An 8 $M_\oplus$ super-Earth in a 2.2 day orbit around the K5V star K2-216


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Received 21 February 2018; accepted xx xx xxxx

ABSTRACT

Context. Although thousands of exoplanets have been discovered to date, far less have been fully characterised, in particular super-Earths. The KeplerSprint consortium identified K2-216 as a planetary candidate host star in the K2 space mission Campaign 8 field with a transiting super-Earth. The planet was also recently validated by Mayo et al. (2018). Our aim was to confirm the detection and to derive the main physical characteristics of K2-216b, including the mass.

Aims. We performed a series of follow-up observations: high resolution imaging with the FastCam camera at the TCS, the Infrared Camera and Spectrograph at Subaru, and high resolution spectroscopy with HARPS (ESO, La Silla), HARPS-N (TNG) and FIES (NOT). The stellar spectra were analysed with the SpecMatch-Emp codes to derive the stellar fundamental properties. We set” technique to simultaneously model the planetary signal and the correlated noise associated with stellar activity.

Methods. We performed a series of follow-up observations: high resolution imaging with the FastCam camera at the TCS, the Infrared Camera and Spectrograph at Subaru, and high resolution spectroscopy with HARPS (ESO, La Silla), HARPS-N (TNG) and FIES (NOT). The stellar spectra were analysed with the SpecMatch-Emp and SBE codes to derive the stellar fundamental properties. We analysed the K2 light curve with the Pyraet software. The radial-velocity measurements were modelled with both a Gaussian process regression and the “floating chunk offset” technique to simultaneously model the planetary signal and the correlated noise associated with stellar activity.

Results. Imaging confirms that K2-216 is a single star. Our analysis discloses that the star is a moderately active K5V star of mass $M_\star \approx 0.70 \pm 0.03 M_\odot$ and radius $R_\star \approx 0.72 \pm 0.05 R_\odot$. Planet b is found to have a radius of $1.8^{+0.2}_{-0.1} R_\oplus$ and a 2.17 day orbit. These values are in agreement with those of Mayo et al. (2018). We find consistent results for the planet mass from both models: $M_b \approx 7.4^{+2.2}_{-2.1} M_\oplus$ from the Gaussian process regression, and $M_b \approx 7.9^{+1.6}_{-1.5} M_\oplus$ from the “floating chunk offset” technique which implies that this planet is a super-Earth. The incident stellar flux is $247^{+52}_{-42} F_\odot$. The incident stellar flux is $247^{+52}_{-42} F_\odot$. Conclusion. The planet parameters put planet b in the middle of, or just below, the gap of the radius distribution of small planets. The density is consistent with a rocky composition of primarily iron and magnesium silicate. In agreement with theoretical predictions, we find that the planet is a remnant core, stripped of its atmosphere, and is one of the largest planets found that have lost its atmosphere.

Key words. Planetary systems – Stars:individual: K2-216 – Techniques: photometric – Techniques: radial velocity

1. Introduction

The NASA K2 mission (Howell et al. 2014) is continuing the success of the Kepler space mission by targeting stars in the...
ecliptic plane through high precision time-series photometry. Thousands of *Kepler/K2* exoplanet candidates have been discovered to date, and hundreds have been confirmed and characterised. One of the surprises was the vast diversity of planets, in particular planets with radii between Earth and Neptune (3.9 $R_{\oplus}$), with no counterparts in our solar system. Short-period super-Earth planets, $R_p \sim 1 - 1.75 \, R_{\oplus}$ (Lopez & Fortney 2014; Fulton et al. 2017) have been found to be very common based on planet occurrence rates and planet candidates discovered by *Kepler* (Burke et al. 2015), although the number of well characterised super-Earths is still low. Only a few dozen have both measured radius and mass as of January 2018, and hence the composition and internal structure for the remaining super-Earths are unknown.

A bimodal radius distribution of small exoplanets at short orbital period was discovered by Fulton et al. (2017) using spectroscopic stellar parameters, and by Van Eylen et al. (2017) using asteroseismic stellar parameters. These findings show that very few planets at $P < 100$ days have sizes between 1.5 and 2 $R_{\oplus}$. The gap is predicted by photo-evaporation models (Lopez & Fortney 2013; Owen & Wu 2013; Jin et al. 2014; Lopez & Fortney 2014; Chen & Rogers 2016; Owen & Wu 2017; Jin & Mordasini 2018), in which close-in planets ($a < 0.1 \, AU$) can lose their entire atmosphere within a few hundred Myr due to intense stellar radiation. The mini-Neptunes and super-Earths thus appear to be two distinct classes with radii of $\sim 2.5 \, R_{\oplus}$, and $\sim 1.5 \, R_{\oplus}$, respectively. These predictions, however, need to be tested against well characterised planets.

The work described in this paper is part of a larger programme performed by the international KESPRINT consortium[1] which combine *K2* photometry with ground based follow-up observations in order to confirm and characterise exoplanetary candidates (e.g. Guenther et al. 2017; Nowak et al. 2017; Niraula et al. 2017; Livingston et al. 2018; Hirano et al. 2017; Eigmüller et al. 2017; Smith et al. 2018). When processing the *K2* Campaign 8 light curves, we found a super-Earth candidate around K2-216 for which we proceeded with follow-up observations and characterisation described in this paper. During our work, planet b was recently validated by Mayo et al. (2018). In this paper, we confirm the planet and derive the previously unknown mass from radial velocity measurements.

The *K2* photometry and transit detection are presented in Sect. 2. The ground based follow-up observations, high resolution imaging and high resolution spectroscopy, are presented in Sect. 3. We analyse the star in Sect. 4 in order to obtain the necessary stellar mass and radius for the transit analysis performed in Sect. 5 and RV analysis in Sect. 6. We end the paper with a discussion and summary in Sect. 7 and 8, respectively.

### 2. K2 photometry and transit detection

Observations of the *K2* Field 8 took place from January 4 to March 23, 2016. The telescope was pointed at the coordinates $\alpha = 01^h05^m21^s$ and $\delta = +05^\circ15'44''$ (J2000). A total of 24 187 long-cadence (29.4 min integration time), and 55 short-cadence (1 min integration time) targets were observed.

We downloaded the *K2* Campaign 8 data from the Mikulski Archive for Space Telescopes[3] (MAST). For the detection of transiting candidates, we searched the data using three different methods, optimised for space-based photometry: (i) the EXOTRANS (Grziwa et al. 2012) routines, (ii) the Détecton Spéciálise de Transits (DST) software (Cabrera et al. 2012), and (iii) a method similar to that described by Vanderburg & Johnson (2014a). The codes have been used extensively on CoRoT, Kepler and other *K2* campaigns. The strategy of using different software has been shown to be successful, since both the false alarm and non-detections are model dependent.

