Follow-up of non-transiting planets detected by Kepler

Confirmation of three hot-Jupiters and validation of three other planets

J. Lillo-Box1, S. Millholland2,3, and G. Laughlin3

1 Centro de Astrobiología (CAB, CSIC-INTA), Depto. de Astrofisica, ESAC campus 28692 Villanueva de la Cañada (Madrid), Spain
e-mail: jorge.lillo@cab.inta-csic.es
2 Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA
3 Department of Astronomy, Yale University, New Haven, CT 06511, USA

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ABSTRACT

Context. The direct detection of new extrasolar planets from high-precision photometry data is commonly based on the observation of the transit signal of the planet as it passes in front of its star. Close-in planets, however, leave additional imprints in the light curve even if they do not transit. These are the so-called phase curve variations that include ellipsoidal, reflection and beaming effects.

Aims. In a previous paper, we scrutinized the Kepler database looking for these phase variations from non-transiting planets. They found 60 candidates whose signals were compatible with planetary companions. In this paper, we perform a ground-based follow-up of a subsample of these systems with the aim of confirming and characterizing these planets and thus validating the detection technique.

Methods. We used the CAFE and HERMES instruments to monitor the radial velocity (RV) of ten non-transiting planet candidates along their orbits. We additionally used AstraLux to obtain high-resolution images of some of these candidates to discard blended binaries that contaminate the Kepler light curves by mimicking planetary signals.

Results. Among the ten systems, we confirm three new hot-Jupiters (KIC 8121913 b, KIC 10068024 b, and KIC 5479689 b) with masses in the range 0.5–2 M_Jup and set mass constraints within the planetary regime for the other three candidates (KIC 8026887 b, KIC 5878307 b, and KIC 11362225 b), thus strongly suggestive of their planetary nature.

Conclusions. For the first time, we validate the technique of detecting non-transiting planets via their phase curve variations. We present the new planetary systems and their properties. We find good agreement between the RV-derived masses and the photometric masses in all cases except KIC 8121913 b, which shows a significantly lower mass derived from the ellipsoidal modulations than from beaming and RV data.

Key words. planets and satellites: detection – planets and satellites: gaseous planets – planet-star interactions – planets and satellites: fundamental parameters

1. Introduction

In the era of high-precision photometric space-based missions, the detection of extrasolar planets through the transit technique has been very fruitful. So far, more than 4300 planets have been found around other stars, with around three-fourths of them detected by this technique. Since the launch of the CoRoT mission (Auvergne et al. 2009), the subsequent NASA planet hunter Kepler (Borucki et al. 2010) and its extended K2 mission (Howell et al. 2014) as well as its successor TESS (Ricker et al. 2014) have scrutinized the sky looking for these planetary fingerprints in the light curves of stellar sources. According to the NASA Exoplanet archive, more than 2400 planets were discovered with Kepler and more than 400 with K2, and presently 137 have been detected and confirmed by TESS using the transit method (Akeson et al. 2013).

Several years after the end of the prime Kepler mission, the high-quality data provided by this telescope are still being profitably mined. Although Kepler was tasked to find Earth-sized planets around Solar-like stars, it explored an unexpectedly large range of planetary and orbital properties, including the first circumbinary planets, super-Earths, planets in highly eccentric orbits, and planets around giant stars, etc. (e.g., Doyle et al. 2011; Borucki et al. 2012; Ciceri et al. 2015; Lillo-Box et al. 2014, respectively).

The transit technique, however, does not provide a full confirmation of the planet candidate signal by itself, as other non-planetary configurations can mimic the imprint of a symmetric dip in the light curve (e.g., background eclipsing binaries, grazing binary eclipses, etc.). Also, any blended source residing inside the photometer aperture can contaminate the light curve and provide inaccurate estimates of the planet candidate’s parameters. Hence, additional follow-up is necessary from the ground. In practice, the confirmation of transiting planet candidates primarily stems from radial velocity (RV) follow-up, which can provide the mass of the transiting body and thus confirm its planetary nature.

The extraordinary quality of the Kepler photometry motivated the proposal of an alternate technique to detect and fully characterize new planets, that is measure the mass and orbital configuration. Previously used in binary systems, the detection of periodic modulations coupled with the orbital phase of

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the planet arose as a new potential detection technique (e.g., Faigler & Mazeh 2011). These photometric variations are mainly due to three effects: reflected stellar light, ellipsoidal modulations, and Doppler beaming (hereafter the REB modulations, see Fig. 1). The reflection effect depends directly on the planet-to-star separation, size, and the geometric albedo of the planet. The ellipsoidal variations are known to be caused by tidal effects produced by a close-in object (e.g., a planet) on the external layers of the star (Morris 1985). Since the amplitude of this modulation depends on the mass of the planet, it can potentially be used to both detect, confirm, and characterize planets. Finally, the Doppler beaming effect represents the photometric signature of the RV variations of the star induced by the planet motion when photometry is obtained on a fixed wavelength range (Hills & Dale 1974; Rybicki & Lightman 1979). The induced RV implies that the stellar spectrum is periodically blue-shifted and red-shifted. As a consequence, more or less light enters in the wavelength domain of the photometric filter, yielding sinusoidal flux variations with an amplitude that depends on the mass of the planet.

The REB modulations have already been used to detect and characterize close-in transiting planets from the Kepler sample (e.g., Mazeh et al. 2012; Lillo-Box et al. 2014). These systematic searches have established several interesting findings, including generally low (but occasionally quite large) hot Jupiter albedos (Demory & Seager 2011) and repeated detections of shifts in the maximum of the phase curve away from the substellar point. Though it is substantial, the sample size (∼15) of Kepler transiting planets with detectable photometric variations (less than 5 with RV confirmations) is short of the count necessary to adequately understand the atmospheric properties in a population sense. It is therefore worthwhile to increase the number of planets with well-characterized optical phase curves by expanding the search to non-transiting planets. Moreover, the masses derived from these modulations seem to not fully match the measurements from RVs in the few (less than 5) cases where both techniques could be applied. This is theoretically attributed to the presence of hot stream clouds in the atmosphere of the hot-Jupiters causing a phase shift in the light curve modulations.

