Radial velocity constraints on the long-period transiting planet Kepler-1625 b with CARMENES

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ABSTRACT

Context. The star Kepler-1625 recently attracted considerable attention when an analysis of the stellar photometric time series from the Kepler mission was interpreted as showing evidence of a large exomoon around the transiting Jupiter-sized planet candidate Kepler-1625 b. However, the mass of Kepler-1625 b has not been determined independently and its planetary nature has not been formally validated. Moreover, Kepler’s long-period Jupiter-sized planet candidates, like Kepler-1625 b with an orbital period of about 287 d, are known to have low statistical false-alarm probability. An independent confirmation of Kepler-1625 b is therefore particularly important.

Aims. We aim to detect the radial velocity (RV) signal imposed by Kepler-1625 b and its putative moon on the host star, or, as the case may be, determine an upper limit on the mass of the transiting object (or the combined mass of the two objects).

Methods. We took a total of 22 spectra of Kepler-1625 using CARMENES, 20 of which were useful. Observations were spread over a total of seven nights between October 2017 and October 2018, covering 125% of one full orbit of Kepler-1625 b. We used the automatic Spectral Radial Velocity Analyser pipeline to deduce the stellar RVs and uncertainties. We then fitted the RV curve model of a single planet on a Keplerian orbit to the observed RVs using a χ² minimisation procedure.

Results. We derive upper limits on the mass of Kepler-1625 b under the assumption of a single planet on a circular orbit. In this scenario, the 1σ, 2σ, and 3σ confidence upper limits for the mass of Kepler-1625 b are 2.90 M_J, 7.15 M_J, and 11.60 M_J, respectively (M_J being Jupiter’s mass). An RV fit that includes the orbital eccentricity and orientation of periastron as free parameters also suggests a planetary mass but is statistically less robust.

Conclusions. We present strong evidence for the planetary nature of Kepler-1625 b, making it the (confirmed) planet with the tenth longest period known today. Our data do not allow us to make any firm conclusions regarding a second, possibly shorter period planet that could be responsible for the observed transit timing variation of Kepler-1625 b.

Key words. planets and satellites: detection – techniques: radial velocities – planets and satellites: fundamental parameters – planets and satellites: individual: Kepler-1625 b

1. Introduction

The stellar system Kepler-1625 (KIC 4760478, KOI 5084) has become famous for its proposed candidate of an extrasolar moon around the transiting Jupiter-sized planet Kepler-1625 b (Teachey et al. 2018; Teachey & Kipping 2018). If confirmed, this moon would be the first known exomoon. However, the exomoon interpretation remains the subject of debate (Rodenbeck et al. 2018; Heller et al. 2019; Kreidberg et al. 2019).

The abundance of moons within the Solar System suggests that there is also a plethora of moons around the thousands of exoplanets known today. These yet-to-be discovered exomoons are interesting objects, given their potential to offer insight into planet formation (Heller et al. 2019; Martin et al. 2019). Moons have also been suggested as habitats beyond the Solar System (Williams et al. 1997; Heller & Podritz 2015), possibly sustained by the tidal heating driven by their host planets even far beyond the stellar habitable zone (Reynolds et al. 1987; Scharf 2006; Heller & Barnes 2013; Heller & Armstrong 2014) defined for planets (Kasting et al. 1993). Confirmation of the exomoon around Kepler-1625 b would therefore have implications for the field of exoplanet research as a whole and possibly even for astrobiology.

Here we want to take one step back from the exomoon scenario around Kepler-1625 and its Jupiter-sized transiting object and address the question of whether Kepler-1625 b is actually a planet. Fressin et al. (2013) found that the false positive rate of planet candidates as a function of planetary radius has a peak in the Jupiter-sized regime with a value of 17.7% for planets with radii between 6 and 22 Earth radii. Heller (2018) showed that the combined uncertainties in the radius measurements of the star and the planet propagate into the possibility of Kepler-1625 b being rather a brown dwarf or possibly even a very-low-mass star. That said, a preliminary Bayesian analysis of the combined transit photometry from the Kepler and Hubble space telescopes by Teachey et al. (2019) resulted in a posterior distribution of the planetary mass (M_p) with a peak at 2.99±2.36 M_J (M_J being the mass of Jupiter) and a median value of 3.91 M_J. The inference of the planetary mass was based on two methods: firstly, an empirical probabilistic mass–radius relation for the planet as implemented in the FORECASTER software (Chen & Kipping 2017), and secondly, using FORECASTER for the moon and computing the planetary mass via the moon-to-planet mass ratio as fitted with photodynamical modelling (Teachey et al. 2018). Assuming a stellar mass (M_☉) of 1.079±0.106 M_☉ (Mathur et al. 2017), where M_☉ is the solar mass, the expected radial
velocity (RV) amplitude of a 3 $M_J$ planet on a 287 d circular orbit (Teachey et al. 2018) is about 88 m s$^{-1}$.

