An Independent Discovery of Two Hot Jupiters from the K2 Mission

Rafael Brahm\textsuperscript{1,2}, Matías Jones\textsuperscript{1}, Néstor Espinoza\textsuperscript{1,2}, Andrés Jordán\textsuperscript{1,2}, Markus Rabus\textsuperscript{1}, Felipe Rojas\textsuperscript{1}, James S. Jenkins\textsuperscript{3}, Cristián Cortés\textsuperscript{2,4}, Holger Drass\textsuperscript{4}, Blake Pantoja\textsuperscript{3}, Maríta G. Soto\textsuperscript{3}, and Maja Vučković\textsuperscript{5}

\textsuperscript{1} Instituto de Astrofísica, Facultad de Física, Pontificia Universidad Católica de Chile, Avenida Vicuña Mackenna 4860, 782-0436 Macul, Santiago, Chile
\textsuperscript{2} Millennium Institute of Astrophysics, Av. Vicuña Mackenna 4860, 782-0436 Macul, Santiago, Chile
\textsuperscript{3} Departamento de Física, Facultad de Ciencias Básicas, Universidad Metropolitana de la Educación, Avenida José Pedro Alessandri 774, 7760197, Nuñoa, Santiago, Chile
\textsuperscript{4} Departamento de Astronomía, Universidad de Chile, Camino al Observatorio 1515, Cerro Calán, Santiago, Chile
\textsuperscript{5} Instituto de Física y Astronomía, Facultad de Ciencias, Universidad de Valparaíso, Gran Bretaña 1111, Playa Ancha, Valparaíso 2360102, Chile

Received 2016 March 5; accepted 2016 June 15; published 2016 October 26

Abstract

We report the discovery of two hot Jupiters using photometry from Campaigns 4 and 5 of the two-wheeled Kepler (K2) mission. K2-30b has a mass of 0.589 ± 0.023 $M_J$, a radius of 1.069 ± 0.021 $R_J$, and transits its G dwarf ($T_{\text{eff}} = 5675 \pm 50$ K), slightly metal-rich ([Fe/H] = +0.06 ± 0.04 dex) host star in a 4.1 day circular orbit. K2-34b has a mass of 1.698 ± 0.055 $M_J$, a radius of 1.377 ± 0.014 $R_J$, and an orbital period of 3.0 days in which it orbits a late F dwarf ($T_{\text{eff}} = 6149 \pm 55$ K) solar metallicity star. Both planets were confirmed via precision radial velocity (RV) measurements obtained with three spectrographs from the southern hemisphere. They have physical and orbital properties similar to the ones of the already uncovered population of hot Jupiters and are well-suited candidates for further orbital and atmospheric characterization via detailed follow-up observations. Given that the discovery of both systems was recently reported by other groups we take the opportunity of refining the planetary parameters by including the RVs obtained by these independent studies in our global analysis.

Key words: planets and satellites: detection

Online material: color figure

1. Introduction

Extrasolar planets with structural properties similar to Jupiter, orbiting at close separations from their host stars ($a < 0.05$ au, $P < 8$ days) are known as hot Jupiters. Currently, ~250 transiting hot Jupiters have been discovered, mostly thanks to the existence of dedicated ground-based photometric surveys like HATNet (Bakos et al. 2004), SuperWasp (Pollacco et al. 2006), and HATSouth (Bakos et al. 2013). The brightness of the host stars of the majority of these transiting planets, coupled with the relatively strong observational signatures (e.g., transit depth, radial velocity semi-amplitude), have allowed the determination of both the radii and the masses of most of the discovered transiting hot Jupiters, which has been used to directly compute their bulk densities. Moreover, by comparing this information with theoretical models (e.g., Fortney et al. 2007; Burrows et al. 2007), the inner structure and composition of these planets can be inferred. In addition to the estimation of the physical parameters, if the hosts stars are bright enough, the execution of detailed photometric and spectroscopic follow-up observations on these systems permit us to characterize their atmospheric structure and composition via transmission spectroscopy and/or secondary eclipses (see, e.g., Seager & Deming 2010; Crossfield 2015), to refine the geometry of the orbit via the measurement of the Rossiter–McLaughlin effect (McLaughlin 1924; Rossiter 1924), and to discover additional planetary companions by performing long-term RV monitoring (e.g., Neveu-VanMalle et al. 2016), TTV analysis (e.g., Steffen et al. 2012), or searching for additional transits in the light curve (e.g., Becker et al. 2015).