EXOTRANS and DST were applied to the pre-processed light curves by Vanderburg & Johnson (2014b). EXOTRANS is built on a combination of the wavelet-based filter technique VARLET (Grziwa & Pizzold 2016) and a modified version of the BLS (Box-fitting Least Squares; Kovács et al. 2002) algorithm to detect the most significant transit. When a significant transit is detected, the Advanced BLS removes a detected transit using a second wavelet based filter routine, PHALET. This routine combines phase-folding and wavelet based approximation to remove and periodic features in light curves. After removing a detected transit, the light curve is searched again for additional transits. This process is repeated fifteen times to detect multiplanet systems. Since the detected features are completely removed, transits near resonant orbits are easily found. DST aims at a specialised detection of transits by improving the consideration of the transit shape and the presence of transit timing variations. The same number of free parameters as BLS are used, and the code implements better statistics with a signal detection. In the third method, described in more detail by Dai et al. (2016) and Livingston et al. (2018), we extracted aperture photometry for the...
BLS

The transit detection routine utilises the standard BLS routine, and an optimal frequency sampling (Ofir 2014).

A shallow transit signal was discovered by all three methods in the light curve of K2-216 (EPIC 220481411) with a period of ~2.2 days and a depth of ~0.05% consistent with a super-Earth orbiting a K5V star. We searched for even-odd transit depth variation and secondary eclipse which would point to a binary scenario, but none were detected within 1σ. K2-216 was proposed by programme GO8042 and observed in the long-cadence mode. The basic parameters of the star are listed in Table 1. The full pre-processed light curve by Vanderburg & Johnson (2014) is shown in Fig. 1, where 36 clear transits are marked with dotted vertical lines.

3. Ground based follow-up

Follow-up observations were performed in order to determine whether the signal is from a planet, and to obtain further information on the planet properties. High resolution imaging was used to check if the transit is a false positive from a fainter unresolved binary included in the K2 sky-projected pixel size of ~4″ (Sect. 3.2). The presence of a binary can lead to an erroneous radius of the transiting object, which propagates into the density which is important for distinguishing between rocky planets and those with an envelope (mini-Neptunes). The binary can be either an unrelated background system or a companion to the primary star. The planetary nature of the transit was then confirmed by our high-resolution radial velocity (RV) measurements described in Sect. 3.4, which also allows a measure of its mass (Sect. 6). This data was in addition used to derive stellar fundamental parameters using spectral analysis codes (Sect. 4).

3.1. FastCam imaging and data reduction

We performed Lucky Imaging (LI) of K2-216 with the FastCam camera Oscoz et al. (2008) at 1.55-m Telescoop Carlos Sánchez (TCS). FastCam is a very low noise and fast read-out speed EMCCD camera with 512 × 512 pixels, a physical pixel size of 16 microns, and a FoV of 21.2″ × 21.2″. On the night of September 6 (UT), 2016, 10,000 individual frames of K2-216 were collected in the Johnson-Cousins infrared I-band (880 nm), with an exposure time of 50 ms for each frame. The typical Strehl ratio in our observation varies with the percentage of the best-quality frames chosen in the reduction process: from 0.05 for the 90% to 0.10 for the 1%. In order to construct a high resolution, long-exposure image, each individual frame was bias-subtracted, aligned and co-added and then processed with the FastCam dedicated software developed at the Universidad Politécnica de Cartagena (Labadie et al. 2010; Fodor et al. 2013). The inset in Fig. 2a shows a high resolution image, which was constructed by co-addition of the 30% best images, with a 150 s total exposure time. Figure 2a also draws the 5σ contrast curve, which quantitatively describe the detection limits of nearby possible companions, computed based on the scatter within the annulus as a function of angular separation from the target centroid (Cortés-Contreras et al. 2017). As shown by the contrast curve, no bright companion was detectable within 8″. Between 2″ and 8″ separation we can exclude companions brighter than ~7 × 10⁻³ than K2-216.

3.2. Subaru/IRCS AO imaging and data reduction

In order to further check for possible unresolved eclipsing binaries mimicking planetary transits, we imaged K2-216 with the Infrared Camera and Spectrograph (IRCS; Kobayashi et al. 2000) with the adaptive-optics (AO) system (Hayano et al. 2010) on the Subaru 8.2-m telescope producing diffraction limited images in the 2~5 μm range.

The high resolution mode was selected at a pixel scale of 0.0206″ per pixel, and a field-of-view of 21″×21″. Adopting K2-216 itself as a natural guide star, we performed AO imaging on Nov 6, 2016 in the H-band (1630 nm) with two different exposures. The first sequence consists of a short exposure (0.4 s × 3 co-additions) with the five-point dithering to obtain unsaturated target images for the absolute flux calibration. We then repeated longer exposures (5 s × 3 co-additions) with the same five-point dithering, for saturated images to look for faint nearby companions. The total scientific exposure time amounted to 225 s. We reduced the IRCS AO data following Hirano et al. (2016); we applied the dark subtraction, flat-fielding, distortion correction, and aligned the frames which were subsequently...
Fig. 2: (a) I-band magnitude 5-σ contrast curve as a function of angular separation up to 8.0′′ from K2-216 obtained with the FastCam camera at TCS. The inset shows the 8.0′′ × 8.0′′ image. (b) H-band (1630 nm) 5-σ magnitude contrast curve as a function of angular separation from K2-216 obtained with IRCS/Subaru. The inset displays the 4′′ × 4′′ saturated image. (c) Reconstructed images in the r- and z-narrow bands from NESSI/WIYN speckle interferometry and the resulting 5σ contrast curves. The inset images are 1.2′′ × 1.2′′. Northeast is up and to the left.

We found that the FWHM of K2-216 is 0″096, as measured from the combined unsaturated image. The inset of Fig. 2b displays the combined saturated image with a field-of-view of 4″×4″. To estimate the contrast achieved by the IRCS imaging, we convolved the combined saturated image with the target’s FWHM and computed the scatter within the small annulus centred at the centroid of the target. The 5-σ contrast curve as a function of angular separation from the target is also drawn in Fig. 2b. No bright nearby sources were found around K2-216. For instance, the contrast curve shows that at a separation of 0.5″ (1.0′′), companions brighter than Δm_H = 5 mag (<7.5 mag) would have been detected with >5σ. Thus we can exclude companions brighter than 1×10⁻⁵ of the target star at a separation of 1″.

