Two planets around Kapteyn’s star: a cold and a temperate super-Earth orbiting the nearest halo red-dwarf

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ABSTRACT

Exoplanets of a few Earth masses can be now detected around nearby low-mass stars using Doppler spectroscopy. In this paper, we investigate the radial velocity variations of Kapteyn’s star, which is both a sub-dwarf M-star and the nearest halo object to the Sun. The observations comprise archival and new HARPS, HIRES and PFS Doppler measurements. Two Doppler signals are detected at periods of 48 and 120 days using likelihood periodograms and a Bayesian analysis of the data. Using the same techniques, the activity indices and archival ASAS-3 photometry show evidence for low-level activity periodicities of the order of several hundred days. However, there are no significant correlations with the radial velocity variations on the same time-scales. The inclusion of planetary Keplerian signals in the model results in levels of correlated and excess white noise that are remarkably low compared to younger G, K and M dwarfs. We conclude that Kapteyn’s star is most probably orbited by two super-Earth mass planets, one of which is orbiting in its circumstellar habitable zone, becoming the oldest potentially habitable planet known to date. The presence and long-term survival of a planetary system seems a remarkable feat given the peculiar origin and kinematic history of Kapteyn’s star. The detection of super-Earth mass planets around halo stars provides important insights into planet-formation processes in the early days of the Milky Way.

Key words: techniques: radial velocities – stars: individual: Kapteyn’s star, planetary systems

1 INTRODUCTION

Sub-ms\(^{-1}\) velocity precision can now be achieved for M-dwarfs resulting from stabilized spectrographs (such as HARPS, Mayor et al. 2003) and specialized spectral analysis techniques (Anglada-Escudé & Butler 2013). This increased sensitivity enables the detection of planets of a few-Earth masses orbiting in the star’s habitable zone. Recently, statistical population analyses of the NASA/Kepler mission (Dressing & Charbonneau 2013), and ground-based Doppler surveys (Bonfils et al. 2013; Tuomi et al. 2014) suggests that every low-mass star has at least one (or more) planet with

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an orbital period less than 50 days. Very small planets in very short-period orbits have recently been discovered by the Kepler mission (e.g., KOI-1843, Ofir & Dreizler 2013). We recently started the Cool Tiny Beats survey to characterise the Doppler variability over short time-scales and search for such small planets in short period orbits around nearby low-mass stars. The program uses the High Accuracy Radial velocity Planet Searcher spectrograph (HARPS) installed at the 3.6m ESO telescope at La Silla/Chile and its northern counterpart at the Telescopio Nationale Galileo/La Palma.

2 KAPTEYN’S STAR

At only 3.91 pc, Kapteyn’s star (or GJ 191, HD 33793) is the closest halo star to the Sun (van Leeuwen 2007). It is sub-luminous with respect to main sequence stars of the same spectral type and was spectroscopically classified as an M1.0 sub-dwarf by Gizis (1997). A radius of 0.291±0.025 R⊙ was directly measured by Ségransan et al. (2003) using interferometry. This combined with an estimate of its total luminosity was then used to derive an effective temperature of 3570±156 K and its mass was estimated to be 0.281±0.014 M⊙. Woolf & Wallerstein (2005) determined a metallicity of [M/H] = -0.86 which coincides with several later estimates within 0.05 dex. We independently obtained estimates of its metallicity and temperature by comparing its observed colors (B, V, J, H, and K) to synthetically generated ones from the PHOENIX library (Husser et al. 2013), obtaining compatible values of [Fe/H] = −0.89 and 3550 ± 50 K. Only an upper limit has been measured for its projected rotation velocity (v sin i < 3 km s−1). Browning et al. (2010), and its X-ray luminosity has been measured to be comparable to other multi-planet host M-dwarfs such as GJ 876 and GJ 581 (Walkowicz et al. 2008). Therefore, planets of a few Earth-masses orbiting such an inactive M-star should be detectable using Doppler spectroscopy (Barnes et al. 2011). A precise age estimation of the star cannot be obtained from models, as they change very little for M < 0.6 M⊙ in the range of ages between 0.4 and 15 Gyr (Baraffe et al. 1995; Ségransan et al. 2003). The low metallicity and halo kinematics suggest an ancient origin, which is consistent with its low-activity and slow rotation.