Even though hot Jupiters are arguably the most characterized type of extrasolar planet, there are several theoretical problems about their existence that remain to be solved. For example, there is no consensus about how these massive planets reached their current short orbital semimajor axes. In situ formation has proven to be unlikely (Rafikov 2006), but the current observational evidence is not able to discriminate between gentle migration by gravitational interactions with the protoplanetary disk (Lin et al. 1996) and high eccentricity migration mechanisms (Rasio & Ford 1996). On the other hand, the mass and radius determination of transiting hot Jupiters have revealed a wide diversity regarding their internal structure. In particular, an important fraction of these systems present radii that are too large to be explained with current theoretical models of planetary structure (e.g., Anderson et al. 2010; Hartman et al. 2011). The inflated radii of these planets has been shown to be correlated with the degree of insolation from their parent stars (Guillot 2005), but the main responsible mechanism is still unknown.
The detection of more hot Jupiters, particularly those transiting bright stars, can be used to test theories about their structure and evolution. We report the discovery of two new systems by using data from the two-wheeled K2 mission. Unlike the original Kepler mission, K2 is currently observing fields that are located close to the ecliptic plane, and ground-based facilities located in the southern hemisphere can be used to confirm the planetary nature of potential candidates. In this context, we are conducting a Chilean-based RV follow-up project of K2 candidates that has already discovered a Neptune-sized planet with a period of \( \approx 42 \) days (Espinoza et al. 2016).

The two hot Jupiters presented in this paper were independently discovered by other teams using facilities from the northern hemisphere (Lillo-Box et al. 2016; Johnson et al. 2016; Hirano et al. 2016).

The paper is structured as follows. In Section 2, we present the data, which include the K2 photometry and the high-resolution spectra and radial velocities obtained with the HARPS, FEROS, and CORALIE spectrographs. Section 3 describes the joint analysis that was applied to the data and presents the derived parameters of the planetary systems. Finally, in Section 4, we discuss our findings.

### 2. Data

#### 2.1. K2 Photometry

We analyzed the photometric data of K2’s Campaigns 4 and 5. In particular, we obtained all the decorrelated light curves from Vanderburg & Jonson (2014), using the photometry with the optimal aperture. The method that we used to select the transiting planetary candidates is described in detail in Espinoza et al. (2016). After performing a box least squares (BLS; Kovács et al. 2002) algorithm, we found that the stars EPIC210957318 (K2-30b) and EPIC212110888 (K2-34b) showed significant periodic signals at 4.1 and 3.0 days, respectively. Both of these systems were selected as strong Jovian planetary candidates based on their transit properties (depths, shapes, and durations) and due to the lack of evident out-of-transit variations. Following Espinoza et al. (2016), both decorrelated light curves were normalized by applying a median filter with a 21-point (\( \sim 10.25 \) hour) window, which was then smoothed using a Gaussian filter with a 5-point standard deviation. These normalized light curves were then used by our transit-fitting pipeline, of which the results are shown in Section 3.3 (see Figures 1 and 2).

#### 2.2. Spectroscopic Follow-up Observations

Once both targets were identified as strong transiting hot-Jupiter candidates, we proceeded to acquire high-resolution spectra with three different stabilized instruments with the goal of measuring the RV variation of the stellar hosts produced by the gravitational pull of the planetary companions. In the case of K2-30, we obtained four spectra using the HARPS spectrograph (Mayor et al. 2003) mounted on the ESO 3.6 m telescope at La Silla Observatory and five spectra using the FEROS spectrograph (Kaufer & Pasquini 1998) mounted on the MPG 2.2 m telescope located in the same observatory. For K2-34 we obtained seven spectra with FEROS and three spectra using the CORALIE spectrograph (Queloz et al. 2001) mounted on the 1.2 m Euler Telescope in La Silla Observatory.

The FEROS and CORALIE data were obtained using a simultaneous calibration method (Baranne et al. 1996), in which we acquired a spectrum of a ThAr lamp with the comparison fiber while the spectrum of the science star is acquired with the principal fiber. We use the ThAr spectra to trace the instrumental instrumental velocity drifts produced by environmental changes inside the spectrograph. On the other hand, since the HARPS nightly drift is typically <1 m s\(^{-1}\), the

---

**Figure 1.** Phase-folded photometric data of the detrended and normalized K2 light curve for the star K2-30. The red solid line corresponds to the model with the posterior parameters obtained by the exonailer code. (A color version of this figure is available in the online journal.)
observations with this instrument were performed with the comparison fiber pointing to the background sky in order to avoid contamination from saturated ThAr lines.