Millholland & Laughlin (2017) used a supervised machine learning approach to perform a systematic search of these modulations in the whole sample of 142 630 FGK Kepler stars without confirmed planets or KOIs (Kepler Objects of Interest). They identified 60 high-probability (>98%) non-transiting hot Jupiter candidates that could readily be confirmed with RVs (see Fig. 1). In this paper, we present the ground-based follow-up of the brightest subsample of these candidates. In Sect. 2, we present the targets and the observations. In Sect. 3, we perform a joint analysis of the light curve and RV data to confirm the planetary nature of some of the candidates and constrain the masses of the remaining subsample. In Sect. 4, we discuss the results of the analysis, and we conclude in Sect. 5.

2. Follow-up observations

2.1. Target selection

This work is based on the follow-up of the Kepler non-transiting planet candidates detected by Millholland & Laughlin (2017) through the phase variations technique. Among the 60 candidates, we focused on those feasible with the Calar Alto Fiber-fed Echelle spectrograph (CAFE, Acetiuno et al. 2013; Lillo-Box et al. 2020). We selected ten of the brightest candidates (Kp < 14 mag) displaying photometric periods of a few days

Fig. 1. Schematic representation of the reflection, ellipsoidal and beaming (REB) modulations. Top panel: orbital path of the planet at different phases and two orbital inclinations. Middle panel: corresponding shape of the REB effects (dotted labelled lines) and the composite phase curve (green solid line). Bottom panel: corresponding RV signal with its appropriate phase relationship.

(\( P < 5 \text{ days} \)) and with estimated RV amplitudes (\( K \sin i \)) from the photometric phase curve analysis feasible with CAFE (\( K \sin i > 10 \text{ m s}^{-1} \)). Table 1 lists our initial selection of targets.

2.2. Kepler light curves

In Sect. 3.2, we perform a joint fit of the RV and light curve data. For the Kepler light curves, we use the same pre-processing techniques as Millholland & Laughlin (2017); further details can be found therein. We began with the pre-search data conditioning (PDC) photometry (Smith et al. 2012; Stumpe et al. 2012, 2014) provided by the Kepler Science Center. We performed two types of detrending: (1) an initial sliding polynomial fit, which was first used to identify candidate periodic signals using a Lomb-Scargle periodogram, and (2) a two-component detrending on the candidate signals, which simultaneously fit a sinusoidal phase curve component and a sliding polynomial stellar variability component. Using this latter fit, we created the detrended light curve by dividing the PDC light curve by the polynomial component of \(^1\)Estimation of \( K \sin i \) is non-traditional, but it arises directly from a measurement of the photometric amplitude of the ellipsoidal variation, \( A_{\text{ellip}} \). That is, \( K \sin i \propto A_{\text{ellip}} \propto M_p \sin^2 i \). (See Eq. (9) ahead or equation 27 of Millholland & Laughlin 2017.) This explains the extra factor of \( \sin i \).

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We used the CAFE instrument (Aceituno et al. 2013) with its recently upgraded capabilities (Lillo-Box et al. 2020) to perform a systematic RV follow-up of the selected planet candidates. CAFE is a fiber-fed high-resolution (\( R = 63000 \)) echelle spectrograph located in the coudé room of the 2.2 m telescope at the Calar Alto observatory (Almería, Spain). Although the instrument has been operating since 2012, in 2016 its gratings suffered a strong degradation that affected its efficiency and necessitated its retirement. This was taken as an opportunity to perform additional upgrades alongside the exchange of the gratings. These improvements included a new double scrambler, introduction of temperature control of the isolated room where the instrument is located, and development of a new Python-based public pipeline (CAFEExtractor, see Lillo-Box et al. 2020) that automatically reduces the data and provides high-level data-products like precise RV measurements using the cross-correlation technique (Baranne et al. 1996). These new capabilities were commissioned during 2018 and 2019, and the instrument was brought to full operation in April 2019. We refer the interested reader to Lillo-Box et al. (2020) for additional details on the new capabilities of CAFE.

The observations were carried out in May–August 2019 under the approved program ID H19-2.2-007 (PI: Lillo-Box). In total, we obtained 53 spectra from the ten targets. We used the new CAFEExtractor pipeline to reduce the spectra and obtain the RVs. The pipeline includes an option to fit the CCF by using either a Gaussian profile (by default) or a rotational profile for the rapidly rotating stars (recommended for stars with \( v \sin i > 10 \, \text{km s}^{-1} \)). The rotational profile is defined as in Gray (2005) and it has already been used in several programs that obtained precise RV measurements of rapidly rotating stars (e.g., Santerne et al. 2012; Aller et al. 2018). For cases with \( v \sin i > 10 \, \text{km s}^{-1} \), we used this approach, while for \( v \sin i < 10 \, \text{km s}^{-1} \), we used the usual Gaussian profile. In four out of the ten observed targets, either the CCF was too broad to extract meaningful RVs (KIC 6783562 and KIC 10931452) or the phase coverage was insufficient to perform a relevant analysis (KIC 5001685 and KIC 8042004). Hence, these targets are not further addressed in this paper. The extracted RVs and the properties of the CCF for the remaining six targets are shown in Tables A.1–A.6.

