Aliasing in the Radial Velocities of YZ Ceti: An Ultra-short Period for YZ Ceti c?

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Abstract

Mid-to-late M stars are opportunistic targets for the study of low-mass exoplanets in transit because of the high planet-to-star radius ratios of their planets. Recent studies of such stars have shown that, like their early-M counterparts, they often host multi-resonant networks of small planets. Here, I reanalyze radial velocity measurements of YZ Ceti, an active M4 dwarf for which the HARPS exoplanet survey recently discovered three exoplanets on short-period ($P = 4.66, 3.06, 1.97$ days) orbits. My analysis finds that the orbital periods of the inner two planets cannot be uniquely determined using the published HARPS velocities. In particular, it appears likely that the $3.06$ day period of YZ Ceti c is an alias and that its true period is $0.75$ days. If so, the revised minimum mass of this planet is less than $0.6$ Earth masses and its geometric transit probability increases to $10\%$. I encourage additional observations to determine the true periods of YZ Ceti b and c and suggest a search for transits at the $0.75$ day period in TESS light curves.

Key words: planets and satellites: detection – stars: individual (YZ Ceti) – stars: late-type

1. Introduction

Mid-to-late M stars are increasingly common targets of exoplanet surveys. Kepler (Borucki et al. 2010) included relatively few such stars in its target list, but its extended mission, K2, has revealed several systems of small planets orbiting very low-mass stars (e.g., Hirano et al. 2016; Mann et al. 2016). TESS (Ricker et al. 2015) has started science operations and will add many more systems to the catalog of exoplanets around late-type stars. At the same time, a collection of near-infrared Doppler spectrographs is going into operation, beginning with CARMENES (Quirrenbach et al. 2016) and the Habitable-zone Planet Finder (HPF; Mahadevan et al. 2014), which will enable ground-based follow-up to determine the masses of planets transiting these cool, faint stars.

Already, several of the most high-profile, recent exoplanet discoveries have been around mid-to-late M stars. TRAPPIST-1, a nearby M8 dwarf, was shown to host a multi-resonant network of seven low-mass exoplanets (Gillon et al. 2017), three of which lie within the liquid-water habitable zone (HZ; Kopparapu et al. 2013). Radial velocity (RV) surveys have also discovered low-mass exoplanets around nearby mid-to-late M stars. Anglada-Escudé et al. (2016) found evidence for a terrestrial-mass planet in the HZ of Proxima Centauri. More recently, Astudillo-Defru et al. (2017) announced the discovery of three Earth-mass exoplanets orbiting the M4.5 dwarf YZ Ceti based on observations from the HARPS spectrograph. At candidate periods of $1.97$, $3.06$, and $4.66$ days, the YZ Ceti system potentially represents another compact multi-harmonic system like TRAPPIST-1. TESS will observe YZ Ceti in late 2018, and all of the reported planets have relatively high ($P \sim 5\%$) geometric transit probabilities.

Ground-based exoplanet surveys are plagued by difficulties associated with temporal sampling. Uneven time sampling caused by shared telescope resources, seasonal target observability, weather, and the day/night cycle limit sensitivity in certain regions of frequency space, and can create ambiguities in others. Aliasing occurs when a continuous signal is observed at a cadence such that the observations cannot distinguish between the true signal frequency and a combination of the signal and observing frequencies. RV surveys are commonly hampered by the “1 day alias,” and periodograms of RV data will often show peaks at the frequency of a planet ($f_p$) and its alias at $f_a = f_p \pm 1 \text{ day}^{-1}$. This effect was demonstrated most powerfully by Dawson & Fabrycky (2010), who revised the period of 55 Cnc e from $2.8$ days (McArthur et al. 2004) to its true value of $0.75$ days, where it was later found to transit (Winn et al. 2011).

In this Letter, I argue that the periods of two of the three planets orbiting YZ Ceti are not well determined due to aliasing in the HARPS RV time series. For planet b, which has a period of either $1.97$ or $2.02$ days, the difference is primarily important for the efficiency of identifying potential transits. On the other hand, the period of planet c may be $0.75$ days rather than $3.06$ days, which significantly alters its derived physical properties and geometric transit probability. Given that the available RVs are unable to clearly distinguish between these candidate periods, it will be especially important to examine all potential transit windows in TESS light curves of YZ Ceti.