The data from these three instruments were processed through dedicated pipelines built from a modular code that was designed to develop completely robust and automated pipelines for reducing, extracting, and analyzing echelle spectra of different instruments in an optimal and homogeneous way (Jordán et al. 2014). Briefly, the pipelines identify the echelle orders using the flat frames, and after correcting by the bias level and the scattered light, the orders of the science and wavelength calibration images are optimally extracted following Marsh (1989). The reference global wavelength calibration solution is computed from the calibration ThAr image acquired in the afternoon by fitting a chebyshev polynomial as a function of the pixel position and echelle order number. If required, the instrumental drifts during the night are computed using the extracted flat frames, which are illuminated either by a ThAr lamp or by a Fabry-Perot etalon. The extracted flat frames are used to perform the correction by the blaze function, and then a low-order polynomial is fitted to each order, with an iterative algorithm that avoids the inclusion of absorption lines in the fit, in order to construct a continuum-normalized spectrum. The barycentric correction is performed using the JPLephem package, and RVs and bisector spans (BSs) are determined by computing the cross-correlation function between the continuum-normalized spectrum and a binary mask that resembles the spectrum of a G2-type star.

We found that both systems present RV variations in phase with the photometric ephemeris and with semi-amplitudes consistent with planetary companions. Table 1 lists the resulting RV variations and BSs computed for both systems, which are plotted against each other in Figure 3. The lack of correlation between both parameters supports the planetary hypothesis as an explanation for the transits observed in K2-30 and K2-34. In Figures 4 and 5, we show the phase-folded RVs for K2-30 and K2-34 obtained in this work, along with the measurements reported by the other groups.

3. Analysis

3.1. Planet Scenario Validation and Transit Dilutions

We performed a blend analysis for both systems by using the vespa package (Morton 2012), which allowed us to compute the false-positive probability (FPP) of the transits being produced by different configurations of diluted eclipsing binaries. By assuming an occurrence rate of 1% for hot-Jupiter-like planets (Wang et al. 2015), and using only the K2 light curves extracted with the optimal aperture according to Vanderburg & Johnson (2014), which corresponds to 3 pixels (12") for K2-30 and 4 pixels (16") for K2-34, we obtain an FPP of 0.18% and 21% for K2-30b and K2-34b, respectively. Given that our RV measurements are in phase with the photometric ephemeris and that their semi-amplitudes are consistent with planetary mass companions, the obtained FFPs correspond to upper limits in both cases. Nonetheless, the FPP of K2-30b is smaller than the accepted 1% threshold (e.g., Montet et al. 2015), and therefore it can be validated by the photometry alone. On the other hand, for validating K2-34b we can further use the information obtained by our spectroscopic data. Given that we do not observe any evident secondary peaks in the CCF and that the radial velocity amplitudes are too small to come from stellar objects, we can set the likelihood of all eclipsing binary scenarios to 0, excluding line-of-sight blends and hierarchical triples. With these assumptions, the FPP of K2-34b drops to 0.052%, which validates its planetary nature. While we reject that the observed transits are produced by eclipsing binaries, we cannot rule out that the observed planetary transits are being diluted by the presence of another foreground or background star, or a bound star in a wide orbit. For K2-30b,
changes in the inferred planetary radius of the order of the errors can be produced by sources located inside the aperture that are at least \( \approx 3.7 \) magnitudes fainter than the host star. On the other hand, for K2-34b, changes in the inferred planetary radius on the order of the errors can be produced by sources that are at least \( \approx 2.0 \) magnitudes fainter than the host star. However, most of these contaminant sources can be rejected from the lack of evident additional stars in the POSS images centered in K2-30 and K2-34, and also are due to the lack of secondary peaks in the CCF plots.

### 3.2. Stellar Properties

In order to obtain the properties of the host stars, we made use of the available photometric and spectroscopic observables for both targets. We retrieved \( B, V, g, r, \) and \( i \) photometric magnitudes from the AAVSO Photometric All-Sky Survey (APASS; Henden & Munari 2014) and \( J, H, \) and \( K \) photometric magnitudes from 2MASS for our analysis. For the spectroscopic data, we used the Zonal Atmospherical Stellar Parameter Estimator (ZASPE; Brahm et al. 2015; Brahm et al. 2016) algorithm with our FEROS spectra as input. ZASPE estimates
the atmospheric stellar parameters and $\nu \sin i$ from our high-resolution echelle spectra via a least squares method against a grid of synthetic spectra in the most sensitive zones of the spectra to changes in the atmospheric parameters. ZASPE obtains reliable errors in the parameters, as well as the correlations between them by assuming that the principal source of error is the systematic mismatch between the data and the optimal synthetic spectra, which arises from the imperfect modeling of the stellar atmosphere or from poorly determined parameters of the atomic transitions. We used a synthetic grid generated using the spectrum code (Gray 1999) and the ATLAS9 stellar atmospheres (Kurucz 1993). The spectral region that was considered for the analysis was from 5000 to 6000 Å, which includes a large number of atomic transitions and the pressure-sensitive Mg I b lines.

The resulting atmospheric parameters obtained by ZASPE were $T_{\text{eff}} = 5575 \pm 50$ K, log($g$) = $4.60 \pm 0.05$, \([\text{Fe/H}] = +0.06\), and $\nu \sin i = 0.5 \pm 0.5$ km s$^{-1}$ for K2-30 and $T_{\text{eff}} = 6149 \pm 55$ K, log($g$) = $4.2 \pm 0.09$, \([\text{Fe/H}] = 0.0 \pm 0.04$, and $\nu \sin i = 6.31 \pm 0.2$ km s$^{-1}$ for K2-34.

