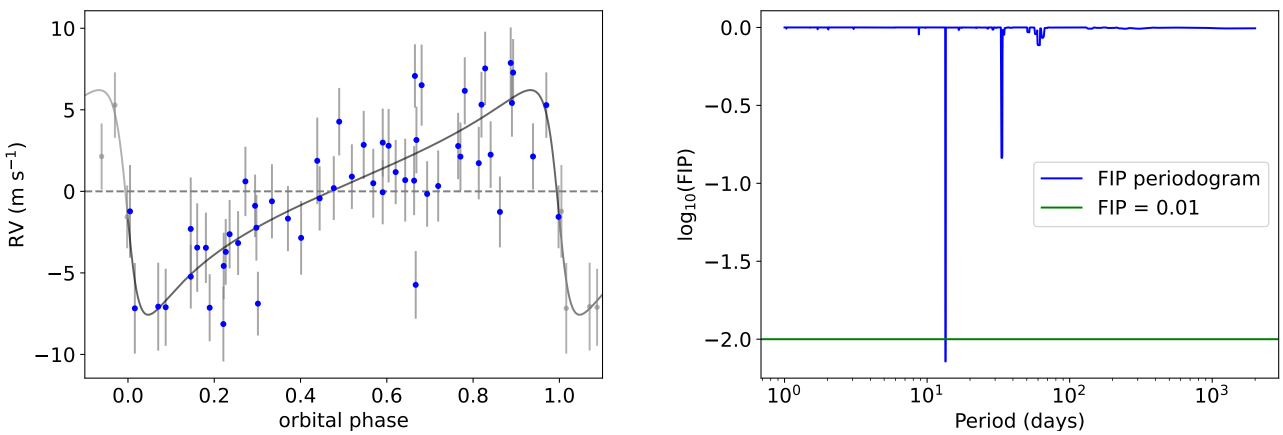

Figure 1. Top: Median values and 1σ uncertainties for the parameters of GJ9404b from `kima`. Bottom left: phase plot of best-fitting planetary solution. Bottom right: in blue the false-inclusion probability (FIP) periodogram, in green the threshold at which the false-incusion probability is 0.01.

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

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

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

3. CONCLUSION

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

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

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Facilities: TNG(HARPS-N)

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

REFERENCES

Baycroft, T. A., Triaud, A. H. M. J., Faria, J., Correia, A. C. M., & Standing, M. R. 2023, MNRAS, 521, 1871, doi: 10.1093/mnras/stad607

Brewer, B. J., & Foreman-Mackey, D. 2018, Journal of Statistical Software, 86, 1, doi: 10.18637/jss.v086.i07

Faria, J. P., Santos, N. C., Figueira, P., & Brewer, B. J. 2018, The Journal of Open Source Software, 3, 487, doi: 10.21105/joss.00487

Gomes da Silva, J., Santos, N. C., Bonfils, X., et al. 2011, A&A, 534, A30, doi: 10.1051/0004-6361/201116971

Hara, N. C., Unger, N., Delisle, J.-B., Díaz, R. F., & Ségransan, D. 2022, A&A, 663, A14, doi: 10.1051/0004-6361/202140543

Kass, R. E., & Raftery, A. E. 1995, Journal of the American Statistical Association, 90, 773, doi: 10.1080/01621459.1995.10476572

Pinamonti, M., Sozzetti, A., Maldonado, J., et al. 2022, A&A, 664, A65, doi: 10.1051/0004-6361/202142828

Standing, M. R., Triaud, A. H. M. J., Faria, J. P., et al. 2022, MNRAS, 511, 3571, doi: 10.1093/mnras/stac113