2. Data and Analysis

2.1. Data

In this Letter, I have analyzed the HARPS observations of YZ Ceti as presented in Table B.4 of Astudillo-Defru et al. (2017). The quantities derived from time-series spectroscopic observations of YZ Ceti include RVs, as well as spectral properties sensitive to stellar magnetic activity. The activity tracers include the FWHM of the cross-correlation function, the line bisector slopes (BIS), and strengths of the calcium H&K ($S_{\text{HK}}$) and Hα absorption lines.

2.2. Stellar Activity

Astudillo-Defru et al. (2017) analyzed photometry of YZ Ceti from the All Sky Automated Survey (Pojmanski 1997) and the HARPS FWHM values, finding evidence of the stellar rotation period at $P_{\text{rot}} \sim 83$ days. They find no evidence for this period in the RV data or the absorption line activity indicators, an assessment with which I agree. However, I note...
that the Hα time series (and SHK, at a lower signal-to-noise ratio (S/N)) does include several interesting periodicities, including at periods near 500 and 53 days, and possibly also a long-period trend. These periods are difficult to interpret in light of the candidate rotation period at 83 days. The 500 day period is shorter than typical stellar magnetic cycles, but could be a “sub-cycle” of the longer-term magnetic evolution indicated by the trend. Similar behavior has been observed for the Sun (e.g., Wauters et al. 2016). It is possible that the rotation period is either 53 or 83 days, and the other period is a typical active region lifetime.

None of the periods identified in the stellar activity indicators appear at significant power in RV. Depending on the model adopted for the planets, I sometimes observe residual power near the ~25 day harmonic of the 53 day period, but at levels far too low to be statistically significant.

Thus, it appears that the timescales for the primary stellar activity signals, as well as their dominant harmonics, lie far from the periods of the candidate exoplanets. Astudillo-Defru et al. (2017) included a Gaussian process (GP) correlated noise component (Rasmussen & Williams 2005) in their three-planet model, but I see no evidence for correlated noise from astrophysical variability near the planets under consideration. I find that the derived properties of the planets do not change significantly when including a GP noise model, and that I cannot meaningfully constrain the hyperparameters of the quasi-periodic GP kernel. Thus, for my analysis, I have modeled the HARPS time series as a sum of three Keplerian functions.

2.3. RV Period Search

I sought to identify periodicity in the RV time series using three periodograms, each with different advantages. I first used the traditional Lomb–Scargle periodogram (GLS), as fully generalized by Zechmeister & Kürster (2009). I also considered the Bayes factor periodogram (BFP), provided in the Agatha software suite by Feng et al. (2017). The BFP computes the power spectrum by comparing the Bayesian information criterion (BIC) for a periodic signal to that of the noise model at each period, and includes options for correlated noise models and correlations with activity proxies. Finally, I computed the compressed sensing periodogram (CSP) as described by Haro et al. (2017). Whereas the GLS and BFP evaluate one period at a time and identify multiple signals iteratively by removing the strongest signal and recomputing, the CSP models the entire frequency parameter space simultaneously by fitting amplitudes to a large library of periodic signals (here, sinusoids). By evaluating all periods simultaneously, the CSP excels at minimizing the impact of aliasing.

I note that the model selection routine in Agatha prefers a white-noise model with no correlations to activity proxies for the RV series. Thus, the GLS and BFP power spectra are largely similar. However, the BFP offers the advantage of a more robust threshold for statistical significance. Namely, as discussed in Feng et al. (2017), peaks with power $\ln(\text{BF}) > 5$ are generally considered significant.

All three periodograms identify the 4.66 day signal of YZ Ceti d as the strongest periodicity in the RV time series. However, subsequent analysis of the power spectra reveals ambiguities for the periods of each of the other two proposed planets in the system. In Figure 1, I show the periodograms of this study. For the GLS and BFP periodograms, I have successively modeled and subtracted the orbits of planet d and b in order to study the residual periodicities. The three periodograms again agree on the second-strongest signal, this time at a period of 0.75 days. This period is a 1 day alias of the 3.06 day period attributed to planet c by Astudillo-Defru et al. (2017). The GLS and BFP power spectra also show significant power at the 3.06 day period, while the CSP converges on a single model that prefers the 0.75 day period.

