An investigation into the radial velocity variability of GJ 581: On the significance of GJ 581g

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1 Introduction

Radial velocity (RV) searches for exoplanets has made great strides in improving the precision of stellar RV measurements. Whereas 30 years ago Campbell & Walker (1980) achieved a breakthrough precision of 13 m s\(^{-1}\), current RV surveys often achieve a precision of \(\approx 1\) m s\(^{-1}\), or a factor of 10 better. Consequently modern surveys are finding exoplanets of lower and lower masses.

Low mass planets often can produce a velocity \(K\)-amplitude comparable to the measurement error or intrinsic stellar variability due to activity or oscillations. Such planets are frequently found in multiple systems that only increase the difficulty in extracting the signal of individual planets. This can lead to discovered planets that are refuted, or that remain controversial. A case in point is the planetary systems – stars: individual (GJ 581, HIP 74995) – techniques: radial velocities

1.1 A case in point is the planetary system around the M dwarf GJ 581. Bonfils et al. (2005) reported the presence of a 5.37-d hot Neptune (GJ 581b), followed by the discovery of two additional planets with periods of 12.93 d, \(m = 5.06\) M\(_\oplus\) (GJ 581c) and \(P = 83.4\) d (GJ 581d). Subsequently Mayor et al. (2009) revised the period of GJ 581d to 67 d as well as provided evidence for a fourth planet with a period of 3.15 d (GJ 581e). The evidence points to GJ 581 hosting 4 planets, although recent work by Baluev (2012) questions whether the fourth planet, GJ 581d is present.

Vogt et al. (2010, hereafter V2010) presented 11 years of RV measurements made with the Keck HIRES spectrograph and combined these with the available HARPS measurements. They could confirm the presence of the four planets, but they also claimed the presence of a fifth, GJ 581g, with a minimum mass of 3.1 M\(_\oplus\) and a period of 36 d. This period placed GJ 581g firmly in the habitable zone of the host star. The presence of this signal seemed to be significant, having a false alarm probability of \(\approx 10^{-7}\). Habitable planets are of considerable interest to the community and this discovery prompted work on both the habitability of this fifth planet (Heng & Vogt 2011; Pierrehumbert 2011; von Bloh et al. 2011), as well as dynamical stability of the GJ 581 system as a whole (Tideu et al. 2012).

The planet GJ 581g proved to be controversial. Tuomi (2011) presented a Bayesian re-analysis of the radial velocities for GJ 581 and concluded that only four planets were present. Stronger evidence against a fifth planet came from Forveille et al. (2011) who used 121 additional HARPS measurements for this star and these along with the previous ones showed no evidence for the presence of GJ 581g. However, GJ 581g would “not go gentle into that good night”.

Vogt, Butler, & Haghighipour (2012, hereafter VBH2012) re-analyzed the HARPS data modeling it with self-consistent orbits and concluded that the HARPS data indeed showed evidence for a 2.2 M\(_\oplus\) but with an orbital period of 32 d. Thus a low mass planet could still be in the habitable zone of the star, although the false alarm probability for this detection was high, at about 4 %. More recently, Gregory (2012) applied a Bayesian analysis to the RV data for GJ 581 and concluded that the GJ 581g was not present in the data.

The purported presence of GJ 581g demonstrates the need for other analyses of RV measurements in order to confirm the discovery of low mass planets. In this paper we use an independent analysis of all available RV measurements for GJ 581 to assess the presence and significance of signals that could be attributed to planets in the system. The tools utilized are simple Fourier pre-whitening and periodogram analyses – the basic tools employed by all planet hunters. The purpose of this paper is not only to confirm previous
planets found in the GJ 581 system (and possibly new ones), but also to see if these simple tools can reach the same conclusions as more sophisticated methods such as Bayesian analysis. It is also important to explore limitations and possible pitfalls when using these standard tools to search for periodic signals in RV data and to assess their statistical significance.

2 Frequency analysis with circular orbits

2.1 Combining the data sets

The Keck and HARPS data sets have different zero points that must be applied to the data before analyzing the combined data set. One can do this by calculating and subtracting the mean of each data set, or by determining the offset of data taken on, or close to the same nights. However, the presence of multi-periodic signals and measurement error may result in a poor determination of the offset values. On the other hand, the presence of a known periodic signal in the data provides a more robust way of determining this offset. For this work we used the periodic variations of planet b – the dominant signal to the data, We first analyzed the HARPS data since it was the most extensive and was of slightly better quality than the Keck data (lower rms scatter). Since the presence of the other planet (GJ 581c, d, and e) could influence the fitting of the orbit to planet b, the contribution of these were removed from the RV measurements.