We used the isochrones package (Morton 2012) and the Dartmouth Stellar Evolution Database (Dotter et al. 2008) to obtain the physical properties of both stars (mass, radius, and age) from the derived atmospheric parameters and the available photometric magnitudes. We took into account the uncertainties in the photometric and spectroscopic properties to estimate the physical properties of the stars, using the MultiNest algorithm (Feroz & Hobson 2008), which allow us to efficiently explore the posterior parameter space. For K2-30 we obtained a radius of $R_* = 0.839^{+0.017}_{-0.014} R_\odot$, a mass $M_* = 0.917^{+0.014}_{-0.012} M_\odot$, an age of $2.2^{+1.8}_{-0.5}$ Gyr, and a distance to the host star of $297.2^{+6.7}_{-5.6}$ pc. For K2-34 we obtained a radius of $R_* = 1.58^{+0.16}_{-0.15} R_\odot$, a mass $M_* = 1.226^{+0.060}_{-0.045} M_\odot$, an age of $4.24^{+0.39}_{-0.37}$ Gyr, and a distance to the host star of $390^{+39}_{-37}$ pc. The stellar parameters of the two host stars are summarized in Table 2.

### 3.3. Joint Analysis

We performed a joint analysis of the detrended and normalized $K2$ photometry and the radial velocities using the EXOplanet tranSits and radial veloCity fitTEr, exonailer, which is made publicly available at Github\(^6\) and its structure and functionalities are described in Espinoza et al. (2016). Given that both systems were recently discovered independently by other groups, we also included the RV measurements of these projects in the analysis in order to further refine the physical parameters of these planets. The joint model fits for the instrumental velocity offsets between different echelle spectrographs and also fits for the jitter of each instrument. For the radial velocities, Gaussian priors were set on the semi-amplitude, $K$, and the RV zero point, $\mu$. The former was centered on zero, while the latter was centered on the observed mean of the RV data set. Initially we considered the eccentricity of both systems as a free parameter; however, we found in both cases that the data was consistent with circular orbits, and therefore we performed a

---

\(^6\) [www.github.com/nespinoza/exonailer](http://www.github.com/nespinoza/exonailer)
second joint analysis again by fixing the eccentricity to 0. For the light curve modeling, we used the selective resampling technique described in Kipping (2010) in order to account for the 30 minute cadence of the K2 photometry, which produces a smearing of the transit shape. In order to minimize the biases in the retrieved transit parameters, we fit for the limbdarkening coefficients in our analysis (see Espinoza & Jordán 2015). We parameterized the limb-darkening effect using the square root law because for the properties of our two systems, it provides the minimum mean square error, following the method described in Espinoza & Jordán (2016). We used a white-noise model to treat the photometric residuals because we tried first to fit a flicker-noise model, but the parameters obtained with this model were consistent with no 1/f noise component. Five hundred walkers were used to evolve the MCMC, and each one explored the parameter space in 2000 links, 1500 of which were used as burn-in samples. This gave a total of 500 links sampled from the posterior per walker, giving a total of 250,000 samples from the posterior distribution. These samples were tested to converge both visually and using the Geweke (1992) convergence test.

The median values of the posterior distributions for each parameter are tabulated in Table 3 along with their errors, which are given by the 16th and 84th percentiles of the posterior distributions for the lower and upper errors, respectively. The priors used for the analysis are shown in Table 4. The modeled light curves with the obtained posterior parameters are plotted in Figures 4 and 5. The derived physical and orbital parameters for both systems are consistent with being hot Jupiters. For K2-30b we obtain $R_p = 1.069 \pm 0.021 R_J$, and an equilibrium temperature of $T_{eq} = 1203 \pm 19K$, assuming zero albedo. On the other hand, for K2-34b we obtain $M_p = 1.685 \pm 0.060 M_J$, $R_p = 1.377 \pm 0.14 R_J$, and $T_{eq} = 1715 \pm 17 K$, where the large uncertainty in the radius is dominated by the large uncertainty in the radius of the host star.