This 88 m s$^{-1}$ RV signal could be in reach of the “Calar Alto High-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs” (CARMENES) at the 3.5 m telescope at Calar Alto Observatory (Quirrenbach et al. 2018; Reiners et al. 2018). In fact, CARMENES has recently reached the 1 m s$^{-1}$ precision level that resulted in the detection of two Earth-mass planets around Teegarden’s star (Zechmeister et al. 2019). However, Teegarden’s star is a relatively bright M dwarf with visual and near-infrared magnitudes of $V = 15.08$ (±0.12) (value from Henden et al. 2015 as cited by Zechmeister et al. 2019) and $J = 8.39$ (±0.03) (Cutri et al. 2003), whereas Kepler-1625 is a slightly evolved ($R_\ast = 1.79^{+0.26}_{-0.48} R_\odot$), significantly fainter solar-type star with a Gaia magnitude of $G = 15.7627$ (±0.0005) (Gaia Collaboration 2018) and $J = 14.364$ (±0.032) (Cutri et al. 2003). Prior to our observations, the stellar properties of Kepler-1625 suggested an RV precision of approximately 60 m s$^{-1}$ in the wavelength range from 650 to 750 nm based on the photon limit alone (Reiners & Zechmeister 2019).\footnote{Computed for an effective temperature of $T_{\text{eff}} = 5600$ K, $J = 14$, a telescope aperture of $D = 3.5$ m, a $S/N = 4$, a resolution of $R = 90,000$, and an exposure time $t_{\text{exp}} = 20$ min using the online Radial Velocity Precision Calculator at www.astro.physik.uni-goettingen.de/research/rvprecision.}

2. Methods

2.1. Observations

CARMENES provides two sets of spectra from its two Échelle spectrographs, or “channels”. One channel covers the near infrared ($0.96 \mu m \leq \lambda \leq 1.71 \mu m$, $\lambda$ being the wavelength), and the other covers the visible light ($0.52 \mu m \leq \lambda \leq 0.96 \mu m$; Alonso-Floriano et al. 2015). Data from both channels were processed using the CARACAL pipeline (of M. Zechmeister) by performing a dark and bias correction, order tracing, flat-relative optimal extraction, cosmic-ray correction, and wavelength calibration.

We took a total of 22 spectra of Kepler-1625 with CARMENES. Table 1 lists the observation dates of the exposures in local time and Barycentric Julian Date (BJD), the mean exposure time (RV) amplitude of a 3 $M_J$ planet on a 287 d circular orbit (Teachey et al. 2018) is about 88 m s$^{-1}$.

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2.2. Radial velocity analysis

We analysed the data with the Spectral Radial Velocity Analyser (Serval; Zechmeister et al. 2018) in order to derive the stellar RVs in each spectral order of every exposure.
Table 1. Logbook of our CARMENES observations of Kepler-1625.

| Date       | BJD            | S/N | RV [m s$^{-1}$] $^\dagger$ | Uncertainty [m s$^{-1}$] | ID |
|------------|----------------|-----|-----------------------------|---------------------------|----|
| 25 Oct 2017| 2 458 052.26775| 5.37| $-48.80$                    | 213.28                    | 1  |
|            | 2 458 052.28352| 4.27| $-13.51$                    | 277.22                    | 2  |
|            | 2 458 052.29859| 5.14| 35.56                       | 255.88                    | 3  |
| 31 Oct 2017| 2 458 058.28172| 6.92| $-48.15$                    | 193.20                    | 4  |
|            | 2 458 058.30206| 4.88| $-156.14$                   | 235.08                    | 5  |
|            | 2 458 058.31763| 5.37| $-81.55$                    | 235.59                    | 6  |
| 28 Apr 2018| 2 458 236.66051| 3.53| 72.84                       | 463.50                    | 7  |
|            | 2 458 236.67569| 3.40| 49.30                       | 552.19                    | 8  |
|            | 2 458 236.69211| 7.06| 813.10                      | 272.56                    | 9  |
| 04 Jun 2018| 2 458 273.60239| 3.49| 28.41                       | 477.13                    | 10 |
|            | 2 458 273.61722| 3.59| $-239.04$                   | 356.24                    | 11 |
|            | 2 458 273.63306| 3.51| $-198.67$                   | 485.05                    | 12 |
| 30 Jun 2018| 2 458 299.54861| 0.83| $(-)$                      | ($(-)$)                   | ($(-)$) |
|            | 2 458 299.57736| 3.88| $-294.20$                   | 317.47                    | 13 |
|            | 2 458 299.59385| 4.32| $-227.46$                   | 297.66                    | 14 |
|            | 2 458 299.60959| 3.92| $-187.11$                   | 386.82                    | 15 |
| 09 Aug 2018| 2 458 340.42432| 3.24| $-143.30$                   | 423.12                    | 16 |
|            | 2 458 340.43902| 4.27| $-10.43$                    | 374.32                    | 17 |
|            | 2 458 340.45349| 4.37| $-46.58$                    | 354.83                    | 18 |
| 23 Oct 2018| 2 458 415.27194| 2.91| $-90.50$                    | 407.24                    | 19 |
|            | 2 458 415.29215| 2.92| $-128.29$                   | 335.98                    | 20 |
|            | 2 458 415.30818| 2.80| $-150.87$                   | 443.99                    | 21 |