3 OBSERVATIONS

The observations comprise both new and archival data from HARPS, HIRES and PFS spectrometers. HARPS is a stabilized high-resolution spectrometer (resolving power ~ 110 000) covering from 380 to 680 nm. The HARPS data we use come from two programs; the Cool Tiny Beats survey and archival data from the first HARPS-GTO survey. The Cool Tiny Beats data were obtained in two 12 night runs in May 2013 (11 spectra) and in Dec 2013 (55 spectra). The HARPS-GTO data contain 30 spectra taken between 2003 and 2009. Bonfils et al. (2013) reported some possible signals on Kapteyn’s star, but no detection claim could be made at the time. Doppler measurements were obtained using the least-squares template-matching approach as implemented by the HARPS-TERRA software (Anglada-Escudé & Butler 2012). For each spectrum, we also use two measurements of the symmetry of the mean-line profile as provided by the HARPS-Data Reduction Software. These are the bisector span (BIS) and the full-width-at-half-maximum (FWHM) of the cross-correlation function. BIS and FWHM are known to correlate with activity induced features that can cause spurious Doppler signals. For example, changes in the line-symmetry caused by co-rotating dark and magnetic spots induce changes in the symmetry of the lines that produce spurious Doppler shifts (e.g., Reiners et al. 2012). The variability in the Ca II H+K emission lines was also measured by HARPS-TERRA through the S-index. The variability in the S-index is also known to correlate with magnetic activity of the star (Gomes da Silva et al. 2012), and localized active regions such as spots. Any Doppler signal with a period equivalent to variability detected in the BIS, FWHM and S-index is likely to be spurious.

We include 30 Doppler measurements spanning between 1999 and 2008 using the HIRES spectrometer at Keck (Vogt et al. 1994). These measurements were obtained using the Iodine cell technique as described in Butler et al. (1996). A new HIRES stellar template was generated by deconvolving a high signal-to-noise iodine-free spectrum of the star applying Maximum Likelihood deconvolution with Boosting (Moráv & Matoušek 2003). The star is never at an altitude greater than 26 deg from Hawaii, which could explain the lower accuracy compared to the HARPS measurements. The long baseline of HIRES puts strong constraints on the long-period variability and mitigates alias ambiguities in the HARPS data. We also included 8 new Doppler measurements obtained with PFS Crane et al. (2010) at Magellan/Las Campanas observatory, also using the Iodine cell technique. While the statistical contribution of PFS is small, the significance of the preferred solution increases thus providing further support to the signals. All spectroscopic measurements used are given in Table I.
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4 SIGNAL DETECTION METHODS

The initial signal detection is performed using log-likelihood periodograms (Baluev 2009, Anglada-Escudé et al. 2013) and tempered Markov Chain samplings using the delayed-rejection adaptive-Metropolis method (or DRAM, Haario et al. 2006) as implemented in Tuomi et al. (2014). These methods produce maps of the maximum likelihood and posterior densities as a function of the period being investigated. As in classic periodograms, preferred periods will appear as peaks (local probability maxima). The significance is then assessed using the Bayesian criteria described in Tuomi et al. (2014). We say that a Doppler signal is detected if 1) its period is well-constrained, 2) its amplitude is statistically significantly different from zero, and 3) inclusion of the signal in the model increases the Bayesian evidence by a factor of 104, which is more conservative than usual because important effects might be missed in the model, especially when combining data from different instruments. The model of the observations is fully encoded in the definition of the likelihood function. In addition to the usual Keplerian parameters, our model includes three nuisance parameters for each instrument (INS): a constant offset $\gamma_{\text{INS}}$, an extra white-noise term $\sigma_{\text{INS}}$, and a Moving Average coefficient $\phi_{\text{INS}}$ that quantifies the amount of correlation between consecutive measurements. $\phi_{\text{INS}}$ is bound between $+1$ and $−1$ (anticorrelation) and a value consistent with zero implies no significant correlation. Our model also assumes an exponential decay of the correlation that depends on a characteristic time-scale $\tau_{\text{INS}}$. Adding it as a free parameter led to overparameterization, so a fixed value of $\tau_{\text{INS}} = 4$ days was set by default. Linear trends caused by the presence of planets with periods much longer than the time-baseline is parameterized as $\gamma(t) = \gamma_o$, where $\gamma$ is also a free parameter of the Doppler model and $t_0$ is an arbitrary reference epoch (see Table 2). The log-likelihood periodograms use the same likelihood model but do not include correlations terms. False alarm probability assessments using likelihood periodograms (or FAP, see Baluev 2008) are also computed to double-check the significance of each detection.