### Table 2

| Parameter | K2-30 | K2-34 | Source |
|-----------|-------|-------|--------|
| EPIC ID   | EPIC210957318 | EPIC21110888 | 2MASS |
| 2MASS ID  | 03292204+2217577 | 08301891+2214092 | 2MASS |
| R.A. (J2000, h:m:s) | 03°29′29.07″ | 08°30′18.91″ | EPIC |
| Decl. (J2000, d:m:s) | 22°17′57.86″ | 22°14′09.27″ | EPIC |
| R.A. p.m. (mas/yr) | 25.9 ± 2.3 | -14.1 ± 0.8 | UCAC4 |
| Decl. p.m. (mas/yr) | -13.6 ± 2.4 | -0.3 ± 0.5 | UCAC4 |
| Spectroscopic properties | | | |
| $T_{\text{eff}}$ (K) | 5575 ± 50 | 6149 ± 55 | ZASPE |
| Spectral Type | G | F | ZASPE |
| [Fe/H] (dex) | 0.06 ± 0.04 | 0.00 ± 0.04 | ZASPE |
| log(g) (cgs) | 4.6 ± 0.05 | 4.2 ± 0.09 | ZASPE |
| $v \sin(i)$ (km s$^{-1}$) | 0.5 ± 0.50 | 6.31 ± 0.20 | ZASPE |
| Photometric properties | | | |
| $K_p$ (mag) | 13.171 | 11.441 | EPIC |
| $B$ (mag) | 14.506 ± 0.030 | 12.429 ± 0.033 | APASS |
| $V$ (mag) | 13.530 ± 0.039 | 11.548 ± 0.057 | APASS |
| $g'$ (mag) | 13.346 ± 0.008 | 11.892 ± 0.119 | APASS |
| $r'$ (mag) | 12.763 ± 0.042 | 11.892 ± 0.119 | APASS |
| $i'$ (mag) | 12.443 ± 0.067 | 11.389 ± 0.026 | APASS |
| $J$ (mag) | 11.63 ± 0.007 | 10.264 ± 0.038 | 2MASS |
| $H$ (mag) | 11.194 ± 0.008 | 10.519 ± 0.004 | 2MASS |
| $K_s$ (mag) | 11.088 ± 0.007 | 10.187 ± 0.010 | 2MASS |
| Derived properties | | | |
| $M_p$ ($M_\odot$) | 0.91^{+0.04}_{-0.04} | 1.22^{0.04}_{-0.04} | isochrones+ZASPE |
| $R_p$ ($R_\odot$) | 0.83^{+0.07}_{-0.04} | 1.58^{+0.15}_{-0.14} | isochrones+ZASPE |
| $\rho_p$ (g/cm$^3$) | 2.02^{+0.14}_{-0.14} | 0.43^{+0.09}_{-0.09} | isochrones+ZASPE |
| $L_p$ ($L_\odot$) | 0.53^{+0.05}_{-0.05} | 3.05^{+0.37}_{-0.37} | isochrones+ZASPE |
| Distance (pc) | 297.2^{+6.7}_{-6.6} | 390^{+30.0}_{-29.0} | isochrones+ZASPE |
| Age (Gyr) | 2.2^{+1.8}_{-0.8} | 4.24^{+0.44}_{-0.44} | isochrones+ZASPE |

**Note.** Logarithms given in base 10.
Table 3: Orbital and Planetary Parameters for K2-30b and K2-34b

| Parameter | K2-30b Posterior Value | K2-34b Posterior Value |
|-----------|------------------------|------------------------|
| \( P \) (days) | 4.09849(0.00002) | 4.09849(0.00002) |
| \( T_0 - 2450000 \) (BJD) | 7067.90599(0.00018) | 7144.3703(0.00008) |
| \( \omega/R_e \) | 10.706(0.28) | 6.304(0.13) |
| \( R_p/R_e \) | 0.13097(0.0009) | 0.0895(0.0007) |
| \( i \) (deg) | 85.86(0.23) | 82.23(0.19) |
| \( q_1 \) ... | 0.53(0.17) | 0.58(0.11) |
| \( q_2 \) ... | 0.42(0.21) | 0.55(0.14) |
| \( \sigma_p \) (ppm) ... | 281.2(3.9) | 78.2(0.7) |

RV Parameters

- \( \nu_{\text{FEROS}} \) (km s\(^{-1}\))...
- \( \nu_{\text{HARPS}} \) (km s\(^{-1}\))...
- \( \nu_{\text{FIES}} \) (km s\(^{-1}\))...
- \( \nu_{\text{SOPHIE}} \) (km s\(^{-1}\))...
- \( \nu_{\text{HARPS-N}} \) (km s\(^{-1}\))...
- \( \nu_{\text{Cafe}} \) (km s\(^{-1}\))...
- \( \sigma_{\nu_{\text{FEROS}}} \) (km s\(^{-1}\))...
- \( \sigma_{\nu_{\text{HARPS}}} \) (km s\(^{-1}\))...
- \( \sigma_{\nu_{\text{FIES}}} \) (km s\(^{-1}\))...
- \( \sigma_{\nu_{\text{SOPHIE}}} \) (km s\(^{-1}\))...
- \( \sigma_{\nu_{\text{HARPS-N}}} \) (km s\(^{-1}\))...
- \( \sigma_{\nu_{\text{Cafe}}} \) (km s\(^{-1}\))...
- \( \sigma_\nu \) (km s\(^{-1}\))...
- \( \epsilon \) (°)

- \( M_p \) (M\(_J\)) ...
- \( R_p \) (R\(_J\)) ...
- \( \rho_p \) (g/cm\(^3\))...
- \( \log g_p \) (cgs)...
- \( w \) (AU) ...
- \( V_{\text{esc}} \) (km s\(^{-1}\))...
- \( T_{\text{eq}} \) (K) ...