3.3. NESSI imaging

For comparison with our FastCam and IRCS imaging, we also show speckle imaging of K2-216 performed with the NASA Exoplanet Star and Speckle Imager (NESSI; Scott et al. 2016 in prep.) at the WIYN 3.5-m telescope. The images were retrieved from ExoFOP (with the observers permission). The contrast curves based on the same data were also used in Mayo et al. (2018) in their FFP calculation. The observations were conducted at 562 nm (r-narrow band) and 832 nm (z-narrow band) simultaneously on Nov 14, 2016. The data were collected and reduced following the procedures described by Howell et al. (2011). The resulting reconstructed images of the host star are 4.6″ × 4.6″, with a resolution close to the diffraction limit of the telescope (0.040″ at 562 nm and 0.060″ at 832 nm). No secondary sources were detected in the reconstructed images. 5σ detection limits were produced from the reconstructed images using a series of concentric annuli as shown up to 1.2″ in Fig. 2c.

3.4. High resolution spectroscopy

We performed high resolution spectroscopy to obtain radial velocity (RV) measurements using three different instruments: FIES, HARPS, and HARPS-N.

**FIES**: We started the RV follow-up of K2-216 with the Fibre-fed Échelle Spectrograph (FIES; Frandsen & Lindberg 1999; Telting et al. 2014) mounted at the 2.56-m Nordic Optical Telescope (NOT) of Roque de los Muchachos Observatory (La Palma, Spain). Eight high-resolution spectra (R ≈ 67 000) were gathered between Sept and Nov 2016, as part of our K2 follow-up programmes 53-016, 54-027, and 54-211. To account for the RV shift caused by the replacement of the charge-coupled device (CCD) which occurred on 30 Sept 2016, we treated the spectra taken in Sept 2016 and those acquired in Oct–Nov 2016 as two independent data-sets. We set the exposure time to 3600 s and followed the same observing strategy described in Gandolfi et al. (2013) and Gandolfi et al. (2015), i.e., we traced the RV drift of the instrument by bracketing the science exposures with long-exposed ThAr spectra. The data reduction was performed using standard IRAF and IDL routines, which include bias subtraction, flat fielding, order tracing and extraction, and wavelength calibration. Radial velocities were extracted via multi-order cross-correlations using the stellar spectrum (one per CCD) with the highest signal-to-noise ratio (S/N) as a template.

**HARPS** and **HARPS-N** are fiber-fed cross-dispersed high-precision échelle spectrographs (R ≈ 115 000), designed to achieve a very high precision and long-term RV measurements. We gathered 9 spectra with the HARPS spectrograph (Mayor et al. 2003) mounted at the ESO 3.6-m telescope of La Silla observatory (Chile), between Oct 2016 and Nov 2017, as part of the observing programmes 099.C-0491 and 0100.C-0808. We also collected 13 spectra with the HARPS-N spectrograph (Cosentino et al. 2012) attached at the Telescopio Nazionale Galileo (TNG) of Roque de los Muchachos Observatory (La Palma, Spain), between Oct 2016 and Jan 2018, during the observing programmes CAT16B_61, CAT17A_91, A36TAC_12, and OPT17B_59. We reduced the data using the dedicated offline HARPS and HARPS-N pipelines and extracted the RVs via cross-correlation with a K5 numerical mask (Baranne et al. 1996; Pepe et al. 2002). The pipeline provides also the bisection inverse slope (BIS) and full-width at half maximum (FWHM) of
In order to derive the stellar fundamental parameters as input (used several different methods which requires stellar fundamental parameters as input ($T_{\text{eff}}$, $[\text{Fe/H}]$, $\log g_\star$, $\rho_\star$, and distance).

4. Stellar analysis

The stellar mass and radius needed for the transit and RV analyses can be determined in several ways. In this paper we have used several different methods which requires stellar fundamental parameters as input ($T_{\text{eff}}$, $[\text{Fe/H}]$, $\log g_\star$, $\rho_\star$, and distance).

4.1. Spectral analysis

In order to derive the stellar fundamental parameters $T_{\text{eff}}$, $\log g_\star$, and $[\text{Fe/H}]$, we analysed the co-added HARPS-N (S/N = 89) and HARPS (S/N = 94) spectra with the spectral analysis package Spectroscopy Made Easy (SME, Valenti & Fischer 2005). Utilising grids of stellar atmosphere models, based on pre-calculated 1D/3D, LTE or non-LTE models, SME calculates, for a set of given stellar parameters, synthetic spectra of stars and fits them to observed spectra using a χ²-minimising procedure. We used the non-LTE SME version 5.2.2, and the ATLAS 12 model spectra (Kurucz 2013) to fit spectral features sensitive to different photospheric parameters. We follow the procedure in Fridlund et al. (2017). In summary, we used the profile of the line wings of the Hα and Hγ lines to determine the effective temperature, $T_{\text{eff}}$ (Fuhrmann et al. 1993; Valenti & Fischer 2005). The core lines were excluded due to its origin in layers above the photosphere. The stellar surface gravity, $\log g_\star$, was estimated from the line wings of the Ca i λ6102, 6122, 6162 triplet, and the Ca i λ6439 line. The Mg i λ5576, 6191, 6182 triplet, which can also be used to determine $\log g_\star$, was not used due to problems with the density of metal lines contaminating the shape of the wings of the Mg lines. The microturbulent velocity, $V_{\text{mic}}$, and the macroturbulent velocity, $V_{\text{mac}}$, were fixed to 0.5 and 1 km s⁻¹, respectively. Doyle et al. (2014) and Grassitelli et al. (2015). The projected stellar rotational velocity, $V \sin i$, and the metal abundances $[\text{Fe/H}]$ and $[\text{Ca/H}]$ (needed for the log $g_\star$ modelling) were estimated by fitting the profile of several clean and unblended metal lines between 6100 and 6500 Å. The model was also in agreement with the Na doublet λ5889 and 5896, which showed no signs of interstellar absorption. The results are listed in Table 2. Note that the spectral type of the star is at the lower end for accurate modelling with SME due to the weak line wings of the hydrogen and calcium lines, the large amount of metal lines interfering with the line profiles, the low S/N due to the faintness of the star, and the uncertainties of model atmospheres of cool stars below ~4500 K.