5 ANALYSIS OF THE TIME-SERIES

The search for signals in the Doppler time-series is summarized in Figure 1. Two very significant periods are detected at 121 and 48.6 days. The Bayesian evidence ratios

![Figure 1. Top panels illustrate the detection periodograms for a model with one-planet (left), and the search for the second signal (right). Brown thick line is the F-ratio periodogram applied to residual data, it does not adjust for the extra-white noise as a free parameter and is only used to initialize the global maximum-likelihood searches. Red triangles represent the top twenty likelihood maxima. Bottom panels show the posterior probability contours as obtained by tempered MCMC samplings using the DRAM algorithm (see text). Horizontal lines indicate relative probability thresholds compared to the maximum posterior. For perfectly known uncertainties and in the absence of correlations, the F-ratio and the log-likelihood ratio statistic should coincide. However, this is hardly the case when dealing with Doppler data. Top panels also illustrate the perils of working with residual data statistics to assess significance of signals. That is, the F-ratio is over-optimistic in the significance of the first candidate (left panel, 121 days brown peak is much higher), while the significance of the second signal at 48.6 days (right panel) would be greatly underestimated.]

| Table 1. Spectroscopic measurements. Median value and a perspective acceleration were subtracted to each RVs set (Ins. 1 is HARPS, 2 is HIRES, 3 is PFS). FWHM, BIS, and S-index are provided for HARPS only. Uncertainty in the FWHM is 2
| JD     | RV [km s$^{-1}$] | $\sigma_{RV}$ [km s$^{-1}$] | Ins | BIS [km s$^{-1}$] | $\sigma_{BIS}$ [km s$^{-1}$] | FWHM [km s$^{-1}$] | BIS-index [\%] | $\sigma_{BIS}$-index [\%] |
|--------|-----------------|----------------------------|-----|-----------------|-----------------------------|-------------------|----------------|------------------|
| 2452985.74111 | 3.11            | 0.80                       | 1   | -4.64         | 0.86                   | 3.21561          | 0.2966         | 0.0042           |
| 2452996.76321 | 3.00            | 0.27                       | 1   | -4.75         | 0.56                   | 3.19206          | 0.2699         | 0.0033           |
| 2453237.80596 | 2.65            | 0.89                       | 1   | -6.17         | 0.76                   | 3.18036          | 0.1859         | 0.0036           |
| 2453668.83537 | -2.57           | 0.52                       | 1   | -10.27        | 0.49                   | 3.21216          | 0.2678         | 0.0026           |

| Period [days] | $\ln L$ | $\Delta \ln L$ |
|---------------|---------|---------------|
| 121 days      | -255.00 | -260.00       |
| 48.6 days     | -245.00 | -250.00       |