Bond albedo of 0.0

Bond albedo of 0.75

Table 4: Priors for the Joint Analysis of K2-30b and K2-34b

| Parameter | K2-30b Prior | K2-34b Prior |
|-----------|--------------|--------------|
| \( P \) (days) | \( N(4.098, 0.01) \) | \( N(2.996, 0.01) \) |
| \( T_0 - 2450000 \) (BJD) | \( N(7067.90, 0.10) \) | \( N(7144.33, 0.10) \) |
| \( \omega/R_e \) | \( U(1, 30) \) | \( U(1, 30) \) |
| \( R_p/R_e \) | \( U(0.01, 0.5) \) | \( U(0.01, 0.5) \) |
| \( i \) (deg) | \( U(80, 90.0) \) | \( U(80, 90.0) \) |
| \( q_1 \) ... | \( \epsilon(0, 1.0) \) | \( \epsilon(0, 1.0) \) |
| \( q_2 \) ... | \( \epsilon(0, 1.0) \) | \( \epsilon(0, 1.0) \) |
| \( \sigma_p \) (ppm) ... | \( J(1.0, 2000.0) \) | \( J(1.0, 2000.0) \) |

RV Parameters

- \( K \) (km s\(^{-1}\))...
- \( \nu_{\text{FEROS}} \) (km s\(^{-1}\))...
- \( \nu_{\text{HARPS}} \) (km s\(^{-1}\))...
- \( \nu_{\text{FIES}} \) (km s\(^{-1}\))...
- \( \nu_{\text{SOPHIE}} \) (km s\(^{-1}\))...
- \( \nu_{\text{HARPS-N}} \) (km s\(^{-1}\))...
- \( \nu_{\text{Cafe}} \) (km s\(^{-1}\))...
- \( \sigma_{\nu_{\text{FEROS}}} \) (km s\(^{-1}\))...
- \( \sigma_{\nu_{\text{HARPS}}} \) (km s\(^{-1}\))...
- \( \sigma_{\nu_{\text{FIES}}} \) (km s\(^{-1}\))...
- \( \sigma_{\nu_{\text{SOPHIE}}} \) (km s\(^{-1}\))...
- \( \sigma_{\nu_{\text{HARPS-N}}} \) (km s\(^{-1}\))...
- \( \sigma_{\nu_{\text{Cafe}}} \) (km s\(^{-1}\))...
- \( \sigma_\nu \) (km s\(^{-1}\))...
- \( \epsilon \) (°)

Note. Logarithms given in base 10.

3.4. Searching for Additional Signals in the K2 Photometry

We searched for additional signals in the photometry of both targets stars in order to search for additional transiting companions, secondary eclipses, and/or optical phase variations due to either reflected light of the detected transiting planets, ellipsoidal variations, and/or Doppler beaming (e.g., Estevés et al. 2013).

The transit search was performed using the BLS algorithm on the data with the transit of the detected planetary companion. For each significant peak on the BLS periodogram, we visually inspected the phased light curve in order to search for additional transits. In addition, the light curve was also inspected at periods 2, 3/2, 1/2, and 2/3 times the period of the detected transiting planet presented in this work in order to search for additional companions in 2:1 and 3:2 mean-motion resonances.

For both K2-30 and K2-34, no additional transiting companions were found, which limit the possible companions to transit depths smaller than 200 ppm and 90 ppm, respectively, at 3σ. Also, no secondary eclipses and optical phase variations were detected on either light curve. Given the transit parameters that we obtain of K2-30b, the non-detection of a secondary eclipse was expected, as they would have to be smaller than \( (R_p/a)^2 \sim 150 \) ppm. Optical phase variations were expected to be below this limit as well. In the case of K2-34b, \( (R_p/a)^2 \sim 200 \) ppm, and our analysis rules out any secondary eclipse larger than 90 ppm at 3σ; this implies that the geometric albedo of K2-34b is constrained by our data to be less than 0.45, which is in agreement again with the typical geometric albedo of hot Jupiters (Heng & Demory 2013). No optical phase variations were detected either.

4. Discussion

In this paper, we present an independent discovery of two transiting hot Jupiters orbiting main sequence stars, that were first
selected as candidates from K2 photometry of Campaigns 4 and 5. The planetary nature of these two objects was then confirmed by precision RV measurements using three high-resolution echelle spectrographs located in the southern hemisphere.