A Fourier pre-whitening procedure (see below) was used to fit sine functions (i.e. circular orbits) to the orbital motions of GJ 581b, c, d, e as these were clearly in the data (see below). The variations of the 3 planets c–e were then removed leaving behind the orbital motion of GJ 581b. An orbital solution was then made to derive the amplitude, period, and ephemeris of planet b.

The pre-whitening procedure was then applied to the Keck data, but in this case only two planets were removed as supported by the pre-whitening process (see below). The result was two data sets containing the orbital variations predominantly from GJ 581b. An orbital solution was then made to the two data sets keeping the amplitude, period, ephemeris of planet b fixed to the values determined from the HARPS data, but allowing the zero point offset to vary. In this way a best fit, in a least squares sense, was made to the zero point offsets between the two data sets. This offset was applied to the original data with all planets, intrinsic variability, and noise still present in the data.

2.2 Fourier analysis with pre-whitening

Fourier analysis with pre-whitening is a standard procedure in the field of stellar oscillations for extracting multi-periodic signals from time series data. One finds the highest peak in the Fourier amplitude spectrum, calculates a least squares sine fit (period, amplitude, and phase), and subtracts this from the data. One then searches for additional signals often taken as the highest amplitude in the residual amplitude spectrum. This process continues until one reaches the level of the noise. This procedure should work well on multi-planet systems in circular or low eccentricity orbits. For this process the program Period04 (Lenz & Breger 2004) was used.

Tables 1–3 show the results of this process for the HARPS data, Keck data, and combined data sets respectively. In Table 1 the first four frequencies are due to planets, whereas the last two frequencies (separated by a line) are of unknown origin. In Table 2 the last frequency (below the line) is the alias frequency. The rms scatter after removing the contributions of planets b–e is 1.98 m s$^{-1}$ for the HARPS data and 2.84 m s$^{-1}$ for the Keck data.

Figures 1 and 2 show the results of the pre-whitening procedure applied to the HARPS and Keck data, respectively. For clarity, narrow frequency windows about the planet signals are shown. In all figures of the amplitude spectra or periodograms the unit of choice is frequency (c d$^{-1}$) which is the natural unit of Fourier transforms and periodograms. Plotting the amplitude (power) as a function of period results in a non-linear scale along the ordinate and this distorts the periodogram. In the discussion both frequency and period units will be used. We only show the individual sets to highlight the differences in results between

| Table 1 | Periods found by pre-whitening of the HARPS data. |
|---------|-----------------------------------------------|
| Frequency (d$^{-1}$) | Period (d) | K-amplitude (m s$^{-1}$) |
| 0.18627 ± 2.8 × 10$^{-6}$ | 5.369 ± 8.4 × 10$^{-5}$ | 12.49 ± 0.18 |
| 0.07740 ± 1.2 × 10$^{-5}$ | 12.920 ± 0.002 | 3.29 ± 0.12 |
| 0.01499 ± 2.5 × 10$^{-5}$ | 66.71 ± 0.01 | 1.77 ± 0.22 |
| 0.31754 ± 2.6 × 10$^{-5}$ | 3.149 ± 2.5 × 10$^{-5}$ | 1.81 ± 0.14 |
| 0.00519 ± 3.3 × 10$^{-5}$ | 192.68 ± 1.22 | 1.06 ± 0.17 |
| 0.02008 ± 3.8 × 10$^{-3}$ | 49.80 ± 0.09 | 0.90 ± 0.24 |

| Table 2 | Periods found by pre-whitening of the Keck data. |
|---------|-----------------------------------------------|
| Frequency (d$^{-1}$) | Period (d) | K-amplitude (m s$^{-1}$) |
| 0.18627 ± 4.4 × 10$^{-6}$ | 5.370 ± 0.0001 | 12.35 ± 0.40 |
| 0.07744 ± 1.9 × 10$^{-5}$ | 12.92 ± 0.003 | 2.93 ± 0.40 |
| 0.03827 ± 2.6 × 10$^{-6}$ | 26.17 ± 0.018 | 1.73 ± 0.40 |
| 0.02734 ± 3.2 × 10$^{-6}$ | 36.54 ± 0.042 | 1.43 ± 0.40 |