Notes. $^\dagger$Values not corrected for the system’s intrinsic RV offset of $-60.43$ m s$^{-1}$ with respect to the Solar System barycenter. $^\ast$Spectrum not analysed.

SERVAL derives RVs by comparing the data of individual spectral orders to a high-S/N template of the observed star, which is created by co-adding B-spline regressions of all available data sets (Zechmeister et al. 2018). The code was run for the spectral orders 20–48, with an oversampling factor for the creation of the template of 0.3. The oversampling factor corresponds to the number of B-spline knots per data point, which we adjusted manually to retain as much spectral information as possible while simultaneously reducing the effect of noise.

We found that the default SERVAL scheme to weight the RV information from different orders produced unrealistic results for our data because of the low S/N. As a consequence, we decided to model the RV of each spectral order as a normal distribution centred on the SERVAL RV estimate of a given order with the SERVAL error estimate as the standard deviation. The resulting normal distributions of spectral orders 20–48 were co-added and normalised for each exposure. In this co-adding process, all orders were given the same weight in the sense that all the
normal distributions from each order were normalised to an area of one. In the next step, we fitted a normal distribution function to the co-added RV distribution. We took the peak position of the fitted curve as the reference RV value and its standard deviation as the uncertainty of a given exposure. Finally, the error-weighted mean and mean standard deviations of the exposures of one night were taken as the RV value and corresponding uncertainty of that night.

In this process, the spectrum with ID 9 turned out to have suffered from unknown systematic effects, which resulted in a suspiciously high average S/N over all orders, a large S/N dispersion between the orders, and an extremely high RV value of about 800 m s\(^{-1}\). For comparison, the RV values that we derived from remaining spectra differ by \(\lesssim 250\) m s\(^{-1}\). We also noticed a sinusoidal variation of the RVs as a function of the order number, which was not present for any other spectrum and which cannot be explained by the astrophysical processes that we are interested in. Hence, we consider this spectrum with ID 9 to be compromised and rejected it for our further RV study.

We considered a Keplerian model of a single planet on a circular orbit with the planetary mass \(M_p\) as the single free parameter. In this model, the stellar RV during the planetary transit is known to be zero once corrected for the system's intrinsic RV with respect to the Solar System. Accordingly, we used the mean RV values of the three observations closest to a planetary transit (IDs 1–3, 4–6, and 16–18) for a zero-point calibration of the stellar RV by means of a linear regression. We obtained an offset of \(-60.43\) m s\(^{-1}\). We then fitted the model to the calibrated RV values. The transit times, orbital period \((P = 287.3776 \pm 0.0024\) d\(^2\)) and stellar mass, \(M_* = 1.079_{-0.130}^{+0.100}\) \(M_\odot\) (Mathur et al. 2017), were known with sufficiently high precision and were therefore fixed at their nominal values. We established an upper mass on \(M_p\) using a \(\chi^2\) minimisation and a statistical analysis of the \(\chi^2\) values for different confidence levels.

3. Results

In Fig. 2 we show the RV values of Kepler-1625 derived with SERVAL, that we corrected for the zero point of the RVs. Small grey dots represent the RV estimates of each spectral order, with the respective error bars being omitted for the sake of clarity. The scatter of the orders is several \(\lesssim\)\(250\) m s\(^{-1}\), which corresponds to the spectrum with ID 9 that we did not consider for our derivation of the RV signal. The black squares represent the error-weighted mean value of each night.