In addition to the SME modelling, we have therefore also used the SpecMatch-Emp code (Yee et al. 2017). This code is an algorithm for characterising the properties of stars based on their optical spectra. The observed spectra are compared to a dense spectral library of 404 well-characterised stars (M5 to F1) observed by Keck/HIRES with high-resolution ($R \sim 50 000$) and high signal-to-noise ($> 100$). Since the code relies on empirical spectra it performs particularly well for stars ~K4 and later which are difficult to model with spectral synthesis models such as SME. However, in extreme cases, such as extremely metal poor/rich stars, the code could fail since the library includes very few such stars in each temperature bin. SpecMatch-Emp directly yields stellar radius rather than the surface gravity since the library stars typically have their radii calibrated using interferometry and other techniques. The direct output is thus $T_{\text{eff}}$, $R_\star$, and $[\text{Fe/H}]$. Note that since HARPS suffers from a wavelength gap around 5320 Å due to the spectrum being recorded on two separate CCD chips, the HARPS-N results should be more accurate. Following Hirano et al. (2018), prior to the analysis we convert the co-added HARPS and HARPS-N spectra into the format of Keck/HIRES spectra which is used by SpecMatch-Emp. In doing so, we made certain that the edges of neighbouring échelle orders overlapped in wavelength. For the HARPS spectra, the gap region was replaced with a slowly varying polynomial function with each flux relative error being 100%. The validity of analysing spectroscopic data from HARPS, HARPS-N, NOT/FIES, and Subaru/HDS with SpecMatch-Emp has been tested by Hirano et al. (2018). The SpecMatch-Emp results and literature values agree with each other for $T_{\text{eff}}$ and radii mostly within 1σ. The $[\text{Fe/H}]$ values sometimes show a moderate disagreement, but are basically consistent within 2σ. The results are listed in Table 2 and 3.

The effective temperatures derived with SME and SpecMatch-Emp HARPS-N are in excellent agreement. The metallicities are in agreement within 1σ. Since the results are in such good agreement, and since we have no clear motivation of preferring one model over the other despite their respective possible issues, we have adopted an average
Table 3: Stellar mass and radius of K2-216 as derived from different methods. Typical values for a KSV star are listed as comparison.

<table>
<thead>
<tr>
<th>Method</th>
<th>$M_\ast$ (M$_\odot$)</th>
<th>$R_\ast$ (R$_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaia</td>
<td>...</td>
<td>0.72 ± 0.05</td>
</tr>
<tr>
<td>SpecMatch–Emp/Torres</td>
<td>0.70 ± 0.03</td>
<td>0.71 ± 0.07</td>
</tr>
<tr>
<td>PARAM 1.3</td>
<td>0.71 ± 0.02</td>
<td>0.66 ± 0.02</td>
</tr>
<tr>
<td>Southworth</td>
<td>0.70 ± 0.03</td>
<td>0.67 ± 0.03</td>
</tr>
<tr>
<td>BASTA</td>
<td>0.70 ± 0.03</td>
<td>0.65 ± 0.02</td>
</tr>
<tr>
<td>Spectral type K5V</td>
<td>0.71</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Notes. (a) Radius calculated from Gaia parallax, our modelled $T_{\text{eff}}$, and apparent visual magnitude. (b) Coupling the SpecMatch–Emp HARPS-N modelling with the calibration equations from Torres et al. (2010). (c) Direct result from SpecMatch–Emp. (d) Southworth (2011) calibration equations.

Table 4: Adopted stellar parameters of K2-216.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>K2-216</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective temperature$^a$ $T_{\text{eff}}$ (K) . . . . . .</td>
<td>4 503 ± 140</td>
</tr>
<tr>
<td>Surface gravity$^b$ log($g_\ast$) (cgs) . . . . . . . . . . . . . .</td>
<td>4.57 ± 0.09</td>
</tr>
<tr>
<td>Density$^c$ $\rho_\ast$ (g/cm$^3$) . . . . . . . . . . . . . . . . . .</td>
<td>2.3$^{+1.8}_{-0.8}$</td>
</tr>
<tr>
<td>[Fe/H]$^b$ (dex) . . . . . . . . . . . . . . . . . . . . . . . . . . . .</td>
<td>0.00 ± 0.12</td>
</tr>
<tr>
<td>Rotational velocity$^d$ $V \sin i$ (km s$^{-1}$) . . . . . . . . .</td>
<td>2.0 ± 1.0</td>
</tr>
<tr>
<td>Mass $M_\ast$ (M$_\odot$) . . . . . . . . . . . . . . . . . . . . . .</td>
<td>0.70 ± 0.03</td>
</tr>
<tr>
<td>Radius $R_\ast$ (R$_\odot$) . . . . . . . . . . . . . . . . . . . . .</td>
<td>0.72 ± 0.05</td>
</tr>
<tr>
<td>Luminosity $L_\ast$ (L$_\odot$) . . . . . . . . . . . . . . . . . .</td>
<td>0.19 ± 0.01</td>
</tr>
<tr>
<td>Spectral type . . . . . . . . . . . . . . . . . . . . . . . . . . . .</td>
<td>K5V</td>
</tr>
<tr>
<td>Rotation period (days) . . . . . . . . . . . . . . . . . . . . . . . .</td>
<td>30 ± 5</td>
</tr>
</tbody>
</table>

Notes. (a) Average from SME HARPS and HARPS-N, and SpecMatch–Emp HARPS-N. (b) SpecMatch–Emp HARPS-N (same value as when calculated from the adopted mass and radius). (c) Derived from transit modelling. (d) Average from SME HARPS and HARPS-N. (e) SpecMatch–Emp/Torres, Southworth (2011), and BASTA. (f) Calculation based on the Gaia DR2 parallax.

The stellar mass must be modelled and this is done with four different methods. (These models also produce a stellar radius, which is, however, only used as a comparison with the radius derived above.) Coupling the SpecMatch–Emp modelling with the Torres et al. (2010) calibration equations, we find a stellar mass, surface gravity, and density of 0.70 ± 0.03 M$_\odot$, log $g_\ast$ = 4.57±0.09 (cgs), and 2.1 ± 0.6 g cm$^{-3}$, respectively. The Torres equations were calibrated with 95 eclipsing binaries where the masses and radii were known to better than 3 %. The log $g_\ast$ is in agreement with the PARAM 1.3 result below and with Mayo et al. (2018), but higher than obtained with SME, although still within the rather large uncertainties. The stellar density is in agreement with the density found from transit modelling.