Figure 1. Top panels illustrate the detection periodograms for a model with one-planet (left), and the search for the second signal (right). Brown thick line is the F-ratio periodogram applied to residual data, it does not adjust for the extra-white noise as a free parameter and is only used to initialize the global maximum-likelihood searches. Red triangles represent the top twenty likelihood maxima. Bottom panels show the posterior probability contours as obtained by tempered MCMC samplings using the DRAM algorithm (see text). Horizontal lines indicate relative probability thresholds compared to the maximum posterior. For perfectly known uncertainties and in the absence of correlations, the F-ratio and the log-likelihood ratio statistic should coincide. However, this is hardly the case when dealing with Doppler data. Top panels also illustrate the perils of working with residual data statistics to assess significance of signals. That is, the F-ratio is over-optimistic in the significance of the first candidate (left panel, 121 days brown peak is much higher), while the significance of the second signal at 48.6 days (right panel) would be greatly underestimated.
Table 2. The Keplerian solution of the combined radial velocities presented as median of the posterior estimates and corresponding 68% credibility intervals. The uncertainties of semi-major axes and minimum masses include uncertainties in the stellar mass. Reference epoch $t_0$ for computation of $M_0$ (mean anomaly) and $\lambda_0$ (mean longitude) is assumed to be $J2000 = 2452985.74111$ days.

| Model parameter | Kapteyn b | Kapteyn c |
|-----------------|-----------|-----------|
| $P$ [day]       | 48.616$^{+0.036}_{-0.032}$ | 121.54$^{+0.25}_{-0.25}$ |
| $K$ [ms$^{-1}$] | 2.25$^{+0.13}_{-0.11}$    | 2.27$^{+0.26}_{-0.26}$   |
| $e$             | 0.21$^{+0.19}_{-0.10}$    | 0.23$^{+0.10}_{-0.12}$   |
| $\omega$ [deg] | 80.4$^{+29.3}_{-29.9}$    | 3.9$^{+29.9}_{-33.2}$    |
| $M_0$ [deg]     | 269.6$^{+38.3}_{-32.2}$   | 357.6$^{+27.9}_{-32.3}$  |
| $\dot{\gamma}$ [ms$^{-1}$ yr$^{-1}$] | $-0.181^{+0.088}_{-0.086}$ | $-0.186^{+0.079}_{-0.086}$ |
| $\sigma_{\text{HARPS}}$ [ms$^{-1}$] | 0.65$^{+0.10}_{-0.09}$    | 0.66$^{+0.11}_{-0.10}$   |
| $\sigma_{\text{Hires}}$ [mas$^{-1}$] | 1.17$^{+0.51}_{-0.47}$    | 1.19$^{+0.47}_{-0.51}$   |
| $\sigma_{\text{FOV}}$ [ms$^{-1}$] | 0.32$^{+0.09}_{-0.04}$    | 0.42$^{+0.09}_{-0.04}$   |
| $\phi_{\text{HARPS}}$ | 0.03$^{+0.08}_{-0.08}$    | 0.03$^{+0.08}_{-0.08}$   |
| $\phi_{\text{Hires}}$ | 0.40$^{+0.50}_{-0.50}$    | 0.40$^{+0.50}_{-0.50}$   |
| $\phi_{\text{FOV}}$ | 0.10$^{+0.30}_{-0.30}$    | 0.10$^{+0.30}_{-0.30}$   |

Derived quantities

\[ \lambda_0 = \omega + M_0 \text{ [deg]} = 350^{+19.1}_{-18.7} \quad 1.6^{+20.5}_{-20.3} \]
\[ m_p \sin i \text{ [M$_\oplus$]} = 4.8^{+0.9}_{-0.0} \quad 7.0^{+1.2}_{-1.0} \]
\[ a \text{ [AU]} = 0.168^{+0.006}_{-0.006} \quad 0.314^{+0.014}_{-0.014} \]
\[ S/S_0 = 40\% \quad 12\% \]
\[ \text{HZ-range [AU]} = 0.126^{+0.236}_{-0.029} \quad 0.021^{+0.021}_{-0.021} \]
\[ P_e/P_b = 2.496^{+0.029}_{-0.029} \]

are $3.2 \times 10^3$ for the one-planet model against the no-planet model, and $3.1 \times 10^9$ for the two-planet solution against the one-planet model. These numbers are well in excess of the $10^3$ threshold indicating very confident detections. The FAPs as derived from the log-likelihood periodograms are $1.5 \times 10^{-6}$ and $8.9 \times 10^{-5}$ respectively, which are also very small further supporting the detections (acceptable detection thresholds using periodogram methods are typically between 1% and 0.1%). The support of the signals by the three data sets is illustrated in the phase-folded curves in Figure 2. The uneven sampling can produce biases in the significance estimates. To investigate this, we also performed the same analysis using nightly averaged measurements. The same two signals are detected well above our significance thresholds, thus providing further confidence in the detections. As for other stars, further follow-up over the next few years is desirable to confirm that both low-amplitude signals remain coherent over time.

