Ghost in the time series: no planet for Alpha Cen B

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ABSTRACT
We re-analyse the publicly available radial velocity (RV) measurements for Alpha Cen B, a star hosting an Earth-mass planet candidate, Alpha Cen Bb, with 3.24 d orbital period. We demonstrate that the 3.24 d signal observed in the Alpha Cen B data almost certainly arises from the window function (time sampling) of the original data. We show that when stellar activity signals are removed from the RV variations, other significant peaks in the power spectrum of the window function are coincidentally suppressed, leaving behind a spurious yet apparently-significant ‘ghost’ of a signal that was present in the window function’s power spectrum ab initio. Even when fitting synthetic data with time sampling identical to the original data, but devoid of any genuine periodicities close to that of the planet candidate, the original model used to infer the presence of Alpha Cen Bb leads to identical conclusions: viz., the 3σ detection of a half-a-metre-per-second signal with 3.236 d period. Our analysis underscores the difficulty of detecting weak planetary signals in RV data, and the importance of understanding in detail how every component of an RV data set, including its time sampling, influences final statistical inference.

Key words: stars: individual: Alpha Centauri B – planetary systems – methods: data analysis – techniques: radial velocities – stars: activity

1 INTRODUCTION
The announcement by Dumusque et al. (2012) of the detection of a planet around the modestly-active, K1 V star α Cen B generated exceptional excitement in the astronomy community: if verified, the claimed planet α Cen Bb would be the closest exoplanet to Earth ever discovered (distance: 1.34 pc), and the lowest-minimum-mass planet detected around a Solar-type star. The claimed planet has an orbital period of 459 ± 33 days, and an estimated minimum mass of 1.13 ± 0.09 M⊕, inferred from an RV semi-amplitude of 0.51 ± 0.04 m s⁻¹.

Dumusque et al. (hereafter D12) obtained 459 HARPS RV datapoints, along with ancillary line width (FWHM), bisector inverse slope (BIS) and chromospheric activity (log R′HK) time series, over a period of 4 years. D12 used a variety of mathematical transformations to try to filter out many sources of RV variance, including star spots, photospheric granulation, and binary motion due to the presence of companion star α Cen A. The amplitude of the binary-motion signal they removed was on the order of hundreds of m s⁻¹; the combined amplitude of nuisance signals ascribed to stellar activity was on the order of a few m s⁻¹; and the final, putative planetary signal they isolated had a semi-amplitude of ∼ 0.5 m s⁻¹. For comparison, HARPS’ long-term precision is 0.8 m s⁻¹ (Mayor et al. 2003).

The detection, however, was a contentious one, with some voicing reservations about the modelling approach used to infer the planet’s presence (e.g., Hatzes 2012, 2013). For example, short-term rotational activity was modelled using sinusoidal waves at the rotational period of the star, and a varying number of harmonics – essentially, a truncated Fourier series. This is not necessarily a good approximation in the case of an evolving rotation signal (e.g., Lanza et al. 2001), and subtracting such a model from the ΔRV time series opens the possibility of inadvertently introducing periodic signals, or harmonics thereof, into the power spectrum. Second, available activity-sensitive time series (BIS and log R′HK) were not jointly modelled with the ΔRV time series, even though the rotational signal was strongest in the log R′HK time series. Instead, a low-pass smoothing filter was applied to the log R′HK time series; this smoothed signal was noted to look similar to the ΔRV time series, and then used to mitigate the effects of long-term activity in the ΔRV time series. Third, each of the four observing seasons was fitted independently of the others, possibly discarding information about long-term correlations in the time series, and resulting in a more complex model than would likely have been the case if fitting were performed for all seasons simultaneously. The model used to fit the ΔRV time series alone, without a planet, contained 23 free parameters, which raises the question of possible over-fitting. These potential reservations aside, however, the signal D12 extracted certainly did seem to bear many of the hallmarks of a
real planetary signal, including a coherent phase over four observing seasons, and low false alarm probability.

We previously attempted (Rajpaul et al. 2015, hereafter R15) to address some of the aforementioned reservations by applying to the D12 data set a Gaussian process (GP) framework that we developed to model RV time series jointly with ancillary, activity-sensitive time series, allowing the activity component of an RV signal to be disentangled from dynamical components. Our modelling framework uses GP draws and derivatives thereof as basis functions to model available time series in a flexible, data-driven way, rather than e.g. sinusoids or other simplistic parametric models. Moreover, the entire framework is accommodated very naturally within the broader framework of Bayesian inference, allowing uncertainties to be handled in a principled way: overly-complex models are automatically penalized, nuisance parameters can be marginalized over, and rigorous model comparisons can be performed. Using this framework, we showed that the observed RV variations could be satisfactorily modelled as stellar activity alone, without requiring a planet. Yet we did not claim that $\alpha$ Cen Bb does not exist, in part because that analysis did not provide any definitive explanation for the origin of the 3.24 d signal uncovered by D12.