| Table 3 | Periods found by pre-whitening of the combined data. |
|---------|-----------------------------------------------|
| Frequency (d$^{-1}$) | Period (d) | K-amplitude (m s$^{-1}$) |
| 0.18627 ± 3.8 × 10$^{-6}$ | 5.3685 ± 0.0001 | 12.47 ± 0.21 |
| 0.07742 ± 1.5 × 10$^{-5}$ | 12.9165 ± 0.0025 | 3.29 ± 0.21 |
| 0.01500 ± 1.4 × 10$^{-5}$ | 66.667 ± 0.062 | 1.81 ± 0.22 |
| 0.31756 ± 1.5 × 10$^{-5}$ | 3.1496 ± 0.0001 | 1.83 ± 0.12 |
the two and because the results for the combined data sets follow those using only the HARPS data.

The Fourier analysis of only the HARPS data was able to find all four planets with periods and amplitudes consistent with the combined data. The pre-whitening of the HARPS data first finds planet b (Panel a in Fig. 1), then planet c (Panel b), followed by planet e (Panel c) and finally Planet e (Panel d). Removing GJ 581b–e from the data results in dominant peak at $\nu = 0.00519 c^{-1}$ ($P = 192.6$ d).

However, there is second peak almost with the same amplitude at $0.0312 c^{-1}$ which corresponds to the 32-d period reported by VBH2012 (marked by the dashed vertical line). Removing the dominant peak at 192-d results in approximately 4 equally strong peaks in the frequency range $0 < \nu < 0.03 c^{-1}$, with the strongest at $0.02 c^{-1}$ ($P = 49.8$ d).

This and the 192-d period are listed in Table 1, but are not considered to be significant. The 32-d period is still present, but with reduced amplitude.

The Fourier analysis of the Keck only data shows a peak near 26 d ($\nu = 0.038 c^{-1}$) (Panel e in Fig. 2). Removing this frequency shows a peak (Panel f) at $\nu = 0.0273 c^{-1}$ corresponding to the 36 d period found by V2010. Although we list these signals in Table 2 we do not consider these as significant.

2.3 Analysis with Keplerian orbits

The previous analysis employed multi-component sine fitting which is valid so long as the orbits are circular. Exoplanets can have significant eccentricity, even for short period planets. In Fourier space an eccentric orbit manifests itself by the presence of harmonics to the orbital frequency ($2\nu_{\text{orbit}}, 3\nu_{\text{orbit}}, \text{etc.}$). In particular the 32-d period seen in the HARPS RV residuals is close to the first harmonic ($2\nu_{\text{orbit}}$) of GJ 581d and might be due to an eccentric orbit.

To investigate the presence of eccentric orbits a multi-component sine fit was made for the 4-planet solution. The
Fig. 2 Fourier pre-whitening performed on the Keck RV data. Panel a: amplitude spectrum of the original RV measurements. Panel b: amplitude spectrum after removing the signal from GJ 581b. Panel c: amplitude spectrum after removing the alias frequency at 0.111 \( \text{c d}^{-1} \). Panel d: amplitude spectrum after removing the true frequency to GJ581c from Panel b. Panel e: same as previous panel, but for the frequency range 0.0 < \( \nu \) < 0.05 \( \text{c d}^{-1} \). Panel f: amplitude spectrum after removing the signal at 0.038 \( \text{c d}^{-1} \) (shown by the vertical line in Panel e). The vertical line in Panel f marks the location of the 36-d period from V2010.

| Parameter | Value          |
|-----------|----------------|
| Period (d) | 66.64 ± 0.08  |
| \( K \) (m s\(^{-1}\)) | 2.20 ± 0.19    |
| \( e \) | 0.205 ± 0.08   |
| \( \omega \) (°) | 2 ± 23         |
| \( T_0 \) | 245141.6407 ± 4.19 |

Table 4 Eccentric orbital solution for GJ 581d.

| Period (d) | \( K \)-amplitude (m s\(^{-1}\)) |
|------------|----------------------------------|
| 5.3706 ± 0.0001 | 12.49 ± 0.17                  |
| 12.920 ± 0.002  | 3.30 ± 0.17                    |
| 3.150 ± 0.001   | 1.87 ± 0.17                    |

Table 5 Fourier pre-whitening of the combined data after removal of eccentric orbital solution for GJ 581d.

| Period (d) | \( K \)-amplitude (m s\(^{-1}\)) |
|------------|----------------------------------|
| 5.3710 ± 0.00001 | 12.47 ± 0.32                  |
| 12.917 ± 0.001  | 3.30 ± 0.32                    |
| 3.149 ± 0.0002  | 1.76 ± 0.32                    |

Table 6 Pre-whitening of Keck data with an eccentric GJ 581d.

orbits of three planets were then subtracted leaving the orbital motion of the remaining planet. An orbital solution was then made to this planet allowing the eccentricity to vary. This was successively done for all four planets in the GJ 581 system.