We computed the \(\chi^2\) distribution as a function of \(M_p\) for our fitting procedure of a one-planet Keplerian model with a circular orbit. The \(\chi^2\) minimum value of 1.43 is found at \(M_p = 0\). The confidence levels of \(1\sigma\), \(2\sigma\), and \(3\sigma\) for upper mass limits of \(2.90\) \(M_J\), \(7.15\) \(M_J\), and \(11.60\) \(M_J\), respectively, are indicated with dashed lines. Figure 3 shows the corresponding RV curves. We note that the RV values near the expected transit times of Kepler-1625 b at about 52 d, 58 d, and 340 d (BJD-2 458 000), the latter of which were fixed in our \(\chi^2\) minimisation procedure, agree within about 75 m s\(^{-1}\), well within their error bars.

In summary, the data can best be explained in the absence of any RV signal induced by Kepler-1625 b and our upper limits on the planetary mass confirm that Kepler-1625 b must be a planet under the assumption of a single planet around Kepler-1625.

4. Discussion

The computed \(\chi^2\) values are relatively small given the number of free parameters. This is due to the relatively large formal error bars compared to the intrinsic scatter of the data (see Fig. 3). This observation suggests that the formal error bars that we derived are overestimated and that our resulting upper limits for \(M_p\) can be regarded as conservative.

For the purpose of completeness, we also investigated non-circular orbits, in which the orbital eccentricity \(e\) and the argument of periastron \(\omega\) were free fitting parameters with flat priors. As a result, we find a mass of Kepler-1625 b that is still in the planetary regime but the formal error bars in each of the fitting parameters are so large that an eccentric orbit is effectively unconstrained. The reason for this lies in the small number of RV measurements, which is comparable to the number of fitting parameters. As a consequence, we do not consider these results as statistically robust and therefore refrain from a more detailed analysis. Moreover, using priors from the transit fit would result in marginal changes of the posterior distributions. These small changes in the formal best-fit values are probably smaller than the systematic errors in our method, which is why we discard a more in-depth analysis.

The mere non-detection of an RV signal still allows for the possibility that the observed transit signal is due to an astrophysical false positive if these scenarios cannot be ruled out otherwise. However, as shown by Morton et al. (2016), the false-positive probability of Kepler-1625 b being caused by either an unblended eclipsing binary, a hierarchical eclipsing binary, or a background/foreground eclipsing binary is \(8.5 \times 10^{-3}\) (\(\pm 5.1 \times 10^{-3}\)). Moreover, the probability of the signal emerging from the target star is 1 (Morton et al. 2016) and the transit sequence has been successfully modelled as resulting from a Jupiter-sized object around Kepler-1625, be it with or without a moon (Teachey et al. 2018; Rodenbeck et al. 2018; Teachey & Kipping 2018; Heller et al. 2019). The only remaining possibility is a Jupiter-sized transiting object around Kepler-1625, which we constrain here to have a mass in the planetary regime.

5. Conclusions

We analysed a total of 21 CARMENES spectra of the star Kepler-1625 distributed over seven nights over a time-span of approximately one year, or 125% of the orbital period of Kepler-1625 b. Our examination of the RVs and their error bars, combined with the previous rejection of an astrophysical false-positive scenario, allows us to confirm the planetary nature of the transiting Jupiter-sized object Kepler-1625 b. Under the assumption of a single planet on a circular orbit, its mass is lower than
2.90 \, M_J, 7.15 \, M_J, or 11.60 \, M_J with a confidence of 1\sigma, 2\sigma, or 3\sigma, respectively. We also investigated eccentric orbits suggestive of a planetary mass, but this fit did not reduce the \chi^2 value substantially and we consider it less robust given the small number of measurements.

Our results make Kepler-1625 b one of the longest-period transiting planets ever detected and confirmed via the RV method. This result would also hold if the planet were orbited by a Neptune-mass moon. The mass of such a moon would need to be subtracted from the total mass estimates that we provide, thereby decreasing the actual mass of the planet by a few percent. However, we cannot exclude a second massive planet in the system, which has been hypothesised to explain the observed transit timing variations of Kepler-1625 b (Teachey & Kipping 2018; Heller et al. 2019). This hypothesis would be best explored with new and more high-quality observations that are particularly sensitive to short-period planets, for example taken during successive nights over the course of several weeks. If successful in the hunt for a second Jupiter-mass, non-transiting planet (as proposed by Heller et al. 2019), these observations would have the potential to reject the exomoon hypothesis for Kepler-1625 b by explaining the observed transit timing variations.

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