2 AN APPARENT PLANETARY SIGNAL

To probe the origins of the planetary signal claimed by D12, we implemented exactly the planet-free model published by D12, and used it to fit the original observations. We optimised model parameters using multiple runs of a Nelder-Mead algorithm, and obtained marginally better goodness-of-fit statistics than those published by D12 (likely because D12 approximated the optimisation problem as a linear one; X. Dumusque, pers. comm., 2015). Nevertheless, our RV residuals corresponded almost exactly to those published by D12, and the 3.24 d signal appeared, with the expected $> 3\sigma$ significance.

Studying the power spectra of the periodic components of D12’s model (see Section 4), in combination with varying levels of noise, proved inconclusive; none of these components appeared to give rise to 3.24 d periodicities. This was consistent with D12’s own bootstrap tests to ascertain whether the 3.24 d signal was introduced during the process of eliminating stellar signals. We next ran a Bayesian model comparison test of D12’s baseline model vs. D12’s planet model. We placed uniform priors on all parameters, with prior domains set arbitrarily to ten times the $\pm 1\sigma$ confidence intervals published by D12; model evidences ($Z$) were computed using the multiNest nested-sampling algorithm (Feroz & Hobson 2008; Feroz et al. 2009, 2013). The planet model was favoured very strongly over the simpler baseline model, with a Bayes factor on the order of $10^5$. Moreover, $\log Z$ for the planet model increased approximately linearly when artificially increasing the number of datapoints used in the modelling (up to a maximum of 459).

However, some further tests suggested – without proving outright that $\alpha$ Cen Bb does not exist – that a planetary origin for the 3.24 d signal is unlikely. These tests are sketched below.

First, we injected into D12’s RV observations different 0.51 m s$^{-1}$ sinusoidal signals, with random phases, and periods uniformly distributed between 3.24士0.2 d, excluding 3.24士0.2 d. We considered 100,000 such signals. In 87% of cases, the normalised least-squares/Lomb-Scargle (LS) power at the period of the injected signal was, after first subtracting the dominant binary signal from the data, higher than the power of the strongest signals between 3.24士0.02 d. (For a given period $P$, the LS periodogram of a signal $f(t)$ represents a test statistic for the corresponding problem of testing between two hypotheses: viz. that $f(t)$ represents white Gaussian noise, vs. a coherent sinusoidal signal with period $P$, based on a fit using a least-squares metric.)

Second, we considered 100,000 sets of random Gaussian noise, drawn at times identical to D12’s observations, and with standard deviations on each point corresponding to D12’s HARPS error estimates. We found that 18% of these noise signals contained more normalised LS power specifically at 3.24士0.02 d than was present in D12’s binary-subtracted observations. Moreover, all of these time series of noise contained at least one signal between 2 d and 10 d with lower false alarm probabilities (FAPs) than any signals between 3.24士0.02 d in D12’s binary-subtracted data.

Third, we found that the statistical significance of D12’s 3.24 d signal could be destroyed by removing as few as 12 (non-
coefficients, all with time sampling identical to D12’s observations. In every case, the strongest periodicity between about 1.1 d and 13.5 d was found at 3.249 d. When fitting and subtracting a polynomial from one of these randomly-generated polynomial ‘observations,’ the power spectrum was flattened out (as expected, since exact fits were possible). However, when first adding non-white noise to the polynomials (e.g. random walk noise, periodic and quasi-periodic signals, GP draws, or combinations thereof) and then fitting and subtracting a polynomial, we observed different behaviour.

In cases where the injected signals ‘drowned out’ the polynomial signals (i.e. the window function imprinted on a polynomial), the power spectra of the residuals tended to match closely those of the injected signals. However, in other cases where the injected signals’ contribution to the total signal variance was much smaller than the polynomial contribution, the original polynomials could be fit well, but not perfectly. This meant that the residuals still contained a small signal bearing the imprint of the window function, so very often in these cases the most significant period (usually between 1.1 d and 13.5 d) in the residuals turned out to be 3.249 d, or a period very close to (within 1% of) 3.249 d. This was not surprising, as our earlier test confirmed that virtually any polynomial with the same sampling as D12’s observations would have in its power spectrum a 3.249 d signal as a local maximum. Slight (< 1%) deviations from 3.249 d in the latter tests could be attributed to biases in the power spectrum introduced by the injected signals. Furthermore, when suppressing other, more significant components of the window function (as before; see Fig. 4), the significance of the ∼ 3.24 d signals could be boosted.