The results of this analysis showed that the orbital motion of GJ 581b, c, and e were consistent with circular orbits. Either the Keplerian fit produced a slight eccentricity that was less than the error, or an unphysical slightly negative eccentricity, again to within the error of being zero. Circular orbits (sine functions) seem to be a valid assumption for the orbital motion of GJ 581b, c, and e. Only GJ 581d showed significant eccentricity. Table 4 shows the final orbital solution for GJ 581d. The eccentricity of \( e = 0.20 \pm 0.02 \) is consistent with that found by Forveille et al. (2011). The pre-whitening analysis was repeated on all the data after removing the eccentric Keplerian motion of GJ 581d. The results are shown in Table 5 for the combined data sets. The results are consistent with the analysis assuming circular orbits for all planets. Even for GJ 581d the Fourier analysis (i.e. circular orbits) results in a comparable \( K \)-amplitude, 1.74 ± 0.17 m s\(^{-1}\) versus 2.20 ± 0.19 m s\(^{-1}\).
The pre-whitening of the Keck data after removing an eccentric orbit for planet d showed a slightly improved result than the one assuming a circular orbit. This is shown in Fig. 3. Removing an eccentric orbit for planet d suppresses the true frequency at the alias frequency at the four planets. The vertical dashed line marks the frequency of the 32-d period signal found by VBH2012.

2.4 Signals from a “fifth” planet

We investigated the presence of periodic signals from a possible fifth planet in the system. A Scargle periodogram was employed since the power of a signal is related to the statistical significance of the signal. As a personal rule of thumb, Scargle power, \( z \), greater than 10 is a sign of a possibly significant signal in the data. Figure 3 shows the periodogram of the RV residuals after subtracting circular orbits (i.e. pre-whitening) calculated using the combined data sets. The panels shows the periodogram of the residuals of the Keck, HARPS, and combined data separately. The Keck data shows a significant peak at \( \nu = 0.0273 \) \( \text{c d}^{-1} \), the 36-d period reported by V2010.

The HARPS data do show evidence for other, possibly significant peaks. There is a peak at \( \nu = 0.00523 \) \( \text{c d}^{-1} \) \((P = 192 \text{ d})\) and another at \( \nu = 0.0058 \) \( \text{c d}^{-1} \) \((P = 172 \text{ d})\). There is also an equally strong peak at \( \nu = 0.031 \) \( \text{c d}^{-1} \). This corresponds to the 32-d period claimed by VBH2012. However, this peak is diminished in the combined data set as are the ones near \( \nu = 0.00523 \) \( \text{c d}^{-1} \). Although the frequency is near the harmonic of the 67-d period, an eccentric orbit can not entirely reproduce the observed amplitude. Tests made with a synthetic eccentric orbit with a period of 67 d and a \( K \)-amplitude of 2 m s\(^{-1}\) resulted in an amplitude the harmonic of no more than 0.5 m s\(^{-1}\), even for highly eccentric orbits. This is significantly less than the amplitude of 0.9 m s\(^{-1}\) seen at \( \nu = 0.03 \) \( \text{c d}^{-1} \). The only remaining possible significant peak in the combined data set is at \( \nu = 0.02292 \) \( \text{c d}^{-1} \) \((P = 43.6 \text{ d})\).

Figure 5 shows the periodograms after removing an eccentric orbit for GJ 581d, and circular orbits for GJ 581b,c, and e. They are similar, but with notable differences. In the Keck data the peak at \( \nu = 0.0273 \text{ c d}^{-1} \) (36 d) is greatly reduced (less significant) In the HARPS data the peak at
3 Statistical significance of frequencies

Here we investigate the statistical significance of the planet signals. For a Scargle periodogram the power, $\nu$, is related to the statistical significance by $\text{FAP} = 1 - (1 - e^{-\nu})^N \approx N e^{-\nu}$, where $N$ is the number of independent frequencies which can be approximated by the number of data points. If the signal is incoherent, or short-lived, adding more data would cause the Scargle power to decrease. On the other hand for a real signal, longer-lived, adding more data would add to the significance of the detection, thus increasing the Scargle power. Scargle periodograms were performed on data containing a single “planet” signal after removing the contribution of the other planets.