We investigated linear correlations with activity indices by including them in the likelihood model of the HARPS data. While we could still easily detect the planetary signals, these models had lower probabilities due to over-parameterization and are not included in the final solution. We also verified whether any indicator of activity showed variability in similar time-scales as the Doppler data. While the BIS does not show any hint of temporal coherence, the FWHM and S-index do share similar periodogram structures with tentative peaks between 140 to 2000 days. However, neither had FAPs that were lower than 5%, indicating little significance.

We also analysed V-band photometry obtained from the latest release of the ASAS program [Pojmanski 1997]. A standard deviation computed using the central 80% percentile was used to remove 4-7 outliers resulting in 503 epochs spanning from Dec 2000 to Sep 2007. A log-likelihood periodogram analysis identified two significant signals at 340 and 1100 days, both with amplitudes of ~ 5 mmag. The signal at 1100 days is compatible with other reports of periodicities in activity indices of M-dwarfs [Gomes da Silva et al. 2012], and the 340-day variability might be caused by seasonal systematic errors, or by a long rotation period. The periodogram structure of the photometry resembles those of the FWHM and the S-index, further supporting potential low-level activity changes happening at timescales of several hundred days. Given that the activity and Doppler signals appear uncorrelated, we conclude that the simplest interpretation of the Doppler data is the presence of two planets (see Table 2). With a period of 48.6 days, Kapteyn b lies well within the liquid water habitable zone of the star [Kopparapu et al. 2013]. Assuming rocky composition, its properties and possible climates should be similar to those discussed for GJ 667Ce [Anglada-Escudé et al. 2013]. Kapteyn c receives ~ 10% of Earth’s irradiance, implying that the possibility of it being able to support liquid water on its surface is less probable.

We used Optimal BLS (Ofir 2014) to search for possible transit events in the ASAS photometry. No transits were found when searching for a signal in the range of parameters compatible with the Doppler solution. Further observations at the predicted transit windows are needed to put meaningful constraints on possible transit signals.

6 DISCUSSION

The age of Kapteyn star can be inferred from its membership to the Galactic halo and peculiar element abundances [Kotoneva et al. 2005]. The current hierarchical Milky Way formation scenario suggests that streams of halo stars were originated as tidal debris from satellite dwarf galaxies being engulfed by the early Milky Way [Klement 2010, and references therein]. This scenario is supported by the age estimations of the stars in the inner halo (~10–12 Gyr), [Jofré & Weiss 2011], and globular clusters. The work by Eggen and collaborators (see, Eggen 1996, as review summary) established the existence of such high-velocity, metal-poor moving groups in the solar neighborhood. Kapteyn’s star is the prototype member of one of these groups, which has been recently investigated by Wylie-de Boer et al. (2010) among others. Stars in Kapteyn’s group share a retrograde velocity of rotation around the Galactic centre of about $-290$ kms$^{-1}$ [Eggen 1996]. Spectroscopic observation of 16 members has shown that the group likely originated from the same progenitor structure as the peculiar globular cluster ω Centauri, but not from within the cluster itself [Kotoneva et al. 2005; Wylie-de Boer et al. 2010]. The origin of Kapteyn’s star within a merging dwarf-galaxy sets its age at about 10 Gyrs, which is the current
estimate of the age of the universe (Planck Collaboration 2013).