4 THE TRUE ORIGIN OF THE PLANETARY SIGNAL

D12’s baseline model used to fit the RVs contained three components, which modelled, respectively: (1) the binary signal; (2) long-term magnetic activity; and (3) stellar rotational activity. Component (1) comprised a polynomial, second order (quadratic) in time, with the same three coefficients used for all observing seasons. Component (2) was proportional to the low-pass filtered log $R'_{HK}$ series; the only free parameter here was a scaling factor to convert the log $R'_{HK}$ to $\Delta RV$ variations. Component (3) included sinusoidal terms, different for each season; in total, it contained 19 free parameters. D12 also considered a model with an added sinusoidal term, (4), to describe a possible planetary contribution to the $\Delta RV$ time series. This took the form $\Delta RV_{\text{planet}} = K_1 \sin(2\pi t/P) + K_2 \cos(2\pi t/P)$; equivalently, $\Delta RV_{\text{planet}} = K \sin(2\pi t/P + \phi)$. All components of the model were fitted simultaneously.

When computing the LS power spectrum of component (1) of the best-fitting model, i.e. the polynomial component, the normalized LS power at 3.25 ± 0.1 d was found to be 99.3% of the normalized power from the raw $\Delta RV$ observations (which included a binary signal, long-term magnetic activity variations, rotational activity, and unknown contributions). In fact, we had to inject into the raw $\Delta RV$ observations sinusoids with semi-amplitudes on the order of tens of m s$^{-1}$ (assuming periods on the order of a few days) to obtain comparable LS power to that observed at 3.25 ± 0.1 d.

This suggests the following scenario: a signal at ∼ 3.24 d was present in the original observations; however, it arose not from a planet, but from the window function. As with the tests described at the end of Section 3, D12’s imperfect model meant that the imprint or ‘ghost’ of the window function remained in the model residuals. Moreover, because other significant components of the window function happen to be suppressed when removing stellar activity,
Figure 3. LS power spectrum of the window function of D12’s observations. The arg max of the power spectrum on three non-trivial domains corresponds to the period of D12’s planetary candidate (left panel), the estimated rotation period of α Cen B (right), and the first harmonic of the rotation period (middle).

i.e. through model component (3), the $\sim 3.24$ d signals end up being boosted in the window function’s imprint on the residuals.

To test this scenario, we generated synthetic observations as follows. Components (1) and (2) of D12’s original model, with free parameters set at their maximum a posteriori (MAP) values, were taken to represent (a) binary, and (b) long-term magnetic variations. We then used the framework from R15 to train a GP with quasi-periodic covariance kernel on the ‘observed’ rotational activity ($\Delta RV$ observations minus binary and magnetic activity models), in tandem with log $R'_HK$ and BIS observations. We took the posterior mean of the GP to represent rotational activity, (c). Finally, components (a), (b), and (c) were co-added with white Gaussian noise to form a set of synthetic observations.

We avoided using component (3) of D12’s model to synthesise the rotational activity: otherwise the synthetic observations would have been generated entirely by D12’s original model, and it would have been naive to expect anything but an excellent fit, with white, Gaussian residuals (see Section 3). Instead, using a GP allowed us to synthesise observations with the same covariance properties – (quasi)periodicities, evolution time-scales, smoothness, noise levels, etc. – as the observed rotational activity, regardless of the extent to which D12’s simple harmonic model might’ve failed to describe such variations. Furthermore, the GP framework meant that any periodicities not also present in the ancillary time series (i.e. through model component (3)) could be captured by the $\Delta RV$ model. We confirmed that the power spectrum of component (c) of our model was free of any significant periodicities on time-scales of a few days; and it certainly contained no signals near 3.24 d.