Figure 4 shows the power in the Scargle periodogram at the planet frequency as a function of the number of data points for GJ 581b, c, d, and e. First the HARPS data was used, followed by adding the Keck data. All four planets show the expected behavior for a real signal that is coherent and long lived — the power and thus significance of the signal increases with more data. Even though the Keck data showed evidence for only two planets, the fact that the overall Scargle power for all planets increases when adding these to the HARPS data supports the fact that GJ 581b-e are indeed all present in the Keck data.

We now turn to the statistical significance of the fifth planet, starting with residuals calculated using circular orbits for all planets. The Keck RV residuals produced assuming circular orbits for all planets show what appears to be a significant signal at $\nu = 0.027 \text{ c d}^{-1}$. The false alarm probability (FAP) of this signal was assessed using a bootstrap randomization procedure. The RV values were randomly shuffled 200,000 times keeping the times fixed, performing periodograms for the random data and then seeing how many random periodograms had power greater than the observed periodogram. The FAP determined in this way was $3.5 \times 10^{-5}$. The periodogram of the residual HARPS data (central panel Fig. 4), on the other hand, shows no evidence for the 36-d period as noted by Forveille et al. (2012).

However, the picture gets more complicated when one examines only a portion of the HARPS data. The residual RV data from HARPS and Keck were combined and sorted according to time. The periodogram was calculated using the first 50 points and subsequently adding more data. Figure 5 shows the Scargle power at the 36-d period as a function of $N$, the number of data points. One can see an increase in the power (and thus significance) up to $N = 230$. This point represents 100 Keck measurements and 130 HARPS measurements. This behavior also seems to be present even when using an eccentric orbit for GJ 581d (triangles), although the overall power is less than for the circular orbit case.

To compare these results to those expected from a known real signal, a sine function having a 36-d period and the same amplitude as the RV data was generated and sampled in the same way as the data. Random noise with $\sigma = 2 \text{ m s}^{-1}$ was added to the simulated data. This value is comparable to the rms scatter of the HARPS data and only slightly less than that of the Keck data ($\sigma = 2.7 \text{ m s}^{-1}$) after removing the 36-d variation. The dots in Fig. 7 represent the behavior of the Scargle power for these simulated data and the line is a least square fit. The power of the 36-d period for the first 230 data points follows that of the fake data and attains a maximum Scargle power of $z = 16$ for the 36-d period. The FAP was determined using 200,000 random shuffles of the data. In no instance did the power of the random data exceed the actual data periodogram and this indicates a FAP $< 2 \times 10^{-6}$. At face value this seems to indicate that the signal at 36-d in the Keck data is not only significant, but it is supported by part of the HARPS data. Adding the first half
of the HARPS points indeed boosts the significance of this signal causing the FAP to drop by a factor of 10.

The addition of the last 100 HARPS measurements, however, quickly causes the 36-d period simply to go away. Including all the HARPS measurements causes the FAP of the 36-d period to drop to \( \approx 6\% \). This signal if real is clearly not coherent or long-lived.

Table 7 lists all the possibly significant periods (frequencies) and their amplitudes found in the residual data after removing GJ 581b–d. Included is the 32-d period found by VBH2012. Listed are the data sets used (Keck, HARPS, or combined) as well as the method: Multi-component sine fitting which is the equivalent to circular orbits (“Sine fitting”), or using an eccentric orbit for planet d, but circular orbits for the other 3 planets (labeled “orbit d + Sine”). The FAP or these signals were estimated using a bootstrap of 200,000 random shuffles of the data. Note that most of these, with the exception of the 192-d period found in the HARPS only data, have an extremely low FAP. Virtually every investigator (the author included) using RV data to search for planets would claim these as significant detections of planetary signals.