Numerical integration of several possible orbits over $10^8$ yr to 1 Myr using Mercury 6 (Chambers 1999) shows very small changes in the orbital parameters. Despite the the periods for the two planet candidates are compatible with a 5:2 period commensurability (see Table 2), the analysis of the resonant angles for the best fit solution did not support the presence of dynamical mean-motion resonances, which existence also depend on a number of other properties such total planet masses and mutual inclinations. We found, however, that the difference in periastron angles $\Delta \omega = \omega_c - \omega_b$ librates around 180 deg; which corresponds to a long-term stable configuration called apsidal locking. This is sufficient to show that the proposed system is compatible with long-term physically-viable solutions. It has been suggested that two-planet systems that underwent weak dissipation (slow migration) should always end up in apsidal locking (Michtchenko & Rodríguez 2011), which has consequences on the likely planet-formation scenario. A more thorough analysis to properly quantify the significance of the apsidal locking and possible mean-motion resonances requires a much more extended discussion (e.g., Anglada-Escudé et al. 2013) which is beyond the scope of this paper.

The detection of two super-Earths here is consistent with the idea that low-metallicity stars are more prone to the formation of low-mass planets rather than gas giants (Udry & Santos 2007; Buchhave et al. 2012). This is further supported by a significant paucity of lowest-mass planets in Doppler searches of metal-rich stars Jenkins et al. (2013), and non-confirmation of previous claims of gas giants around extremely metal-poor stars Desidera et al. (2013; Jones & Jenkins 2014). These observational findings are compatible with recent population synthesis experiments such as those in Mordasini et al. (2012).

Once the planets signals are included in the Doppler model, the RV residuals variability are reduced to instrumental noise (i.e. extra jitter term is compatible with reported stability of HARPS, and correlation coefficients compatible with 0). This indicates that the star is very Doppler stable, possibly more stable than the instruments themselves. This indeed would be expected because pulsation and convective motions are thought to be much smaller in inactive low-mass stars than in earlier types. At the likely age of the system, most G and K dwarfs are evolving away from the main sequence into giants, which makes the Doppler detection of small planets uneffable due to increased activity levels (e.g., Nowak et al. 2013). As a result, original architectures of the first planetary systems can only be explored by observing venerable low-mass stars which are still on the main-sequence such as Kapteyn’s star.

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The detection of two super-Earths here is consistent with the idea that low-metallicity stars are more prone to the formation of low-mass planets rather than gas giants (Udry & Santos 2007; Buchhave et al. 2012). This is further supported by a significant paucity of lowest-mass planets in Doppler searches of metal-rich stars Jenkins et al. (2013), and non-confirmation of previous claims of gas giants around extremely metal-poor stars Desidera et al. (2013; Jones & Jenkins 2014). These observational findings are compatible with recent population synthesis experiments such as those in Mordasini et al. (2012).

Once the planets signals are included in the Doppler model, the RV residuals variability are reduced to instrumental noise (i.e. extra jitter term is compatible with reported stability of HARPS, and correlation coefficients compatible with 0). This indicates that the star is very Doppler stable, possibly more stable than the instruments themselves. This indeed would be expected because pulsation and convective motions are thought to be much smaller in inactive low-mass stars than in earlier types. At the likely age of the system, most G and K dwarfs are evolving away from the main sequence into giants, which makes the Doppler detection of small planets uneffable due to increased activity levels (e.g., Nowak et al. 2013). As a result, original architectures of the first planetary systems can only be explored by observing venerable low-mass stars which are still on the main-sequence such as Kapteyn’s star.

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APPENDIX A: ON-LINE TABLE

Spectroscopic measurements on Kapteyn's star (Anglada-Escude+, 2014)

Description:
Time-series of spectroscopic measurements used in the paper. Median value and a perspective acceleration were subtracted to each RVs set (Ins. 1 is HARPS, 2 is HIRES, 3 is PFS). Measurements of the FWHM, BIS of the cross-correlation profiles and measurements of the S-index are provided for HARPS data only. Uncertainty in the FWHM is 2.5 times the uncertainty in BIS. Check 2012ApJS..200...15A, for more detailed definitions of the measurements and their uses.