We next used D12’s model to fit our baseline set of synthetic observations – to be quite clear, a set of observations synthesized only from non-planetary components of D12’s model, a conservative activity model for the original observations, and white noise. As before, uninformative priors were placed on all parameters in D12’s model, and parameter inference was performed using MultiNest. The strongest feature in the power spectrum of the residuals from the MAP fit was a significant peak at $\sim 3.236$ d, with estimated FAP of $0.04\%$; see Fig. 5. When adding a zero-eccentricity Keplerian (sinusoidal) component to D12’s overall model, we obtained an RV semi-amplitude for the Keplerian of $K = 0.46 \pm 0.03 \text{ m s}^{-1}$, and a period of $3.2358 \pm 0.0002$ d. As before, the more complex sinusoidal model was strongly favoured over the baseline model, with a Bayes factor of $\sim 10^5$.

We repeated these tests 10 times using different ‘observations’, synthesized by perturbing the MAP parameters from components (1) and (2) of D12’s model, within their 1$\sigma$ confidence intervals; by using different GP draws for the rotational activity model, within a 1$\sigma$ envelope of the GP posterior mean function; and by using different seeds when generating additive white Gaussian noise. In each case, a significant signal appeared at $\sim 3.236$ d in the residuals, and when including a Keplerian in the model, a MAP period consistent with $3.2358$ (within 1$\sigma$) was obtained. However, a range of semi-amplitudes was obtained – the smallest was $K = 0.33 \pm 0.03 \text{ m s}^{-1}$, and the largest, $K = 0.53 \pm 0.04 \text{ m s}^{-1}$. For comparison, the planet claimed by D12 had best-fitting parameters $K = 0.51 \pm 0.04 \text{ m s}^{-1}$, and $P = 3.2357 \pm 0.0008$ d.

It is exceptionally implausible that synthetic data simply with the same time sampling and activity-related covariance properties as D12’s dataset, but no planet, would consistently lead to the detection of the same planet claimed by D12, if indeed D12’s planet were real. We thus conclude that the 3.24 d signal that D12 originally recovered was most likely nothing more than a ‘ghost’ of the window function, amplified during the modelling process to non-trivial significance levels.

5 DISCUSSION AND CONCLUSIONS

We have demonstrated that the 3.24 d signal observed in the α Cen B data almost certainly arises from the window function of the original data. When stellar activity signals are filtered out from the RV variations, other significant peaks in the power spectrum of window function are coincidently suppressed, leaving behind a spurious yet apparently-significant ‘ghost’ of a 3.24 d signal that was present in the window function’s power spectrum ab initio.

Our analysis underscores the difficulty of detecting weak planetary signals in RV data, and the importance of understanding in detail how every component of an RV data set, including its time sampling, influences final statistical inference. In future attempts at
detecting low-mass exoplanets in RV data sets, it would be prudent to study the window function of the observations carefully. A planet candidate should be treated with extreme circumspection if its period happens to coincide closely with an \( \arg \max \) of the window function’s power spectrum on some non-trivial domain; in the case of the D12 data, 3.24 d happened to be the \( \arg \max \) of the window function’s power spectrum on an interval between about 1 d and two weeks. Additionally, D12’s data set was particularly pathological because the window function happened to contain periodicities that coincided with the stellar rotation period of \( \alpha \) Cen B, and its first harmonic; when these signals were filtered out, the significance of the 3.24 d signal was preferentially boosted.

We alluded to a number of other tests we believe worth carrying out when considering the reliability of planet detections from noisy, discretely-sampled signals. These include using the same model used to detect the planet instead to fit synthetic, planet-free data (with realistic covariance properties, and time sampling identical to the real data), and checking whether the ‘planet’ is still detected; comparing the strength of the planetary signal with similar Keplerian signals injected into the original observations; performing Bayesian model comparisons between planet and no-planet models; and checking how robust the planetary signal is to datapoints being removed from the observations. As this study has demonstrated, simply considering the false alarm probability of a signal in a model’s residuals, or (somewhat equivalently) checking whether a signal has a coherent phase over a full set of observations, is clearly insufficient. Even rigorous, Bayesian model comparisons do not necessarily shed light on the origins of a planet-like signal.

The authors propose to carry out, in the near future, a systematic study of the properties of spurious yet coherent signals that can arise in noisy datasets with real (e.g. HARPS-like) observing calendars. This will hopefully inform best practices for identifying or mitigating such signals; it might also prove relevant to already-published cases of planets whose existence was supported by rigorous model comparison tests, yet not by follow-up observations. Certainly, when carrying out future observations of \( \alpha \) Cen B, it would be worth ensuring that the window function of the proposed observations did not contain significant power at 3.24 d, or \( P_{\text{rot}} \pm 2 \sigma \) and harmonics thereof.

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