To investigate the reality of these we can apply the “significance versus number of points” test. This was done by looking at the Scargle power of a signal by first adding in succession the HARPS data, followed by the Keck data. This was done for 3 periods: 32 d, 43 d, and 192 d and the results are shown in Fig. 8 (The 176.7-d period behaves the same as the 192-d period and is not shown.) The vertical dashed line marks the point at which Keck data was added to the periodogram. As a gauge of what one should expect for a real signal, we generated a sine function with the same amplitude found in the analysis (Table 7) that was sampled in the same way as the real data. For the noise level we used 2 m s\(^{-1}\) for the HARPS data and 2.7 m s\(^{-1}\) for the Keck data, values consistent with the actual ones. The lines show the behavior of the power of a signal as a function of data points for the simulated data. It behaves as one expects for a real signal - the power (significance) monotonically increases with more data.

None of the found periods show the behavior expected for a real signal. The 32-d and 192-d period show an initial increase in significance, but that flattens out even in the HARPS data. Adding the Keck data shows a further drop in the significance in the signal. The 43-d period does show an increase in power when adding the Keck data as does the 32-d period when adding the last few points. However, this behavior is highly suspect as one sees a dramatic increase only after adding the Keck data. For example the 43-d period shows a increase in a factor of two in power by adding the first 50 Keck points, whereas adding the last 50 HARPS point to the data keeps the power constant. Most likely these sharp increases in the Scargle power are related to different systematic errors in the data sets that cause false periods to appear due to merging the data. In spite of the formal low FAP listed in Table 7, none of the periods listed there are deemed significant.
the other planetary signals reported in the literature, namely increases with more data and their presence is also supported alone. The statistical significance of these four planets in- detection of four planets could be made with the HARPS data Table 7

| Set     | Method      | Period (d) | K (m s⁻¹)      | FAP  |
|---------|-------------|------------|----------------|------|
| Keck    | Sine fitting| 36.54      | 2.02           | 3.5×10⁻⁵ |
| HARPS   | Sine fitting| 192.3      | 0.94           | 8.7×10⁻⁴ |
| All     | Sine fitting| 176.67     | 0.94           | 1.9×10⁻⁴ |
| Keck    | orbk₄ + Sine| 36.57      | 1.97           | 1.5×10⁻⁴ |
| HARPS   | orbk₄ + Sine| 191.93     | 0.89           | 0.018 |
| All     | orbk₄ + Sine| 43.63      | 0.93           | 3.85×10⁻⁴ |

4 Discussion

The results of this analysis of the RV measurements for GJ 581 confirms the presence of four planets (GJ 581 b, c, d, and e) previously reported in the literature. A reliable detection of four planets could be made with the HARPS data alone. The statistical significance of these four planets increases with more data and their presence is also supported by independent data from Keck HIRES. On the other hand, the other planetary signals reported in the literature, namely the 36-d and 32-d periods are not confirmed. GJ 581 is at the present time only a four planet system.

V2010 also reported a 433-d period in their RV data. Gregory (2012) in his analysis of the same data claimed that a period of 399 d was present in the data which may be associated with the 433-d period found by V2010. The pre-whitening procedure could not find any significant peak at ν = 0.0025 c d⁻¹ with an upper limit on the amplitude of 0.5 m s⁻¹. Thus, we find no strong evidence for a period of ~ 400 days in the data.

The most important aspect of this analysis is not the confirmation of only four planets around GJ 581, but rather how one can be fooled by apparently significant signals in the data that are not real. For complicated multi-planet systems and especially with different data sets having different systematic errors, sampling pathologies, etc., the answer you get depends on the details of the analysis. Spurious periodic signals can creep into frequency space when combining data sets with different systematic errors. Unknown intrinsic stellar variability that can be stochastic, incoherent, short lived, etc. coupled with the data window can also cause spurious periodic signals that appear to be highly significant, only to disappear with more data. There is a lesson to be learned here: When dealing with complicated RV variations and different data sets even highly significant signals should be treated with caution, and their nature not so readily attributed to planetary companions.

A case in point is the 36-d period first reported by V2010. Given the data available to the authors at the time of publication a 36-d period was indeed present at a significant level and possibly due to another planet. Furthermore, the presence of this signal, as shown here, was supported by two independent data sets. The authors reached a reasonable conclusion based on the available data at hand. One can speculate whether this signal was in fact real, and possibly due to stellar variability. Interestingly, in their study of the M dwarf Barnard’s star (GJ 699) Küster et al. (2003) also found RV variations with a period of ≈ 32 d that appeared to be significant, but that showed correlations with variations of Hα hydrogen Balmer line that was interpreted as due to convective redshift. Possibly such similar investigations of Hα may help to distinguish between variations caused by planets and those due to stellar variability, particularly for M dwarf stars like GJ 581.