| Bytes | Format | Units | Label | Explanations |
|-------|--------|-------|-------|--------------|
| 1-13  | F13.5  | d     | JD    | Barycentric Julian date |
| 15-19 | F5.2   | m/s   | RVel  | Radial velocity      |
| 21-24 | F4.2   | m/s   | eRVel | Uncertainy in RV     |
| 26    | I1     | ---   | Ins   | Instrument used      |
| 28-33 | F6.2   | m/s   | BIS   | Bisector span of the CCF |
| 35-38 | F4.2   | m/s   | eBIS  | Uncertainty in BIS   |
| 40-46 | F7.5   | km/s  | FWHM  | FWHM of the CCF (1)  |
| 48-53 | F6.4   | ---   | Sidx  | CaII H+K S-index in the Mount Wilson system |
| 55-60 | F6.4   | ---   | eSidx | Uncertainty in S-index |

Note (1): Uncertainty in FWHM is 2.5x eBIS

| Date  | Time  | RV   | eRV  | Instrument | FWHM | eFWHM | Sindex | eSindex | Notes |
|-------|-------|------|------|------------|------|-------|-------|--------|-------|
| 2452985.74111 | 3.11 | 0.86 | 3.21561 | 0.2966 | 0.0042 |
| 2452996.76321 | 3.00 | 0.27 | 9.75 | 0.2699 | 0.0033 |
| 2453337.80096 | 2.65 | 0.89 | 8.17 | 0.1859 | 0.0036 |
| 2453668.83537 | 2.57 | 0.52 | 10.27 | 0.2678 | 0.0026 |
| 2453670.73947 | 3.76 | 0.59 | 13.27 | 0.2636 | 0.0022 |
| 2454141.57444 | 0.56 | 0.53 | 13.62 | 0.2968 | 0.0021 |
| 2454167.53051 | 2.47 | 0.54 | 14.86 | 0.2616 | 0.0020 |
| 2454424.73161 | 2.40 | 0.54 | 14.00 | 0.2305 | 0.0018 |
| 2454429.46873 | 2.59 | 0.73 | 13.00 | 0.2926 | 0.0034 |
| 2454345.87966 | 0.29 | 0.45 | 12.34 | 0.2549 | 0.0017 |
| 2454349.83417 | 0.35 | 0.45 | 17.60 | 0.2346 | 0.0017 |
| 2454424.73161 | 2.40 | 0.54 | 14.00 | 0.319613 | 0.2305 | 0.0018 |
| 2454429.71897 | 4.68 | 0.56 | 12.71 | 0.39 | 0.2990 | 0.0020 |
| 2454449.76051 | 1.27 | 0.61 | 13.88 | 0.31870 | 0.2318 | 0.0023 |
| 2454450.64700 | 1.67 | 0.57 | 13.85 | 0.39 | 0.19968 | 0.2346 | 0.0020 |
| 2454452.70683 | 1.15 | 0.74 | 17.21 | 0.53 | 0.19416 | 0.2540 | 0.0028 |
| 2454459.64359 | 0.16 | 0.56 | 15.85 | 0.35 | 0.20016 | 0.2377 | 0.0017 |
| 2454462.70572 | 1.82 | 0.55 | 10.81 | 0.35 | 0.20233 | 0.2457 | 0.0018 |
| 2454463.69854 | 2.61 | 0.49 | 12.56 | 0.43 | 0.19982 | 0.2341 | 0.0022 |
| 2454464.68243 | 1.07 | 0.53 | 12.38 | 0.42 | 0.20015 | 0.2452 | 0.0021 |
| 2454733.98725 | -0.93 | 0.60 | 15.14 | 0.36 | 0.20390 | 0.2536 | 0.0018 |
| 2454754.83883 | -2.37 | 0.57 | 13.84 | 0.41 | 0.20737 | 0.2538 | 0.0021 |
| 2454767.75805 | 0.08 | 0.58 | 14.73 | 0.43 | 0.20601 | 0.2393 | 0.0021 |
| 2454879.55605 | -2.33 | 0.59 | 15.14 | 0.43 | 0.19513 | 0.4865 | 0.0032 |