2.5. HERMES/Mercator high-resolution spectra

We observed five of the targets from the selected sample with the high-resolution fiber-fed HERMES spectrograph (Raskin et al. 2011) at the Mercator telescope in La Palma in August 2020. HERMES is a sibling of the CORALIE instrument at La Silla. It provides a resolution of \( R = 85000 \) and a wavelength coverage of 377–900 nm. We used the simultaneous wavelength calibration mode, which uses a second fiber to inject a thorium-argon spectrum in between the science orders to monitor the nightly drift of the wavelength calibration for precise RV measurements. The instrument’s automatic pipeline provides the basic
3. Analysis

3.1. Radial velocity standalone modeling

We first performed a RV analysis of the CAFE data, since the number of RV measurements from the HERMES instrument was low for this preliminary analysis. Given the limited number of observations for most of the systems, we used a simplistic RV model that assumes circular orbits (likely a good approximation given the short periods of these candidates) and adopts Gaussian priors on the period and time of conjunction obtained from the light curve analysis in Millholland & Laughlin (2017). Consequently, the only two free parameters of the model are the systemic velocity ($V_{\text{sys}}$) and the semi-amplitude of the RV signal ($K$). For each of these parameters, we assumed a uniform prior with broad ranges corresponding to $\mathcal{U}(-100, 100) \text{ km s}^{-1}$ for $V_{\text{sys}}$ and $\mathcal{U}(0.0, 10) \text{ km s}^{-1}$ for $K$.

We used the Markov chain Monte Carlo affine invariant ensemble sampler emcee (Goodman & Weare 2010; Foreman-Mackey et al. 2013) to explore the posterior probability of the two parameters. We ran a first set of 20 walkers with 10,000 steps per walker to identify the maximum likelihood location of the parameter space. Then we ran another 10 walkers with 10,000 steps per walker in a nearby region around this maximum likelihood location of the parameter space to properly sample the posterior distributions. The results are shown in Tables A.1–A.6.

Fig. 2. Results of the analysis of the high-spatial resolution images obtained with the AstraLux lucky-imaging instrument. Each panel shows the contrast curve calculated as in Lillo-Box et al. (2014) as a white line. The color-code of the contrast curve represents the contamination produced by a blended star of the given magnitude contrast as shown in the color bar. The inset panel displays the AstraLux image, with redder colors indicating more intensity.
in Figs. 3 and 4, and the priors, median and confidence levels of the posterior distributions for each parameter are shown in Tables A.7–A.12.

Among the six systems with appropriate phase coverage, we find clear detection in three of the targets (KIC 8121913, KIC 10068024, and KIC 5479689), see Fig. 3. In these cases, the RV semi-amplitude is detected with a confidence larger than 99.7% (corresponding to 3σ) and thus are considered as confirmed planets. In two other cases (KIC 878307 and KIC 1136225, see Fig. 4), the data is insufficient to measure the planet mass but the low amplitude of the RV variations and the absence of contaminants in the AstraLux images validate their planetary nature. In the case of KIC 8026887, we find either a large amplitude of several hundred of meters per second or a strong linear trend with a smaller RV amplitude. Additionally, by using a period equal to twice the photometric period (2 × P = 3.8464 days), we find a clear signal compatible with a Keplerian model with K ∼ 610 ± 180 m s⁻¹ (see Fig. 4, right panel). This is further investigated in the joint light curve and radial velocity analysis in the next section.

3.2. Joint radial velocity and light curve modeling

To examine the consistency of the RV observations and Kepler light curves, we performed a simultaneous fit of the two datasets for the four targets with sufficiently precise RVs: KIC 8121913, KIC 10068024, KIC 5479689, and KIC 8026887. The key goal of this simultaneous fit is to verify that the periods and phases
suggested by the photometric detections are consistent with the RVs. Moreover, we also wish to investigate whether the companion mass estimates agree between the two datasets. Here we adopt a fitting approach that is as simplified as possible, on account of our relatively small number of RV data points and our goal to simply demonstrate RV and light curve consistency.

We model the phase curve variations using a four-component sum of sinusoids at the orbital phase

$$\phi \equiv (t - T_0)/P,$$

where $T_0$ is the epoch of inferior conjunction (or the transit time if the companion is transiting):

$$F(\phi) = A_0 - A_{\ell \text{ip}} \cos(2\pi(\phi + \delta)) - A_{\ell \text{ip}} \cos(4\pi\phi) + A_{\ell \text{beam}} \sin(2\pi\phi).$$

(2)

Here, $\delta$ is a phase offset in peak brightness of the reflection component, and $A_{\ell \text{ip}}$, $A_{\ell \text{ip}}$, and $A_{\ell \text{beam}}$ are positive quantities representing the photometric amplitudes of the atmospheric/reflection, ellipsoidal, and beaming components of the phase curve (Esteves et al. 2015; Shporer 2017). These amplitudes will be treated as free parameters in our model. In Sect. 4.1, we describe the origin of these phase curve components and their approximate relationships to fundamental physical and orbital parameters. We also verify that they have been fit with reasonable values.

This four-component phase curve model is fit to the detrended Kepler light curves introduced in Sect. 2.2. These light curves are phase-folded using the period $P$ and epoch $T_0$ from Eq. (1) (both of which are free parameters in the fit) and binned into 400 bins, with the $j$th bin having mean flux, $F_j$, and standard deviation, $\sigma_{F,j}$. We now proceed to the RV component of the joint fit. We model the Doppler velocities simply as

$$v(t) = -K \sin(2\pi\phi) + \gamma(t - T_0) + \gamma_{\text{inst}},$$

where we have assumed a negligible orbital eccentricity. The RV semi-amplitude, $K$, is strictly positive, and $\phi$ and $T_0$ are the same phase and epoch as defined in Eq. (1). In addition to the sinusoidal signal, we include a long-term linear trend with acceleration $\gamma$ and instrument-specific offset, $\gamma_{\text{inst}}$.