Both systems were recently announced by other teams that performed independent follow-up campaigns using spectroscopic facilities located in the northern hemisphere (Lillo-Box et al. 2016; Johnson et al. 2016; Hirano et al. 2016). Even though the data presented in this work were sufficient for confirming the planetary nature of both candidates and to obtain reliable estimations for their physical parameters, we decided to include the radial velocity measurements obtained in these three other works in order to refine the estimation of the planetary parameters. This procedure allowed us to have a better phase coverage for both orbits, which was particularly useful in the case of K2-34b, for which the use of velocity measurements obtained from facilities at different geographical longitudes allow us to partially counteract the effect produced by the peculiar value of the orbital period of this planet, which is almost exactly a multiple of one day. By combining the radial velocity data we obtained smaller uncertainties in the masses for both planets with respect the the errors reported by the other three groups. However, the planetary mass estimations obtained by all the different groups agree with each other at the level of the reported uncertainties.

We found that the mass of K2-30b is in-between the Saturn and Jupiter mass \((M_p = 0.589 \pm 0.023 M_J)\), while its radius \((R_p = 1.069 \pm 0.021 R_J)\) is slightly larger than the one of Jupiter. In contrast, we found that K2-34 is significantly more massive \((M_p = 1.698 \pm 0.056 M_J)\) and larger \(R_p = 1.377 \pm 0.014 R_J\) than Jupiter. However, the physical and orbital properties of both of these systems resemble quite well the ones of the typical population of known hot Jupiters, which can be visualized with Figure 6. In the left panel of Figure 6, the mass–radius diagram for the complete population of discovered transiting hot Jupiters \((P < 10\) days, \(R_p > 0.5 R_J)\) shows that according to our analysis, the physical parameters of K2-30b and K2-34b lie in densely populated regions of the parameters space and that both planets share a similar density, close to half the one of Jupiter \((\rho_J = 0.67 \text{ g cm}^{-3})\). Another particularity to note from Figure 6 is that while the inferred radius of K2-30b can be explained with the models of planetary structure of Fortney et al. (2007) by requiring a core mass of \(\sim 15\) M⊕, the radius of K2-34b is significantly larger than that predicted by these models and suffers from the radiative and/or tidal inflation mechanisms that typical hot Jupiters are victims of (see Spiegel & Burrows 2010). However, it is important to note that while the radius for K2-30b computed by Johnson et al. (2016) is consistent with the one presented in this work requiring the presence of a solid core, Lillo-Box et al. (2016)

\[\text{Figure 6. Left: the mass–radius diagram for the population of known transiting hot Jupiters. We show as colored circles and triangles the values obtained for K2-30b and K2-34b, respectively (red: this work, green: Lillo-Box et al. 2016, blue: Hirano et al. 2016, and light blue: Johnson et al. 2016). The light dashed lines correspond to isodendity curves of 0.67, 1.33, and 3.66 g cm}^{-3}, \text{from left to right. The dark dashed lines correspond to the Fortney et al. (2007) models for typical properties of hot Jupiters (a = 0.945 au, 3 Gyr), and central core masses of 100 M}_\oplus\text{ (bottom curve) and 0 M}_\oplus\text{ (top curve). According to this figure, the two new systems can be classified as common hot Jupiters having densities close to half the one of Jupiter. However, for K2-30b the radius calculated by Lillo-Box et al. (2016) seems to be significantly larger than the estimations obtained in this work and in Johnson et al. (2016). Right: radius as function of the theoretical equilibrium temperature for the complete population of discovered transiting hot Jupiters. Symbols and colors are the same as in the left panel. Both systems follow the known correlation between the level of insolation and the degree of inflation in radii. The radius of K2-30b can be explained with the Fortney et al. (2007) models because its equilibrium temperature lies close to the lower limit of 1000 K (dashed line), below which planets are not expected to be inflated.}
\]
found a larger radius for this planet that requires no core and a certain level of inflation. The origin of this discrepancy relies in the estimation of the physical parameters of the host star. While the stellar radius for K2-30 reported in this work ($0.839 \pm 0.015 \, R_\odot$) is consistent with the estimation of Johnson et al. (2016; $0.844 \pm 0.032 \, R_\odot$), Lillo-Box et al. (2016) obtain a significantly larger value ($0.941 \pm 0.041 \, R_\odot$). This issue shows the importance of performing homogeneous analysis when global trends and correlations between planetary and stellar parameters are searched. For K2-34b the different estimations of the planetary radius presented by the other groups are consistent with the value reported in this work.