Furthermore, the GLS and BFP periodograms indicate two possible periods for planet b, one at the published value of 1.97 days, and one at a slightly longer period of 2.02 days. Again, the 2.02 day period is a 1 day alias of the 1.97 day period. While the physical properties of planet b are minimally dependent on such a small difference in period, it will be important to identify the correct period for future transit searches.

The CSP does not recover the 2 day planet at any significant amplitude. In general, I find that the detections of planets b and c are marginal, and strongly dependent on the RVs from the first season of high-cadence observations in 2013. The stellar activity indicators suggest YZ Ceti is relatively quiet during this season, and I do not observe periodicity near the planet periods in the activity tracers when isolating the 2013 observations. Thus, there is no particular reason to exclude or disfavor these data. However, it will be important to confirm these planets with additional observations.

2.4. Attempts to Break the Period Degeneracies

2.4.1. Simulated Signals

I attempted to break the degeneracies between the periods of planets b and c using two techniques. First, I considered the method suggested by Dawson & Fabrycky (2010)—which relies on the periodogram peaks and phases of the signals in

$^1$ Ordinarily, the BFP automatically models and subtracts the strongest periodogram peak at each step. For the purpose of determining the period of planet c, I have manually removed planets d and b even though the peaks associated with planet c are stronger.
comparison to simulated time series—to examine the period of planet c. My application of this technique involves first computing a pair of three-planet Keplerian fits, one for each candidate period for planet c. Then, using the parameters derived for planet c, I generated a simulated time series for a single planet at the candidate period, using the time stamps and derived for planet c, I generated a simulated time series for a candidate period for planet c. Then, using the parameters computing a pair of three-planet Keplerian phase rows.

1.8 m s$^{-1}$ comparison to simulated time series

The Astrophysical Journal Letters, 864:L28 (5pp), 2018 September 10 Robertson

Figure 2. GLS periodogram of the YZ Ceti RVs (black/gray) after subtracting planets b and d, compared to simulated time series for planets at 3.06 days (red, middle row) and 0.75 days (blue, bottom row). The periodogram of the original data is shown in all three rows for visual comparison. The dials above each peak show the phase ($M_i$) derived by modeling a Keplerian at that period. I do not show dials at peaks for which I fixed the planet’s phase.

I performed this exercise for models using periods of 1.97 and 2.02 days for planet b. In Figure 2, I show the results for the test using $P_b = 2.02$ days, although the choice of $P_b$ makes little difference. I show the version using $P_b = 2.02$ primarily because it exhibits the greatest discrepancy between the two hypotheses. For the simulated signals, I find that each candidate period creates significant periodogram power at the 1 day alias, and that the phases of models to the “wrong” period are similar to those derived from the original RVs. The one significant difference I observe between the periodograms of the simulated data and the original is that the periodogram power at the true period of the simulated 3-day planet is significantly stronger than that of the original data. I note, however, that this could be caused by random fluctuation due to the jitter added to the simulated data. Alternatively, it could indicate incompatibility of the 3.06 day period with the 2.02 day period. In general, I find that this test does not unambiguously distinguish between the candidate periods, since a planet at either period can create power at both periodogram peaks, and result in Keplerian models that match the phases derived from fitting to incorrect periods. Furthermore, I elected not to repeat this experiment to distinguish between the candidate periods of planet b because of the greater ambiguity of the period of planet c.

2.4.2. Model Comparison

Another way to determine which periods are preferred by the current data is to check goodness-of-fit statistics for models to the RVs. I fit Keplerian models to each of the candidate period combinations using the Markov Chain Monte Carlo (MCMC) RV modeling package RadVel (Fulton et al. 2018). For each model, I set the Keplerian orbital elements of each planet, zero-point offsets, and additional white-noise terms (“jitters”) for the HARPS velocities before and after the fiber upgrade, as free parameters. The MCMC chains use 150 random walkers, and up to 100 000 iterations, although the calculation stops if the chains are found to have converged as determined by yielding a value of the Gelman-Rubin statistic less than 1.003 (Ford 2006). Where possible, I have retained the model priors used by Astudillo-Defru et al. (2017). When evaluating models with $P_c = 0.75$ days, I shifted the period prior to uniform between 0.5 and 1 day.