We perform a joint RV and phase curve fit to the observations using the standard practices of Bayesian inference. The log-likelihood is here composed of the sum of the individual log-likelihoods of the RV and light curve datasets:

$$\ln \mathcal{L} = \ln \mathcal{L}_{\text{RV}} + \ln \mathcal{L}_{\text{LC}}.$$  (4)

Assuming Gaussian-distributed noise, the RV log-likelihood is

$$\ln \mathcal{L}_{\text{RV}} = -\frac{1}{2} \sum_j \left( \frac{(v_j - F_{\text{mod}}(t_j))^2}{(\sigma_{v,j}^2 + \sigma_{\text{jit},j}^2)} + \ln(2\pi[\sigma_{v,j}^2 + \sigma_{\text{jit},j}^2]) \right).$$  (5)

Here, $v_j$ and $\sigma_{v,j}$ are the $j$th velocity measurement and measurement error, and $F_{\text{mod}}(t_j)$ is the model RV (Eq. (3)) at time $t_j$.

Similarly, the light curve log-likelihood is given by

$$\ln \mathcal{L}_{\text{LC}} = -\frac{1}{2} \sum_j \left( \frac{(F_j - F_{\text{mod}}(\phi_j))^2}{\sigma_{F,j}^2} + \ln(2\pi\sigma_{F,j}^2) \right),$$  (6)

where $F_j$ and $\sigma_{F,j}$ are the $j$th measurement and error resulting from the folded and binned light curve data. $F_{\text{mod}}(\phi_j)$ is the model phase curve (Eq. (2)) at phase $\phi_j$.

The posterior distributions of the parameters were sampled through the Markov chain Monte Carlo affine invariant ensemble sampler emcee (Goodman & Weare 2010; Foreman-Mackey et al. 2013) using uniform priors and the likelihood function given by Eqs. (4)–(6). We collect 20 000 samples across 200 chains, discarding the first 5000 samples as burn-in. Convergence was assessed by inspecting trace plots to see that the chains were well-mixed. We provide corner plots of the joint prior parameter distributions in Appendix B.

The results of the joint fit are presented in Table 2, and the best-fitting models for KIC 8121913, KIC 10068024, and KIC 5479689 are displayed in Fig. 5. We observe that consistent solutions for the joint RV/phase curve fit can be found for these systems. Specifically, there are sets of $P$ and $T_0$ for which the two datasets agree within uncertainties. The amplitudes of
the phase curve and RV signals are also generally consistent in terms of the physical system parameters they correspond to, as discussed in Sect. 4.1.

In the case of KIC 8026887, the phase curve clearly shows ellipsoidal variations when folded at \( P = 1.9232 \) days. Hence the double period hypothesis is unlikely. In any case, we tested it to ensure that the \( P = 1.9 \) days is able to jointly model the RV and LC data. We then tested four models including priors on the period and turning on and off the linear trend. We then estimated the Bayesian evidence for the four models and concluded that the model with \( P = 1.9 \) and the linear trend shows the largest evidence for the current dataset. This model is able to reconcile both RVs and light curve modulations and provides a planet mass of \( 3.44 \pm 0.42 \, M_{\text{Jup}} \). The difference in log-evidence is +7 compared to the model without a linear trend and +135 compared to the model with \( 2 \times P \). The candidate absolute mass is hence significantly detected and we can hence validate the planetary nature of this candidate. Given the poor radial velocity phase coverage, however, we remain conservative and do not claim confirmation yet.

### 4. Discussion

#### 4.1. Consistency of RVs and phase curve component amplitudes

In the previous section, we treated the phase curve component amplitudes as free parameters within the joint RV/phase curve fit. These amplitudes are not truly free parameters, however, since they stem from physical effects in the star-planet system. Thus, the comparison of the phase curve component amplitudes to another and to the RV semi-amplitudes can inform whether the joint fits are physically consistent. Here we describe the relation of the amplitudes to physical parameters and assess their consistency. Within this, we adopt stellar parameters from the \textit{Gaia}-Kepler Stellar Properties Catalog (Berger et al. 2020; these are provided in Table 3).

The atmospheric component of optical phase curves, \( A_{\text{eff}} \), includes both light from the primary star reflected off the companion, as well as thermal emission from the companion itself. It is generally difficult to separate reflected light from thermal emission, and it depends on the system as to which dominates. The amplitude of the atmospheric component is given by (Shporer 2017),

\[
A_{\text{eff}} \approx \frac{a_{\text{ref}}}{10} \left( \frac{R_\text{p}}{a} \right)^2 \sin i
\]

\[
\approx 57a_{\text{ref}} \sin i \left( \frac{M_\star}{M_\odot} \right)^{-2/3} \left( \frac{P}{\text{day}} \right)^{-4/3} \left( \frac{R_\text{p}}{R_\odot} \right)^2 \text{ppm.}
\]

\*\*\*
Here \( \alpha_{\text{refl}} \) is an order-unity coefficient that depends on the planet’s albedo and the efficiency of heat redistribution.

In addition to phase modulations from the planet’s atmospheric brightness, there are also gravitationally-induced photometric signals from the host star. The phase component due to Doppler beaming (also known as Doppler boosting) stems from periodic blueshifts and redshifts of the stellar spectrum in response to the orbiting planet. The amplitude of the beaming component is given by

\[
A_{\text{beam}} \approx \frac{4K\alpha_{\text{beam}}}{c} \approx 2.7\alpha_{\text{beam}} \left( \frac{P}{\text{day}} \right)^{-1/3} \left( \frac{M_*}{M_\odot} \right)^{-2/3} \left( \frac{M_p \sin i}{M_\odot} \right) \text{ ppm.}
\]

Here, \( K \) is the radial velocity semi-amplitude, \( c \) is the speed of light and \( \alpha_{\text{beam}} \) is an order-unity coefficient equal to the photon-weighted bandpass-integrated beaming factor.