The 32-d period reported by VBH2012 is not confirmed by our study. In the periodogram a peak is seen in the HARPS data at 32-d, but higher peaks are seen at other periods. Furthermore, the presence of this 32-d period should have become more significant when adding the Keck data and it did not. The behavior of the 32-d period when including more data is not consistent with the presence of coherent signal. To complicate matters, in the combined data sets the strongest peak in the periodogram of the residual RV data is at 43 d, not 32 d, but this signal is not considered to be significant.

Low mass planets in the habitable zone of stars are of particular interest to researchers wishing to model their atmospheres and assess the possibility of habitability. The detection of these, however, will be challenging. Many of these will be found in multiple systems and the velocity reflex motion from a single planet may be comparable to the measurement error. Intrinsic stellar variability from activity and systematic errors with an unknown frequency spectrum may dominate the variability of the bona fide planets. Furthermore, because of sparse sampling at one site we may be forced to combine measurements from different sites, dif-
ferent instruments, and each with its own systematic error characteristics. The amplitude spectra of the combined data may be complicated, and not just from planetary signals. However, planet hunters searching for such planets need to deliver the best possible candidates. Investigators should not be investing time modeling atmospheres of non-existent planets. To help confirm such planets there a several things to consider:

– It is essential to perform different analyses and with different approaches to see how robust periodic signals are in the data. GJ 581 is a case in point. Different groups analyzing the same data set come to completely different conclusions using reasonable and valid analysis tools. Such exoplanet discoveries should be treated with caution.

– When combining different data sets it is essential that detected periodic signals are present at some level in all data sets. If a signal is not seen in one data set one should check that the statistical significance increases in an understandable way when adding other data sets. Periods that suddenly appear when another data set is added should be treated with caution.

– A low false alarm probability, even with FAP \(< 10^{-4}\), for a periodic signal in a multi-planet system is no guarantee that this signal is real. This is especially true if the amplitude of the signal is comparable to the measurement error.

Finally, this study demonstrates that traditional analysis tools like Fourier pre-whitening and Scargle periodograms are powerful tools for extracting multi-periodic (i.e. planets) signals from RV data. These tools even work well in the case of eccentric orbits, one needs only to cautious about the interpretation of the harmonics of a main frequency. The Scargle periodogram is a standard and valuable tool for assessing the FAP, but the “user should beware”. Even highly significant detections with formally low FAP should be treated with caution. It can be that in the process of removing other signals and thus variations in data, that this could artificially boost the significance of a remaining signal. Examinations of subsets of the data as well as the use of simulated data are needed to assess how significant a signal is.

References

Baliev, R. V. 2012, MNRAS, 429, 2052
Bonfils, X., Forveille, T., Delfosse, X., et al. 2005, A&A, 443, L15
Campbell, B., Walker, G.A.H. 1979, PASP, 91, 540
Forveille, T., Bonfils, X., Delfosse, X., et al. 2011, astro-ph/1109.2505
Gregory, P.C. 2012, MNRAS, 415, 2523
Heng, K., Vogt, S.S. 2011, MNRAS, 415, 2145
Kürster, M., Endl, M., Rouesnel, F., et al. 2003, A&A, 403, 1077
Lenz, P., & Breger, M. 2004, Period04: A Software Package to Extract Multiple Frequencies from Real Data, in The A-Star Puzzle, ed. J. Zverko, J. Ziznovsky, S.J. Adelman, & W.W. Weiss, IAU Symp. 224 (Cambridge University Press), 786
Mayor, M., Udry, S., Lovis, C., et al. 2009, A&A, 507, 487
Pierrehumbert, R. T. 2011, ApJ, 726, 8
Tadeu dos Santos, M., Silva, G.G., Ferraz-Mello, S., & Michtchenko, T.A. 2012, Celestial Mechanics and Dynamical Astronomy, 113, 49
Tuomi, M. 2011, A&A, 528, 5
Vogt, S.S., Butler, R.P., Rivera, E.J., et al. 2010, ApJ, 723, 954 (V2010)
Vogt, S.S., Butler, R.P., & Haghighipour, N. 2012, Astron. Nachr., 333, 561 (VBH2012)
von Bloh, W., Cuntz, M., Frank, S., & Bounama, C. 2011, A&A, 528, A133