4.2. Stellar mass and radius

We calculated the stellar radius by combining the distance obtained from the Gaia DR2$^6$ parallax (8.6325 ± 0.0525 mas corresponding to a distance of 115.8 ± 0.7 pc) with our spectroscopically derived $T_{\text{eff}}$ and the apparent visual magnitude. We first calculated the luminosity from the relations $M_{\text{bol}} = V - 5 \times \log_{10}(g) + 5 + A_V + BCv$ and $M_{\text{bol}} = -2.5 \times \log_{10}(L/L_\odot) + M_{\text{bol,}\odot}$, where $M_{\text{bol}}$ is the absolute bolometric magnitude, $BCv$ is the bolometric correction function of $-0.62 ± 0.05$ (Cox 2000), $A_V$ is the visual extinction here assumed to be zero given the proximity of K2-216, and $M_{\text{bol,}\odot} = -5.25$...

$^6$ http://gea.esac.esa.int/archive/

$^7$ http://stev.oapd.inaf.it/cgi-bin/param_1.3
Normalised flux (cgs), and an age of 5.0 ± 4.1 Gyr. A mass and radius was also estimated with the Southworth (2011) calibration equations built on the basis of 90 detached eclipsing binaries with masses up to 3 M_⊙. The advantage with this model is that the input parameters are the stellar density (derived from transit modelling), together with the spectroscopically derived T_eff and [Fe/H]. We find a stellar mass of 0.70 ± 0.03 M_⊙ and a radius of 0.67 ± 0.03 R_⊙. Finally, we used the Bayesian Stellar Algorithm (BASTA; Silva Aguirre et al. 2015). BASTA uses a Bayesian approach to isochrone grid-modelling and fits observables to a grid of BaSTi isochrones (Pietrinferni et al. 2004). We fit spectroscopic (T_eff, log g, [Fe/H]) and photometric (ρ) constraints and find a stellar mass and radius of 0.70 ± 0.03 M_⊙ and 0.65 ± 0.02 R_⊙, respectively, and an age of 8.2^{+4.8}_{−3.3} Gyr.

All estimates of the stellar mass are in very good agreement and are listed in Table 3, along with a typical mass and radius for a K5V star for comparison. We choose to adopt a value of 0.70 ± 0.03 M_⊙ since three of the models give this stellar mass, and the fourth (PARAM 1.3) only slightly higher. This mass is also in excellent agreement with Mayo et al. (2018). All final adopted stellar parameters are listed in Table 4.

### 4.3. Stellar activity and rotation period

Before analysing the RV measurements, we need to check whether they are affected by stellar activity. Photometric variability in solar-like stars can be caused by stellar activity, such as spots and plages, on timescale comparable to the rotation period of the star. The presence of active regions coupled to stellar rotation distorts the spectral line profile, inducing periodic and quasi-periodic apparent RV variation, which is commonly referred to as “RV jitter”.

The presence of active regions hamper our capability of detecting small planets using the RV method. This is because the expected RV wobble induced by small planets is of the same order of magnitude, or even smaller, than the activity-induced jitter. Nevertheless, if the orbital period of a planet is much smaller than the activity period of the star, then the correlated noise due to stellar rotation can easily be distinguished from the planet-induced RV signal (Hatzes et al. 2011). An inspection of the K2 light curve shows, quasi-periodic photometric variations with a typical peak-to-peak amplitude of about ~ 0.4−0.5 %. Given the spectral type of the star, the variability is very likely associated to the presence of spots on the photosphere of the star, combined with stellar rotation and/or its harmonics. The light curve shows also that spots evolve with a time-scale that is comparable to the duration of the K2 observations (about 80 days).

Inspecting the Ca II H & K lines in the HARPS-N spectrum, we find that both lines are seen in emission as shown in Fig. 3. We measure an average Ca II chromospheric activity index, log (R′_HK) in Table A.1 (appendix A), of ~4.668 ± 0.059 and ~4.658 ± 0.069 from HARPS and HARPS-N, respectively, indicating that the star is moderately active.

Using the code SOAP2.1 (Dumusque et al. 2014) and adopting the stellar parameters reported in Table A.1 (appendix A), an average peak-to-peak variation of 0.45 %, the same limb darkening coefficients used in the transit modelling in Sect. 5 and modelling two starspots with a size relative to the star of about 0.07, we found that the expected RV jitter is ~ 4 m s^{-1}.

The upper panel of Fig. B.1 (appendix B) displays the generalized Lomb-Scargle (GLS; Zechmeister & Kürster 2009) periodogram of the K2 light curve of K2-216. Prior to computing the periodogram, we removed the transit signals using the best-fitting transit model derived in Sect. 5 and subtracted and a linear fit to the K2 data to remove the flux drift often observed across many K2 stars, which is likely caused by slow changes in the spacecraft orientation and/or temperature. The remaining panels of Fig. B.1 show the GLS periodograms of the RV, BIS, FWHM, and log (R′_HK) extracted from the HARPS and HARPS-N data, which were first combined by subtracting the corresponding means of each instrument’s data sets. The false-alarm probability (FAP) were determined following the bootstrap technique described in Kuerster et al. (1997). The periodogram of the K2 light curve displays a very significant peak (FAP > 1) at 30 ± 5 days (vertical dashed blue line in Fig. B.1), which we interpreted as being the rotation period of the star (P_rot). Assuming that the star is seen equator-on, this value is within the limits obtained from the stellar radius and the spectroscopically-derived projected rotational velocity V sin i. We found that P_rot ≈ 2πR⋆/V should be between 11 and 39 days, including the uncertainties on V sin i and R_⋆.

The dashed vertical red line in Fig. B.1 marks the orbital frequency of the transiting planet, whereas the horizontal lines represent the 1 % FAP. The periodogram of the RV measurements displays a peak at the orbital frequency of the transiting planet.

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8 The presence of active regions at different longitudes can induce photometric signals at rotation period harmonics.

9 http://www.astro.up.pt/resources/soap2/
with a FAP of about 2 %, which has no counterparts in the peri-
odograms of the activity indicators, suggesting that this signal is in-
duced by the transiting planet. We note that presence of peaks in
periodogram of the BIS and FWHM whose frequencies are
close to the rotation frequency of the star.

5. Transit modelling

We used the orbital period, mid-transit time, transit depth and
transit duration identified by EXOTRANS as input values for more
detailed transit modelling by the software pyaneti (Barragán
et al. 2017a), also used in e.g. Barragán et al. (2016), Gand-
dolfi et al. (2017), and Fridlund et al. (2017). Pyaneti is a
PYTHON/FORTRAN software that infers planet parameters us-
ing Markov chain Monte Carlo (MCMC) methods based on
Bayesian analysis.

Pyaneti allows a joint modelling of the transit and ra-
dial velocity data. Stellar activity can, however, only be mod-
elled in pyaneti as a coherent signal, not changing in time or
phase, which is only possible when the RV observational sea-
son is small compared to the evolution time-scale of active re-
geons (e.g. Barragán et al. 2017b). Since this is not the case for
K2-216 where the observations extend over 440 days, we only
used pyaneti to model the transit data.