The second gravitational signal results from the ellipsoidal distortion of the host star due to tidal potential of the companion. This signal is dominated by a \( \cos(4\phi) \) term, although a more complete expansion includes smaller amplitude harmonics such as \( \cos(2\phi) \) and \( \cos(6\phi) \), which we have ignored in Eq. (2) for simplicity. The photometric amplitude of the ellipsoidal distortion is approximately

\[
A_{\text{ellip}} \approx \frac{M_p \alpha_{\text{ellip}} \sin^2 i}{M_*} \left( \frac{R_p}{a} \right)^3 \approx 13\alpha_{\text{ellip}} \sin i \left( \frac{R_p}{R_\odot} \right)^3 \left( \frac{M_*}{M_\odot} \right)^{-2} \left( \frac{P}{\text{day}} \right)^{-2} \left( \frac{M_p \sin i}{M_\odot} \right) \text{ ppm.}
\]

The \( \alpha_{\text{ellip}} \) coefficient is order-unity, and it relates to the stellar limb darkening and gravity darkening,

\[
\alpha_{\text{ellip}} = \frac{3(15 + u)(1 + g)}{20(3 - u)},
\]

where \( u \) is the linear limb darkening coefficient and \( g \) is the gravity darkening coefficient (Claret & Bloemen 2011).

To investigate the consistency of the phase curve components and the RV semi-amplitudes for each system, we compare their respective constraints on \( M_p \sin i \). The minimum mass \( M_p \sin i \) is most robustly constrained from the RV semi-amplitude \( K \), but \( A_{\text{beam}} \) and \( A_{\text{ellip}} \) also provide weak estimates. We first solve Eqs. (8) and (9) for \( M_p \sin i \). Next, we use the posterior samples from the joint fits in Sect. 3.2 and the stellar parameter estimates (Table 3) to calculate the posterior distributions of \( M_p \sin i \). Specifically, for the stellar parameters, we sample from distributions of \( M_* \) and \( R_* \) consistent with the observed means and error estimates in Table 3. The \( A_{\text{ellip}} \) amplitude includes an extra factor of \( \sin i \) (\( A_{\text{ellip}} \propto M_p \sin^2 i \); Eq. (9)), so we average over it by assuming an isotropic distribution of the inclination. As for the order-unity coefficients \( \alpha_{\text{beam}} \) and \( \alpha_{\text{ellip}} \), we set them to fixed values based on simple linear relationships with \( T_{\text{eff}} \), which were shown to be good fits to these coefficients in the Kepler bandpass (Millholland & Laughlin 2017):

\[
\alpha_{\text{beam}} \approx -(6 \times 10^{-4} \text{K}^{-1}) T_{\text{eff}} + 7.2
\]

\[
\alpha_{\text{ellip}} \approx -(2.2 \times 10^{-4} \text{K}^{-1}) T_{\text{eff}} + 2.6.
\]

This is an appropriate simplification because the uncertainties in the derived \( M_p \sin i \) are primarily driven by the spread in posterior samples of \( A_{\text{beam}} \) and \( A_{\text{ellip}} \). Finally, putting all of this together, we calculate the posterior distributions of \( M_p \sin i \). The resulting means and 1\( \sigma \) ranges are given in Table 2.

We find that the \( M_p \sin i \) estimates from RV, \( A_{\text{beam}} \), and \( A_{\text{ellip}} \) are consistent in almost all cases for our three targets. The one exception arises within the \( M_p \sin i \) estimates derived from \( A_{\text{ellip}} \), which are systematically lower than those derived from \( K \) and \( A_{\text{beam}} \) in all three cases, up to \( \approx 4\sigma \) lower in the case of KIC 8121913. This discrepancy could arise from the extra factor of \( \sin i \), which we marginalized over. Additionally, it could be related to uncertainties in \( \alpha_{\text{ellip}} \), which we ignored. More broadly, however, this mass discrepancy is common in photometric phase curve analyses and has been pointed out in previous studies (see Shporer 2017 and references therein). An inconsistency between the ellipsoidal and RV-derived masses was found for KOI-74 by Bloemen et al. (2011), an eclipsing binary composed by an A-type and a white dwarf star, with the mass ratio derived by RVs being larger than from ellipsoidal modulations, as in the case of KIC 8121913. Although the reason for this discrepancy is not yet understood, several studies have pointed out different possible causes (e.g., van Kerkwijk et al. 2010; Pfahl et al. 2008).

The above analysis provided a consistency check on both the RVs and the beaming and ellipsoidal components of the phase curve. It is also worthwhile to check the reflection phase curve component amplitude, \( \alpha_{\text{refl}} \), although this is complicated by the unknown \( \alpha_{\text{refl},R} \), \( R_p \), and \( \sin i \). One approach is to use the posterior samples of \( \alpha_{\text{refl}} \) from Sect. 3.2 to calculate the combination of parameters \( \alpha_{\text{refl}}R_p^2 \sin i \) via Eq. (7). We can then examine whether the constraints are reasonably consistent with the RVs. The derived values of \( \alpha_{\text{refl}}R_p^2 \sin i \) are given in Table 2. The values for KIC 8121913 and KIC 10068024 are unity or greater, thus consistent with \( R_p \geq R_{\text{Jup}} \) planets, whereas KIC 5479689 suggests a somewhat smaller \( R_p \) and/or smaller \( \sin i \). This constraint is independent consistent with the inferred \( M_p \sin i \) for KIC 5479689, which was found to be smaller than the other two systems.