Prior to computing the MCMC models, I excluded two RVs (BJD = 2457258.798094, 2457606.952332), each of which is more than 6σ from the data mean. I removed these values primarily to prevent a biased estimate of the velocity offset between the pre- and post-upgrade RVs.

I evaluated models for solutions of zero, one, two, and three planets to compare the relative importance of changing the planet periods to that of adding or removing planets. However, I emphasize that the model comparison used in this study is a simple exercise intended primarily to test whether I could
distinguish between the aliases for the periods of planets b and c. A more thorough exploration of the parameter space, including, for example, the impact of various noise models or additional planets, is beyond the scope of this work.

For each model configuration, we compared the BIC and the log of the likelihood (ln L). The results of this comparison are summarized in Table 1. I have assigned values for the false alarm probability (FAP) by comparing the ln L values between models with different numbers of planets using the “unbiased” likelihood improvement $\tilde{Z}$ from Baluve (2009, their Equation (18)). The FAP then scales approximately as $\text{FAP} \propto e^{-Z/\tilde{Z}}$ (e.g., Baluve 2008). The FAPs listed in Table 1 are relative to the highest-likelihood model with one fewer planet than the model under consideration.

Unfortunately, I cannot identify any single model that is clearly preferable to the others. The FAP values in Table 1 show a clear preference for the two-planet model with $P = 4.66, 0.75$ over the single-planet model, but the case for adding a third planet is marginal compared to the improvement yielded by changing the period of planet c to 18 hr.

Because I used uniform priors in my MCMC models, I may evaluate the relative probabilities of models with the same number of free parameters as $\frac{P_1}{P_2} = e^{\ln L_1 - \ln L_2}$. Thus, for the three-planet models, I find that the specific configuration proposed by Astudillo-Defru et al. (2017) is approximately 3200 times less likely than my highest-likelihood model, which uses $P_1 = 0.75$ days. However, the rest of the models are more similar, with no model above the $\frac{P_1}{P_2} = 150$ threshold typically used as a minimum for unambiguously preferring one model over another (e.g., Feroz et al. 2011). Thus, rather than choosing a single “best” model, I summarize some qualitative results revealed by this analysis as follows.

1. Models with $P_1 = 0.75$ days are consistently preferred over those with the original 3.06 day period. The two-planet solution with $P = 4.66, 0.75$ days is clearly the best such model, and both of the highest-likelihood three-planet models have $P_1 = 0.75$ days.

2. In light of the two-planet solution with $P = 4.66, 0.75$ days, the addition of a third planet with a period near 2 days is only marginally supported by my analysis. The FAP for the best three-planet solution relative to the best two-planet model is 0.2%, suggesting planet b is probably real, but requires additional observations to be confirmed. Interestingly, the best two-planet solution was identified in the CSP, suggesting that—as argued by Hara et al. (2017)—the compressed sensing technique is especially useful for avoiding ambiguities caused by aliasing.

3. Distinguishing between periods of 1.97 and 2.02 days for planet b is particularly difficult. The 1.97 day period is especially disfavored when adopting the 3.06 day period for planet c or excluding it altogether. On the other hand, the best model in Table 1 uses the 1.97 day period.

3. Discussion

In Table 2, I list the modeled and derived parameters for the best fit in this study to the system with planet periods of 4.66, 1.97, and 0.75 days. The values in Table 2 assume a stellar mass of $M_* = 0.13 \pm 0.01 M_\odot$ derived from the Delfosse et al. (2000) K-band mass–luminosity relationship ($K = 6.42 \pm 0.02$; Cutri et al. 2003) and the Gaia DR2 parallax $\pi = 269.36 \pm 0.08$ mas (Gaia Collaboration 2018). I present this solution not as a replacement for the model presented in Astudillo-Defru et al. (2017), but rather to serve as a comparison elucidating the consequence of adopting the shorter value of $P_c$.