In order to prepare the light curve for pyaneti and to re-
duce the amplitude of any long-term systematic or instrumen-
tal flux variations, we used the exotrending (Barragán & Gan-
dolfi 2017) code to detrend the Vanderburgh transit light curve
(Fig. 1) by fitting a second order polynomial to the out-of-transit
data. Input to the code is the mid-time of first transit, \( T_0 \) and
orbital period, \( P_{\text{orb}} \). Three hours around each of the 36 transits
was masked in order to ensure that no in-transit data were used
in the detrending process.

We follow the procedure in Barragán et al. (2015) for the
pyaneti transit modelling. For the mid-time of first transit
(\( T_0 \)), the orbital period, \( P_{\text{orb}} \), the scaled orbital distance (\( a/R_\ast \)),
the planet-to-star radius ratio (\( R_\text{p}/R_\ast \)), and the impact param-
eter (\( b \equiv \cos(i)/R_\ast \)), we set uniform priors meaning that we
adopted rectangular distributions over given ranges of the par-
meter spaces. \( T_0 \) is measured relatively precise compared to
the cadence of the light curve, and \( P \) is measured very pre-
cise because of the large number of transits (36), and the ab-
scence of measurable transit timing variations. The ranges are
thus \( T_0 = [7394.03887, 7394.05887] \) (BJD TDB- 2454833) days,
\( P = [2.17249, 2.17649] \) days, \( a/R_\ast = [1.1, 1.0] \), \( b = [0, 1] \),
\( R_\text{p}/R_\ast = [0, 0.1] \). Circular orbit was assumed, hence the eccen-
tricity (\( e \)) was fixed to zero, and the argument of periastron, \( \omega \),
was set to 90°. The transit models were integrated over ten steps
to account for the long integration time (30 minutes) of K2 (Kip-
ning 2010). We adopted the quadratic limb darkening equa-
tion by Mandel & Agol (2002) which uses the linear and quadratic
coefficients \( u_1 \) and \( u_2 \), respectively. We followed the parametri-
sation \( q_1 = (u_1 + u_2)^2 \) and \( q_2 = 0.5u_1(u_1 + u_2)^{-1} \) from
Kipping (2013). We first ran a fit using uniform priors for the limb
darkening coefficients (LDCs) and noticed that the LDCs were not
well constrained by the light curve. This is due to the fact that
the LDC are not well constrained for small planets using uni-
form priors (e.g. Csizmadia et al. 2013). Thus, we used the on-
line applet written by Eastman et al. (2013) to interpolate the
Claret & Bloemen (2011) limb darkening tables to the spec-
tral parameters of K2-216 to estimate \( u_1 \) and \( u_2 \). We use this
values to set Gaussian priors to \( q_1 \) and \( q_2 \) LDCs with 0.1 error
bars. The planetary and orbital parameters are consistent for both
LDC prior selections. We use the model with Gaussian priors on
LDC for the final parameter estimation.

We explore the parameter space with 500 independent chains
created randomly inside the prior ranges. We checked for con-
vergence each 5 000 iterations. Once convergence is found, we use
the last 5 000 iterations with a thin factor of 10 to create the pos-
terior distributions for the fitted parameters. This leads to a pos-
terior distribution of 250 000 independent points for each param-
eter. The posterior distributions for all parameters were smooth
and unimodal. The final planet parameters are listed in Table 5
and the resulting stellar density is listed in Table 4. The folded
light curve and best fitted model is shown in Fig. 4.

6. Radial velocity modelling

6.1. Gaussian process regression

We used a Gaussian Process (GP) regression model described by
Dai et al. (2017) to simultaneously model the planetary sig-
nal and the correlated noise associated with stellar activity. This
code is able to fit a non-coherent signal, assuming that activity
acts as a signal whose period is given by the rotation period of
the star, and whose amplitude and phase change on a time scale
given by the spot evolution time scale. GP describes a stochas-
tic process as a covariance matrix whose elements are gener-
ated by user-specified kernel functions. With suitable choice of
the kernel functions and the hyperparameters that specify them,
GP can be used to model a wide range of stochastic processes.
GP regression has been successfully applied to the radial ve-
locity analysis of several exoplanetary systems where correlated
stellar noises cannot be ignored, e.g. CoRoT-7 (Haywood et al.
2014), Kepler-78 (Grunblatt et al. 2015), and Kepler-21 (López-
Morales et al. 2016).

Magnetic active regions on the host star, coupled with stellar
rotation, result in quasi-periodic variations in both the measured
RV and the flux variation. Given their similar physical origin,
both the quasi-periodic flux variation and the correlated stellar
noise in the RV measurement encode physical information about
the host stars e.g. the stellar rotation period and the lifetime of
the starspots. These informations are reflected in the “hyperpa-
rameters” of GP used to model these effects. In particular, there

Fig. 4: Transit light curve folded to the orbital period of K2-216 and residuals. The red points mark the K2 photomet-
ric data and their error bars. The solid line marks the pyaneti best-fitting transit model.

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10 http://astroutils.astronomy.ohio-state.edu/exofast/limbdark.shtml
is a good correspondence between the stellar rotation period and the period of the covariance, \( T \), while the correlation timescale, \( \tau \), and the weighting parameter, \( \Gamma \), together determines the lifetime of starspots. We can thus model both the rotational modulation in the light curve and the correlated noise in RV as Gaussian processes.

Since the \( K_2 \) light curve was measured with high precision, high temporal sampling and an almost continuous temporal coverage, we trained our Gaussian Process model on the \( K_2 \) light curve. The constraints on the hyperparameters were then used as priors in the RV analysis. We used the covariance matrix and the likelihood function described by Dai et al. (2017), and adopted a quasi-periodic kernel

\[
C_{i,j} = h^2 \exp \left[ -\frac{(t_i - t_j)^2}{\tau^2} - \Gamma \sin^2 \left( \frac{\pi (t_i - t_j)}{T} \right) + \left( \sigma_i^2 + \sigma_j^2 + \sigma_{ij}^2 \right) \delta_{i,j} \right]
\]

where \( C_{i,j} \) is an element of the covariance matrix, and \( \delta_{i,j} \) is the Kronecker delta function. The hyperparameters of the kernel are the covariance amplitude, \( h \), \( T \), \( \tau \), the time of \( i \)th observation, \( t_i \), and \( \Gamma \) which quantifies the relative importance between the squared exponential and periodic parts of the kernel. For the planetary signal, we assumed a circular Keplerian orbit. The corresponding parameters are the RV semi-amplitude, \( K \), the orbital period, \( P_{\text{orb}} \), and the time of conjunction, \( t_c \). Since our dataset consists of observations from several observatories, we included a separate jitter parameter, \( \sigma_{\text{jit}} \), to account for additional stellar/instrumental noise, and a systematic offset, \( \gamma \), for each of the observatories (listed in Table A.1 appendix A). The orbital periods and time of conjunction are much better measured using the transit light curve. We thus imposed Gaussian priors on \( P_{\text{orb}} \) and \( t_c \) as derived from the \( K_2 \) transit modelling. We imposed a prior on \( T \) using the stellar rotation period measured from the periodogram (30 ± 5 days). The scale parameters \( h, \tau, K, \) and the jitters were sampled uniformly in log space, basically imposing a Jeffrey’s priors, and uniform priors were imposed on the systematic offsets.