5. Summary and conclusions

We performed ground-based follow-up observations of ten non-transiting planet candidates detected through their phase curve modulations via a supervised machine learning approach by Millholland & Laughlin (2017). Adequate phase coverage was obtained for six of them. High-spatial resolution images and radial velocity monitoring with the CAFE and HERMES instruments was obtained, yielding planet confirmation for three of the candidates (KIC 8121913 b, KIC 10068024 b, and KIC 5479689 b) and adding credence to the planetary nature of the other three (KIC 5878307 b, KIC 11362225 b, and KIC 8026887 b). These follow-up observations highlight the potential of phase curve modulations as a detection technique for non-transiting planets.

We find KIC 10068024 b is a massive hot-Jupiter (\( M_p = 2.0 \pm 0.4 \ M_{\text{Jup}} \)) around a F8-G0 type star potentially in the early stages of the subgiant phase. KIC 5479689 b is found to be a sub-Jupiter-mass planet (\( M_p = 0.5^{+0.3}_{-0.2} \ M_{\text{Jup}} \)) orbiting with a 1.7 days orbital period around a main-sequence solar-like star. Finally, we find KIC 8121913 b is a Jupiter-mass planet with a RV-derived mass in the Jupiter regime (\( M_p = 2.1 \pm 0.4 \ M_{\text{Jup}} \)), in agreement with the beaming amplitude of the phase curve. However, in this case, we find a significant discrepancy with the ellipsoidal amplitude, which points toward a lower mass for this planet of \( M_p = 0.3^{+0.2}_{-0.1} \ M_{\text{Jup}} \). This discrepancy has already been reported in other systems with phase curve modulations, but its origin
remains unknown. Hence, KIC 8121913 b, and additional systems like it can help in the interpretation of this discrepancy and the physics behind it.

Additionally, our RV data suggests that the orbital period of the candidate planet in KIC 8026887 is actually twice the photometric period derived in Millholland & Laughlin (2017). Under such an assumption, our RV analysis provides a significant detection with a planet mass corresponding to a massive gaseous giant ($M_p \approx 4.0^{+0.7}_{-0.5} M_{Jup}$). However, because we cannot obtain a strong joint fit of both the light curve and RV data with the same orbital period, we do not consider this as a confirmed planet. Finally, we obtained an upper limit to the masses of the other two candidates of 8.5 $M_{Jup}$ (KIC 5878307 b) and 4.4 $M_{Jup}$ (KIC 11362225 b).

These hot Jupiters are not known to possess nearby planetary companions and are thus of less interest from the perspective of planetary orbital architectures. However, this phase curve detection technique offers the most promising approach for detecting hot Jupiters in multi-planet systems with mutually-inclined orbits (Millholland et al. 2016). Specifically, if we consider a hypothetical system with a known, transiting super-Earth/sub-Neptune on a $\geq 10$ day orbit, we can inspect the stellar light curve for photometric variations from a non-transiting hot Jupiter on an interior $\leq 5$ day orbit. As shown by Millholland et al. (2016), the detection of astrometrically induced transit-timing variations for the exterior transiting orbit may serve as an additional predictor for the existence of the potential non-transiting hot Jupiter. Systems containing a mutually-inclined hot Jupiter and exterior, small-mass planet are predicted to exist if some fraction of hot Jupiters form in situ (Batygin et al. 2016). The search for phase curve detections of non-transiting hot Jupiters (and the subsequent radial velocity monitoring) offers a means toward a direct test of this hypothesis.

The targets presented in this paper are the first non-transiting planets to be confirmed after initial detection of their full-phase photometric variations3. The photometric detection of non-transiting planets will continue to be relevant to exoplanet exploration as new space-based missions are launched. The Kepler mission provided several candidates in this regime and many more will come from TESS (Ricker et al. 2014) and the future PLATO mission (Rauer et al. 2014). Currently, the Cheops mission through one of its working packages is also focused on the study of phase curves through high-precision and high-cadence observations. The targets presented here, and especially KIC 8121913 b, offer excellent opportunities to probe hot Jupiter atmospheres and understand the possible discrepancies between RV-derived and photometric masses. Moreover, the method as a whole can be used as a test of theories of hot Jupiter formation, which is still one of the biggest open questions in the field of exoplanets today.

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3 We note that Faigler et al. (2013) first found Kepler-76 through phase curve modulations, but it was subsequently found to transit its host star.
Appendix A: Tables

Table A.1. Cross-correlation function properties for KIC5479689.

| JD             | RV (km/s) | eRV (km/s) | FWHM (km/s) | Inst. |
|----------------|-----------|------------|-------------|-------|
| 2458645.652628276 | 8.117     | 0.064      | 8.0         | CAFE  |
| 2458646.513237323 | 8.69      | 0.10       | 8.3         | CAFE  |
| 2458674.652914972 | 7.47      | 0.18       | 7.8         | CAFE  |
| 2458675.518614139 | 7.763     | 0.075      | 8.0         | CAFE  |
| 2458675.627853993 | 7.755     | 0.057      | 7.7         | CAFE  |
| 2458701.433922937 | 7.752     | 0.042      | 7.2         | CAFE  |
| 2458701.550056568 | 7.618     | 0.071      | 7.7         | CAFE  |
| 2459046.493358    | 7.747     | 0.018      | 7.1         | HERMES|
| 2459046.6134008   | 7.098     | 0.022      | 10.0        | HERMES|
| 2459049.6490909   | 6.998     | 0.019      | 6.5         | HERMES|
| 2459050.4994282   | 7.430     | 0.017      | 7.2         | HERMES|

Table A.2. Cross-correlation function properties for KIC5878307.