| 2454879.69685 | -1.36 | 0.85 | 14.42 | 0.68 | 0.19309 | 0.2085 | 0.0034 |
| 2454880.52165 | -0.01 | 1.56 | -0.65 | 1.28 | 0.19636 | 0.2472 | 0.0053 |
| 2454880.67387 | -2.96 | 0.76 | 13.39 | 0.57 | 0.19398 | 0.2071 | 0.0028 |
| Time  | Delta | Mag  | Refine | Delta2 | Mag2 | Refine2 | Delta3 | Mag3 | Refine3 | Delta4 | Mag4 | Refine4 | Delta5 | Mag5 | Refine5 | Delta6 | Mag6 | Refine6 | Delta7 | Mag7 | Refine7 | Delta8 | Mag8 | Refine8 | Delta9 | Mag9 | Refine9 | Delta10 | Mag10 | Refine10 |
|-------|-------|------|--------|--------|------|--------|--------|------|--------|--------|------|--------|--------|------|--------|--------|------|--------|--------|------|--------|--------|------|--------|--------|------|--------|
| 2456417.46007 | -0.10 | 0.60 | 1 | -14.56 | 0.68 | 3.20851 | 0.2682 | 0.0044 |
| 2456417.46745 | -0.54 | 0.68 | 1 | -7.42 | 0.75 | 3.20894 | 0.2566 | 0.0047 |
| 2456418.46471 | 1.80 | 0.43 | 1 | -16.75 | 0.55 | 3.20068 | 0.2761 | 0.0040 |
| 2456420.47541 | 0.63 | 0.39 | 1 | -15.72 | 0.47 | 3.19810 | 0.3089 | 0.0037 |
| 2456421.46438 | 1.82 | 0.76 | 1 | -18.81 | 0.95 | 3.20174 | 0.2562 | 0.0056 |
| 2456422.45767 | 2.00 | 0.72 | 1 | -13.54 | 0.71 | 3.19709 | 0.2700 | 0.0049 |
| 2456423.46236 | 2.00 | 0.73 | 1 | -11.24 | 0.89 | 3.20416 | 0.1930 | 0.0056 |
| 2456424.46156 | 1.08 | 0.55 | 1 | -10.70 | 0.68 | 3.21574 | 0.2927 | 0.0042 |
| 2456425.56057 | 0.24 | 0.75 | 1 | -14.31 | 0.68 | 3.21076 | 0.2827 | 0.0040 |
| 2456427.46436 | 1.82 | 0.76 | 1 | -18.81 | 0.95 | 3.20174 | 0.2562 | 0.0056 |
| 2456428.46236 | 2.00 | 0.73 | 1 | -11.24 | 0.89 | 3.20416 | 0.1930 | 0.0056 |
| 2456429.46436 | 1.82 | 0.76 | 1 | -18.81 | 0.95 | 3.20174 | 0.2562 | 0.0056 |
| 2456430.46436 | 1.82 | 0.76 | 1 | -18.81 | 0.95 | 3.20174 | 0.2562 | 0.0056 |
| 2456431.46436 | 1.82 | 0.76 | 1 | -18.81 | 0.95 | 3.20174 | 0.2562 | 0.0056 |
| 2456432.46436 | 1.82 | 0.76 | 1 | -18.81 | 0.95 | 3.20174 | 0.2562 | 0.0056 |
| 2456433.46436 | 1.82 | 0.76 | 1 | -18.81 | 0.95 | 3.20174 | 0.2562 | 0.0056 |
Two super-Earths around Kapteyn's star

| Date         | Position | Velocity | Type | Distance | Magnitude | Magnitude Error | Distance Error | Magnitude Error | Distance Error |
|--------------|----------|----------|------|----------|-----------|----------------|----------------|----------------|----------------|
| 2456667.67412 | 2.21 0.79 1 | -16.97 0.72 3.21627 0.3009 0.0049 |
| 2456667.74602 | 1.04 0.57 1 | -14.67 0.64 3.20707 0.3147 0.0052 |

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