The likelihood function has the following form:

\[
\log L = -\frac{N}{2} \log 2\pi - \frac{1}{2} \log |C| - \frac{1}{2} \mathbf{r}^T \mathbf{C}^{-1} \mathbf{r}
\]

where \( L \) is the likelihood, \( N \) is the number of data points, \( C \) is the covariance matrix, and \( \mathbf{r} \) is the residual vector (the observed RV minus the calculated value). The model includes the RV variation induced by the planet and a constant offset for each observatory.

We first located the maximum likelihood solution using the Nelder-Mead algorithm implemented in the Python package \texttt{scipy}. We sampled the posterior distribution using the affine-invariant MCMC implemented in the code \texttt{emcee} (Foreman-Mackey et al., 2013). We started 100 walkers near the maximum likelihood solution. We stopped after running the walkers for 5000 links. We checked for convergence by calculating the Gelman-Rubin statistics which dropped below 1.03 indicating adequate convergence. We report the various parameters using the median and 16% − 84% percentiles of the posterior distribution. The hyperparameters were constrained to be \( \tau = 4.8^{+7.3}_{-2.9} \) days and \( \Gamma = 1.28 \pm 0.63 \). These were incorporated as priors in the subsequent GP analysis of the RV data.

We followed a similar procedure when analysing the RV dataset, we first found the maximum likelihood solution and then sampled the posterior distribution with MCMC. We removed four isolated RV measurements (separated by more than approximately two \( \tau \) from any neighbouring data points) from the GP modelling. Without neighboring data points, the stellar variability component of these isolated data points are causally disconnected. As a result, GP tends to overfit these data points and thus underestimate the planetary signal. The removed RVs are marked in column six, Table A.1 (appendix A). The RV semi-amplitude for planet \( K_2 \)-216b was constrained to be \( 4.6^{+1.4}_{-1.3} \) m s\(^{-1}\). Using the stellar mass derived in Sect. 4.2 of \( 0.70 \pm 0.03 \) M\(_{\odot}\), this translates to a planet mass of \( 7.4^{+2.2}_{-2.2} \) M\(_{\oplus}\) (precision in mass is 30%). As a comparison, keeping all the RVs with \( S/N > 20 \), we obtain \( 3.8^{+1.5}_{-1.3} \) m s\(^{-1}\) corresponding to a planet mass of \( 6.1^{+1.6}_{-1.8} \) M\(_{\oplus}\). The amplitude of the correlated stellar noise...
is $h_{\nu} = 2.4^{+1.6}_{-0.1} \text{ m s}^{-1}$, in agreement with the SOAP2.0 modelling in Sect. 4.3. The 95% upper bounds of the jitters were $< 5.1 \text{ m s}^{-1}$ (FIES), $< 4.7 \text{ m s}^{-1}$ (FIES2), $< 2.5 \text{ m s}^{-1}$ (HARPS), and $< 2.6 \text{ m s}^{-1}$ (HARPS-N). Figure 5 shows the measured RV variation of K2-216 and the GP model. The folded RV diagram as a function of orbital phase is shown Fig. 6. The results are listed in Table 5.

6.2. Floating chunk offset technique

It is difficult to remove the influence of activity from RV measurements in a reliable way, particularly for sparse data. The GP method often gives good results, but in our case it is “trained” using the K2 light curve which was taken before the RV measurements. Possibly at that time the activity signal could have shown different characteristics. It is therefore important to use independent techniques, when possible, to determine the K-amplitude of the orbit.

The floating chunk offset (FCO) technique is another method for filtering out the effects of activity, but in a model independent way (Hatzes 2014). Basically, it fits a Keplerian orbit to RV data that have been divided into small time “chunks”, keeping the period fixed, but allowing the zero point offsets to “float”. The only assumption of the method is that the orbital period of the planet is less than the rotational period of the star, or other planets. The RV variations in one time chunk is predominantly due to the orbital motion of the planet and all other variations constant. This method also naturally accounts for different velocity offsets between different instruments or night-to-night systematic errors. As long as the time scales for these are shorter than the orbital period, their effects are absorbed in the calculation of the offset.

The FCO method is usually applied to ultra-short period planets ($P_{\text{orb}} < 1 \text{ day}$), where the orbital motion in one night can be significant (see Hatzes 2014). However, it can also be applied for planets on longer period orbits as long as these are shorter than say, the rotational period of the star. One also should have relatively high cadence measurements. In the case of K2-216, the orbital period of the planet is 2.17 days and the best estimate of the rotational period of the star is $\sim 30 \text{ days}$. Furthermore, we have high cadence measurement where observations were taken on several consecutive nights. The conditions are right for applying the FCO method.

The data were divided into six data sets or chunks. It is important to exclude isolated measurements, separated by more than several orbital periods as these provide no shape information for the RV curve. We divided the RV data into six time chunks that were separated by no more than two days, with the exception of one that covered a time span of four days. In particular, the HARPS data were divided into two chunks with one overlapping point. The last one had only two RV measurements separated by three days. In order to include the last data points, we first tried to account for any activity signal in a way independent from the GP model. To do this we placed all the data on several consecutive nights. The conditions are right for applying the FCO method.

We first checked if the planet signal was present in our data using the co-called FCO-periodogram (Hatzes 2014). For this, the RV chunks are fit using a different trial period. The resulting $\chi^2$ as a function of period is a form of a periodogram, and the $\chi^2$ should be minimised for the period that is present in the data. This was done with trial periods spanning 0.5 – 10 days. The reduced $\chi^2$ was minimised for a period of 2.17 days as shown in Fig. 3 (appendix B). This confirms that the RV variations due to the planet are clearly seen in our data.