| JD             | RV (km/s) | eRV (km/s) | FWHM (km/s) | Inst. |
|----------------|-----------|------------|-------------|-------|
| 2458645.53556366 | -25.42    | 0.26       | 10.3        | CAFE  |
| 2458674.524131845 | -25.50    | 0.19       | 11.3        | CAFE  |

Table A.3. Cross-correlation function properties for KIC8026887.

| JD             | RV (km/s) | eRV (km/s) | FWHM (km/s) | Inst. |
|----------------|-----------|------------|-------------|-------|
| 2458645.611684904 | 9.320     | 0.090      | 9.2         | CAFE  |
| 2458646.451271749 | 9.289     | 0.096      | 6.4         | CAFE  |
| 2458674.611682581 | 8.54      | 0.11       | 9.2         | CAFE  |
| 2458675.47803279  | 8.786     | 0.049      | 9.1         | CAFE  |
| 2458675.585808265 | 8.248     | 0.086      | 9.1         | CAFE  |
| 2458701.511810438 | 8.07      | 0.12       | 8.5         | CAFE  |
| 2458701.686715424 | 7.84      | 0.28       | 8.2         | CAFE  |
| 2459047.5033592   | 8.552     | 0.022      | 7.2         | HERMES|
| 2459050.6230106   | 8.983     | 0.020      | 7.8         | HERMES|
### Table A.4. Cross-correlation function properties for KIC8121913.

| JD            | RV (km/s) | cRV (km/s) | FWHM (km/s) | Inst. |
|---------------|-----------|------------|-------------|-------|
| 2458645.450517782 | -23.483  | 0.075     | 11.5        | CAFE  |
| 2458646.412329766 | -23.359  | 0.064     | 9.7         | CAFE  |
| 2458674.442495487 | -22.996  | 0.040     | 11.0        | CAFE  |
| 2458675.439193288 | -23.460  | 0.046     | 10.6        | CAFE  |
| 2458675.547551508 | -22.940  | 0.043     | 10.6        | CAFE  |
| 2458701.396477561 | -23.354  | 0.043     | 10.9        | CAFE  |
| 2458617.59298275 | -23.098  | 0.044     | 10.8        | CAFE  |
| 2458617.54995345 | -22.850  | 0.042     | 10.8        | CAFE  |
| 2458618.558319524 | -23.032  | 0.035     | 11.3        | CAFE  |
| 2458618.631484145 | -23.159  | 0.037     | 11.2        | CAFE  |
| 2458626.556106488 | -23.161  | 0.046     | 11.0        | CAFE  |
| 2458626.57112051 | -23.336  | 0.080     | 10.9        | CAFE  |
| 2458627.631194962 | -22.944  | 0.094     | 11.3        | CAFE  |
| 2459024.455894218 | -23.007  | 0.048     | 10.9        | CAFE  |
| 2459024.583168107 | -23.411  | 0.062     | 10.5        | CAFE  |
| 2459025.468880206 | -23.193  | 0.043     | 10.7        | CAFE  |
| 2459025.586753734 | -23.311  | 0.043     | 11.2        | CAFE  |
| 2459046.4690974 | -23.263  | 0.014     | 11.1        | HERMES|
| 2459046.7003785 | -23.327  | 0.016     | 11.9        | HERMES|
| 2459047.5290948 | -22.968  | 0.013     | 11.2        | HERMES|
| 2459047.6427982 | -24.361  | 0.022     | 12.8        | HERMES|
| 2459049.4647511 | -23.142  | 0.015     | 11.7        | HERMES|
| 2459049.6083404 | -23.458  | 0.019     | 10.3        | HERMES|
| 2459050.4744119 | -23.703  | 0.015     | 11.7        | HERMES|
| 2459050.656347   | -23.407  | 0.014     | 13.4        | HERMES|

### Table A.5. Cross-correlation function properties for KIC10068024.

| JD            | RV (km/s) | cRV (km/s) | FWHM (km/s) | Inst. |
|---------------|-----------|------------|-------------|-------|
| 2458645.46993691 | -22.23   | 0.18       | 12.3        | CAFE  |
| 2458646.544204343 | -22.527  | 0.096      | 9.5         | CAFE  |
| 2458674.412376203 | -23.261  | 0.062      | 11.5        | CAFE  |
| 2458675.408493705 | -22.716  | 0.077      | 11.1        | CAFE  |
| 2458675.656267811 | -23.55   | 0.15       | 11.2        | CAFE  |
| 2458701.577313185 | -23.161  | 0.060      | 11.2        | CAFE  |
| 2458701.642292621 | -23.42   | 0.13       | 10.9        | CAFE  |
| 2458702.549648101 | -22.795  | 0.067      | 12.0        | CAFE  |
| 2459046.5195146 | -23.501  | 0.021      | 9.3         | HERMES|
| 2459047.5494006 | -23.952  | 0.024      | 13.1        | HERMES|
| 2459047.6733413 | -23.343  | 0.034      | 12.5        | HERMES|
| 2459049.5179242 | -24.418  | 0.026      | 8.7         | HERMES|
Table A.6. Cross-correlation function properties for KIC1362225.

| Parameter                  | Priors          | Posteriors          |
|---------------------------|-----------------|---------------------|
| Orbital period, \( P_b \) [days] | \( G(3.2943,0.0029) \) | 3.2944\(^{+0.0014}_{-0.0015} \) |
| Time of mid-transit, \( T_{0,b} \) - 2400000 [days] | \( G(56427.86897,0.001) \) | 56427.8689\(^{+0.010}_{-0.011} \) |
| RV semi-amplitude, \( \delta \) [m/s] | \( U(0.0,1000.0) \) | 252\(^{+53}_{-44} \) |
| \( \sigma_{CAFE2} \) [m/s] | \( U(-30.0,-20.0) \) | -23.172\(+0.035_{-0.035} \) |
| Planet mass, \( m_b \) sin \( i_b \) [\( M_\oplus \)] | (derived) | 780\(+170_{-160} \) |