The presented dichotomy in the structure of K2-30b and K2-34b can be explained by the different insolation levels to which these planets are subjected. The right panel of Figure 6 shows the radii of the discovered transiting hot Jupiters as a function of their obliquity angle. This effect has indeed been already measured for long-slit transmission spectroscopy. On the other hand, the similar brightness, which can be used as a comparison source for the Rossiter–McLaughlin effect, has a prograde orbit with low obliquity.

References

Anderson, D. R., Hellier, C., Gillon, M., et al. 2010, ApJ, 709, 159
Bakos, G., Noyes, R. W., Kovács, G., et al. 2004, PASP, 116, 266
Bakos, G. Á., Csabry, Z., Penev, K., et al. 2013, PASP, 125, 154
Baranne, A., Queloz, D., Mayor, M., et al. 1996, AAPS, 119, 373
Becker, J. C., Vanderburg, A., Adams, P. C., et al. 2015, ApJL, 812, L18
Brahm, R., Jordán, A., & Hartman, J. D. 2015, AJ, 150, 33
Brahm, R., Jordan, A., Hartman, J. et al. 2016, arXiv:1607.05792
Burrows, A., Hubeny, I., Budaj, J., et al. 2007, ApJ, 661, 502
Crossfield, I. J. M. 2015, PASP, 127, 941
Demory, B. O., & Seager, S. 2011, ApJS, 197, 12
Dotter, A., Chaboyer, B., Jevremović, D., et al. 2008, ApJS, 178, 89
Espinoza, N., & Jordán, A. 2015, MNRAS, 450, 1879
Espinoza, N., & Jordán, A. 2016, MNRAS, 457, 3573
Espinoza, N., Brahm, R., Jordán, A., et al. 2016, arXiv:1601.07608
Esteves, L. J., De Mooij, E. J. W., & Jayawardhana, R. A. 2013, ApJ, 772, 51
Feroz, F., & Hobson, M. P. 2008, MNRAS, 384, 449
Fortney, J. J., Marley, M. S., Barnes, J. W., et al. 2007, ApJ, 659, 1661
Geweke, J. 1992, in Bayesian Statistics 4, ed. J. M. Bernardo et al. (Oxford: Oxford Univ. Press), 169
Gray, R. O. 1999, Astrophysics Source Code Library, ascl:9910.002
Guillot, T. 2005, AREPS, 33, 493
Hartman, J. D., Bakos, G. Á, & Torres, G. 2011, ApJ, 742, 59
Henden, A., & Munari, U. 2014, Contributions of the Astronomical Observatory Skalnate Pleso, 43, 518
Heng, K., & Demory, B. O. 2013, ApJ, 777, 100
Hirano, T., Nowak, G., Kuzuhara, M., et al. 2016, arXiv:1602.00638
Johnson, M. C., Gandolfí, D., Fridlund, M., et al. 2016, arXiv:1601.07844
Jordán, A., Brahm, R., Bakos, G. Á, et al. 2014, AJ, 148, 29
Kaufer, A., & Pasquini, L. 1998, Proc. SPIE, 3355, 844–845
Kipping, D. M. 2010, MNRAS, 408, 1715
Kovács, G., Zucker, S., & Mazeh, T. 2002, A&A, 391, 369
Kovács, G., Bakos, G. Á, & Hartman, J. D. 2010, ApJ, 724, 866
Kurucz, R. L. 1993, yCat, 6039, 0
Lillo-Box, J., Demangeon, O., Santerne, A., et al. 2016, arXiv:1601.07635
Lin, D. N. C., Bodenheimer, P., & Richardson, D. C. 1996, Natur, 380, 606
Marsh, T. R. 1989, PASP, 101, 1032
Mayor, M., Pepe, F., & Queloz, D. 2003, Msngr, 114, 20
McLaughlin, D. B. 1924, ApJ, 60, 22
Montet, B., Morton, T., Foreman-Mackey, D., et al. 2015, ApJ, 809, 25
Morton, T. D. 2012, ApJ, 761, 6
Neveu-VanMalle, M., Queloz, D., & Anderson, D. R. 2016, A&A, 586, A93
Queloz, D., Mayor, M., Udry, S., et al. 2001, Msngr, 105, 1
Pallavicini, D. L., Skilling, I., Collier Cameron, A., et al. 2006, PASP, 118, 1407
Rafikov, R. R. 2006, ApJ, 648, 666
Rasio, F. A., & Ford, E. B. 1996, Sci, 274, 954
Rossiter, R. A. 1924, ApJ, 60, 15
Seager, S., & Deming, D. 2010, ARA&A, 48, 631
Spiegel, D. S., & Burrows, A. 2010, ARA&A, 48, 631
Steffen, J. H., Ford, E. B., Rowe, J. F., et al. 2012, ApJ, 756, 186
Vanderburg, A., & Jonson, J. 2014, PASP, 126, 948
Wang, J., Fischer, D. A., Horch, E. P., et al. 2015, ApJ, 799, 229