If the true period of planet c is in fact 0.75 days, it becomes somewhat unique among the known exoplanets. The minimum masses of the YZ Ceti planets are already the smallest ever discovered with RV, but the revised minimum mass $m_c \sin i = 0.58M_\oplus$ would establish it as firmly subterrestrial in mass. It would be beneficial to acquire additional RV observations of YZ Ceti during TESS observations in order to better evaluate potential activity contributions to the RVs, and more precisely determine the orbital properties of the low-mass planets in this system.

I used the probabilistic mass–radius prediction routine Forecaster (Chen & Kipping 2017) to estimate the expected radius of planet c under the assumptions that $P_c = 0.75$ days, and that the YZ Ceti system is viewed edge-on. Forecaster predicts a radius of $R_c = 0.86 \pm 0.1 \ R_\oplus$. The K-band radius–luminosity relationship of Mann et al. (2015) yields a radius of $R_* = 0.169 \pm 0.001 \ R_\odot$ for YZ Ceti, which results in a geometric transit probability of 10%, more than double the probability derived from the 3.06 day period. The small stellar radius also yields a relatively high expected transit depth of 0.22%, which could even potentially be observed from the ground (Stefansson et al. 2017). Thus, if the true period of YZ Ceti c is 0.75 days, it offers the potential opportunity for a high S/N study of a transiting subterrestrial exoplanet orbiting a relatively bright nearby star. TESS is currently scheduled to observe YZ Ceti in Sector 3 (2018 September–October) of its survey of the southern hemisphere. TESS should easily recover the transit signatures of all three planets if they are inclined so as to transit.

If $P_c = 18$ hr, the small orbital separation (high temperature) and small mass (low escape velocity) of the planet could result in significant levels of mass loss. The planet’s atmosphere (e.g., GI 436b, Ehrenreich et al. 2015) or surface (e.g., KIC 1255b, Rappaport et al. 2012) may be escaping, creating an extended tail of material extending from its surface and causing variable
transit depths and durations. The expected surface temperature of YZ Ceti c at the 18-hour period (~1000 K, according to Equation (5) of Rappaport et al. 2012) is too low to vaporize silicates, but tidal forces could result in enhanced volcanic activity that would launch dust from the surface. Thus, if the planet (or just its exosphere/tail) is transiting, it may provide a unique opportunity to study its atmospheric and interior composition via transit spectroscopy with JWST.

4. Conclusion

This analysis suggests the available HARPS RVs of YZ Ceti are incapable of distinguishing unambiguously between 1 day aliases for the periods of planets b and c. My periodograms and model comparisons show a slight preference for revising the period of planet c to 0.75 days, but determining an exact period for planet b is more difficult. If the period of planet c is in fact 0.75 days, its minimum mass drops to just above half the Earth’s mass, and its transit probability increases to 10%.

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References

Anglada-Escudé, G., Amado, P. J., Barnes, J., et al. 2016, Natur, 536, 437
Asthudillo-Defru, N., Diaz, R. F., Bonfils, X., et al. 2017, A&A, 605, L11
Baluev, R. V. 2008, MNRAS, 385, 1279
Baluev, R. V. 2009, MNRAS, 393, 969
Borucki, W. J., Koch, D., Basri, G., et al. 2010, Sci, 327, 977
Chen, J., & Kipping, D. 2017, ApJ, 834, 17
Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, yCat, 2246
Dawson, R. I., & Fabrycky, D. C. 2010, ApJ, 722, 937
Delfosse, X., Forveille, T., Ségransan, D., et al. 2000, A&A, 364, 217
Ehrenreich, D., Bourrier, V., Wheatley, P. J., et al. 2013, Natur, 522, 459
Feng, F., Tuomi, M., & Jones, H. R. A. 2017, MNRAS, 470, 4794
Feroz, F., Balan, S. T., & Hobson, M. P. 2011, MNRAS, 415, 3462
Ford, E. B. 2006, ApJ, 642, 505
Fulton, B. J., Petigura, E. A., Blunt, S., & Sinukoff, E. 2018, PASP, 130, 044504
Gaia Collaboration 2018, yCat, 1345
Gillon, M., Triand, A. H. M. J., Demory, B.-O., et al. 2017, Natur, 542, 456
Harra, N. C., Boué, G., Laskar, J., & Correia, A. C. M. 2017, MNRAS, 464, 1220
Hirano, T., Fukui, A., Mann, A. W., et al. 2016, ApJ, 820, 41
Kopparapu, R. K., Ramirez, R., Kasting, J. F., et al. 2013, ApJ, 765, 131
Mahadevan, S., Ramsey, L. W., Terrien, R., et al. 2014, Proc. SPIE, 9147, 91471G
Mann, A. W., Gaidos, E., Boyajian, T., & von Braun, K. 2015, ApJ, 804, 64
Mann, A. W., Gaidos, E., Mace, G. N., et al. 2016, ApJ, 818, 46
McArthur, B. E., Endl, M., Cochran, W. D., et al. 2004, ApJL, 614, L81
Pojmanski, G. 1997, AcA, 47, 467
Quirrenbach, A., Amado, P. J., Caballero, J. A., et al. 2016, Proc. SPIE, 9908, 990812
Rappaport, S., Levine, A., Chiang, E., et al. 2012, ApJ, 752, 1
Rasmussen, C. E., & Williams, C. K. I. 2005, Gaussian Processes for Machine Learning (Cambridge, MA: The MIT Press)
Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2015, IATIS, 1, 014003
Stefansson, G., Mahadevan, S., Hebb, L., et al. 2017, ApJ, 848, 9
Wauters, L., Dominique, M., & Dammaseh, I. E. 2016, SoPh, 291, 2135
Winn, J. N., Matthews, J. M., Dawson, R. I., et al. 2011, ApJL, 737, L18
Zechmeister, M., & Kürster, M. 2009, A&A, 496, 577