Table A.7. Prior and posterior distributions for the analysis of CAFE radial velocities of KIC8121913 from Sect. 3.1.

| Parameter                  | Priors          | Posteriors          |
|---------------------------|-----------------|---------------------|
| Orbital period, \( P_b \) [days] | \( G(2.0735,0.0012) \) | 2.0735\(+0.0003_{-0.0004} \) |
| Time of mid-transit, \( T_{0,b} \) - 2400000 [days] | \( G(56424.26451,0.001) \) | 56424.2645\(+0.0001_{-0.0001} \) |
| RV semi-amplitude, \( \delta \) [m/s] | \( U(0.0,1000.0) \) | 344\(+91_{-89} \) |
| \( \sigma_{CAFE2} \) [m/s] | \( U(-27.0,-17.0) \) | -22.984\(+0.086_{-0.084} \) |
| Planet mass, \( m_b \) sin \( i_b \) [\( M_\oplus \)] | (derived) | 750\(+239_{-200} \) |

Table A.8. Prior and posterior distributions for the analysis of CAFE radial velocities of KIC10068024 from Sect. 3.1.

| Parameter                  | Priors          | Posteriors          |
|---------------------------|-----------------|---------------------|
| Orbital period, \( P_b \) [days] | \( G(1.7012,0.0008) \) | 1.70139\(+0.00045_{-0.00035} \) |
| Time of mid-transit, \( T_{0,b} \) - 2400000 [days] | \( G(56423.38036,0.001) \) | 56423.3802\(+0.0010_{-0.0009} \) |
| RV semi-amplitude, \( \delta \) [m/s] | \( U(0.0,1000.0) \) | 239\(+82_{-80} \) |
| \( \sigma_{CAFE2} \) [m/s] | \( U(-10.0,10.0) \) | -53\(+74_{-72} \) |
| Planet mass, \( m_b \) sin \( i_b \) [\( M_\oplus \)] | (derived) | 400\(+150_{-120} \) |

Table A.9. Prior and posterior distributions for the analysis of CAFE radial velocities of KIC5479689 from Sect. 3.1.

| Parameter                  | Priors          | Posteriors          |
|---------------------------|-----------------|---------------------|
| Orbital period, \( P_b \) [days] | \( G(3.8464,0.0009) \) | 3.8458\(+0.00029_{-0.00020} \) |
| Time of mid-transit, \( T_{0,b} \) - 2400000 [days] | \( G(56424.27252,0.001) \) | 56424.2726\(+0.0010_{-0.0010} \) |
| RV semi-amplitude, \( \delta \) [m/s] | \( U(0.0,1000.0) \) | 505\(+4.0_{-2.9} \) |
| \( \sigma_{CAFE2} \) [m/s] | \( U(0.0,20.0) \) | 8.78\(+1.1_{-0.9} \) |
| \( \sigma_{HERMES} \) [m/s] | \( U(0.0,3.0) \) | 243\(+9_{-10} \) |
| Planet mass, \( m_b \) sin \( i_b \) [\( M_\oplus \)] | (derived) | 1270\(+290_{-270} \) |
Table A.11. Prior and posterior distributions for the analysis of CAFE radial velocities of KIC11362225 from Sect. 3.1.

| Parameter | Priors | Posteriors |
|-----------|--------|------------|
| Orbital period, $P_b$ [days] | $G(2.7513,0.0021)$ | $2.7512_{-0.0017}^{+0.0025}$ |
| Time of mid-transit, $T_{0b} - 2400000$ [days] | $G(56423.94574,0.001)$ | $56423.9458_{-0.0011}^{+0.0010}$ |
| RV semi-amplitude, $K_b$ [m/s] | $U(0.0,1000.0)$ | $(170_{-120}^{+140})$ |
| $\delta_{\text{CAFE2}}$ [km/s] | $U(-27.0,-15.0)$ | $-19.27_{-1.14}^{+0.15}$ |
| $\sigma_{\text{CAFE2}}$ [m/s] | $U(0.0,0.3)$ | $99_{-68}^{+110}$ |
| Planet mass, $m_b \sin i_b$ [M$_\oplus$] | (derived) | $310_{-360}^{+320}$ |

Table A.12. Prior and posterior distributions for the analysis of CAFE radial velocities of KIC5878307 from Sect. 3.1.

| Parameter | Priors | Posteriors |
|-----------|--------|------------|
| Orbital period, $P_b$ [days] | $G(2.0466,0.0013)$ | $2.0465_{-0.0012}^{+0.0013}$ |
| Time of mid-transit, $T_{0b} - 2400000$ [days] | $G(56424.92085,0.1)$ | $56424.923_{-0.098}^{+0.099}$ |
| RV semi-amplitude, $K_b$ [m/s] | $U(0.0,1000.0)$ | $370_{-260}^{+290}$ |
| $\delta_{\text{CAFE2}}$ [km/s] | $U(-26.0,-24.0)$ | $-25.42_{-0.33}^{+0.37}$ |
| $\sigma_{\text{CAFE2}}$ [m/s] | $U(0.0,0.3)$ | $134_{-35}^{+110}$ |
| Planet mass, $m_b \sin i_b$ [M$_\oplus$] | (derived) | $690_{-480}^{+660}$ |
Appendix B: Posterior distributions from the joint radial velocity and light curve fit

Fig. B.1. Corner plot of the joint posterior parameter distributions for KIC 8121913.
Fig. B.2. Corner plot of the joint posterior parameter distributions for KIC 10068024.
Fig. B.3. Corner plot of the joint posterior parameter distributions for KIC 5479689.