Table 2

Modeled and Derived Orbital Parameters for the Best-fit MCMC Model in This Study to the RVs of YZ Ceti

| Parameter | Planet b | Planet c | Planet d |
|-----------|----------|----------|----------|
| Period $P$ (days) | $1.9689 \pm 4 \times 10^{-4}$ | $0.75215 \pm 1 \times 10^{-5}$ | $4.6568 \pm 4 \times 10^{-4}$ |
| Time of inferior conjunction $T_C$ (BJD—245,0000) | $7662.1 \pm 0.2$ | $7661.56 \pm 0.05$ | $7657.9 \pm 0.2$ |
| $\sqrt{P} \cos \omega$ | $0.2 \pm 0.4$ | $0.2 \pm 0.3$ | $0.1 \pm 0.3$ |
| $\sqrt{P} \sin \omega$ | $0.02 \pm 0.3$ | $-0.01 \pm 0.3$ | $0.1 \pm 0.3$ |
| RV amplitude $K$ (m s$^{-1}$) | $1.3 \pm 0.3$ | $1.6 \pm 0.3$ | $1.8 \pm 0.3$ |
| HARPS pre-upgrade zero-point offset (m s$^{-1}$) | $0.1 \pm 0.2$ | $1.0 \pm 0.3$ | $0.1 \pm 0.3$ |
| HARPS pre-upgrade white-noise jitter $\sigma_{pre}$ (m s$^{-1}$) | $0.1 \pm 0.2$ | $0.1 \pm 0.2$ | $0.1 \pm 0.2$ |
| HARPS post-upgrade zero-point offset (m s$^{-1}$) | $-0.1 \pm 0.3$ | $-0.1 \pm 0.3$ | $-0.1 \pm 0.3$ |
| HARPS post-upgrade white-noise jitter $\sigma_{post}$ (m s$^{-1}$) | $1.7 \pm 0.3$ | $1.7 \pm 0.3$ | $1.7 \pm 0.3$ |
| Minimum mass $m \sin i$ ($M_{\oplus}$) | $0.65 \pm 0.15$ | $0.58 \pm 0.11$ | $1.21 \pm 0.2$ |
| Semimajor axis $a$ (au) | $0.0156 \pm 4 \times 10^{-4}$ | $0.0082 \pm 2 \times 10^{-4}$ | $0.0276 \pm 7 \times 10^{-4}$ |
| Eccentricity $e$ | $0.03^{+0.05}_{-0.04}$ | $0.02^{+0.06}_{-0.06}$ | $0.02^{+0.06}_{-0.06}$ |
| Longitude of periastron $\omega$ (°) | $354 \pm 90$ | $30 \pm 80$ | $315 \pm 120$ |