An orbital fit was then made to the chunk data using the program Gaussfit (Jefferys et al. 1988). The period and ephemeris were fixed to the transit values, but the zero point offsets for each chunk and the K-amplitude were allowed to vary. The resulting K-amplitude is $4.96 \pm 0.96 \text{ m s}^{-1}$ which corresponds to a planet mass of $7.9 \pm 1.6 \text{ M}_\oplus$ (Table 5). The precision in mass is 20%. If we remove the double point (chunk 3/4) we get essentially the same amplitude ($K = 5.1 \pm 1.0 \text{ m s}^{-1}$). Figure 7 shows the phased orbit fit after applying the calculated offsets. Different symbols indicate the different chunks. This velocity amplitude is in very good agreement with the GP analysis. The very small differences merely reflect the variations due to a different treatment of the activity signal.

When using the FCO method it is important to check that it can reliably recover an input K-amplitude. The time sampling of the data or harmonics of the rotational period (e.g. $P_{\text{rot}}/2 \approx 15 \text{ days}$) may effect the recovered K-amplitude in a systematic way. This was explored through simulations.

We then added the orbital signal of the planet to this activity signal using a range of K-amplitudes. The median error of our RV measurements is 2.8 m s$^{-1}$ so we added random
noise with \( \sigma = 3 \text{ m s}^{-1} \). We also added a large velocity offset \( (\approx -26 \text{ km s}^{-1}) \) between the simulated FIES and HARPS/N measurements. Finally, for good measure we added an additional random velocity component ranging between \( -10 \) to \( +8 \text{ m s}^{-1} \) to the individual chunks to account for any additional activity “jit-
tering”. For each input \( K \)-amplitude a total of 50 sample data sets
were generated using different random noise generated with dif-
ferent seed values. The mean and standard deviations were
calculated for each. The \( K \)-amplitude was reliably recovered in the
full amplitude range \( 1 \text{–} 6 \text{ m s}^{-1} \). Figure B.2 (appendix B) shows the
output \( K \) amplitude as a function of input \( K \) amplitude. The
red square is the value for K2-216.

### 7. Discussion

Combining our mass and radius estimates of K2-216b, we find
mean densities of \( 7.5_{-2.9}^{+3.1} \text{ g cm}^{-3} \) and \( 8.1_{-2.6}^{+2.5} \text{ g cm}^{-3} \) from
the GP and FCO methods, respectively, in excellent agreement with
each other. In Fig. 8 we display the position of planet b on a
mass-radius diagram compared to all small exoplanets \( (R_p \leq 2 R_\oplus) \) with masses \( \leq 30 M_\oplus \) known to better than 20 %, as
listed in the NASA Exoplanet Archive. The insolation flux of
the planets is colour coded. The figure also displays the Zeng
et al. (2016) theoretical models of planet composition in differ-
ent colours: 100 % water to 100 % iron. The density of K2-216b is consistent with a rocky composition of primarily iron
and magnesium silicate.

The radius of K2-216b puts it in the middle of the bimodal
distribution of small planets (Fulton et al. 2017), or just
below the lower edge using the location and shape of the radius
gap as estimated by Van Eylen et al. (2017) with

\[
\log(R) = m \times \log(P) + a \, ,
\]

where \( m = -0.09^{+0.04}_{-0.04} \) and \( a = 0.37^{+0.04}_{-0.02} \). For a period of
2.17 days, the location of the centre of the valley is around
\( 2.2 R_\oplus \). This suggests that K2-216b is a remnant core, stripped
of its atmosphere.

To estimate the likelihood of K2-216b having an extended at-
mosphere, we begin by considering that during the early phases
of planet evolution, when a planet comes out of the proto-
planetary nebula, it goes through a phase of extreme thermal
Jeans escape, the so called “boil-off” (Owen & Wu 2017). Af-

\[
\log(R) = m \times \log(P) + a \, ,
\]

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of planet evolution, when a planet comes out of the proto-
planetary nebula, it goes through a phase of extreme thermal
Jeans escape, the so called “boil-off” (Owen & Wu 2017). Af-
fter this phase, the planet arrive at a more stable configuration in
which the escape is driven by the stellar XUV flux (Fossati et al.
2017a). Whether a planet lies in the boil-off regime or not, can be
determined on the basis of the restricted Jeans escape parameter,

### Table 5: Final K2-216b parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\text{orb}} )</td>
<td>Period (days)</td>
<td>2.17479 ± 0.00005</td>
</tr>
<tr>
<td>( T_0 )</td>
<td>Time of transit (BJD$_{TTDB}$)</td>
<td>7394.04186 ± 0.00094</td>
</tr>
<tr>
<td>( T_14 )</td>
<td>Total duration (hours)</td>
<td>1.838$^{+0.050}_{-0.041}$</td>
</tr>
<tr>
<td>( b )</td>
<td>Impact parameter</td>
<td>0.43 ± 0.31</td>
</tr>
<tr>
<td>( i )</td>
<td>Inclination (degrees)</td>
<td>87.1$^{+2.1}_{-3.8}$</td>
</tr>
<tr>
<td>( e )</td>
<td>Eccentricity</td>
<td>0</td>
</tr>
<tr>
<td>( R_P/R_* )</td>
<td>Ratio of planet radius to stellar radii</td>
<td>0.0220$^{+0.0007}_{-0.0007}$</td>
</tr>
<tr>
<td>( a/R_* )</td>
<td>Ratio of semi-major axis to stellar radii</td>
<td>8.44$^{+0.80}_{-2.01}$</td>
</tr>
<tr>
<td>( a )</td>
<td>Semi-major axis (AU)</td>
<td>0.028$^{+0.004}_{-0.007}$</td>
</tr>
<tr>
<td>( u_1 )</td>
<td>Linear limb-darkening coeff.</td>
<td>0.58 ± 0.14</td>
</tr>
<tr>
<td>( u_2 )</td>
<td>Quadratic limb-darkening coeff.</td>
<td>0.13 ± 0.14</td>
</tr>
<tr>
<td>( K^c )</td>
<td>RV semi-amplitude variation (m s$^{-1}$)</td>
<td>4.6$^{+1.3}_{-1.4}$</td>
</tr>
<tr>
<td>( K^d )</td>
<td>RV semi-amplitude variation (m s$^{-1}$)</td>
<td>5.0 ± 1.0</td>
</tr>
<tr>
<td>( R_P )</td>
<td>Planet radius (R$_\oplus$)</td>
<td>1.8$^{+0.2}_{-0.1}$</td>
</tr>
<tr>
<td>( M_P^c )</td>
<td>Planet mass (M$_\oplus$)</td>
<td>7.4 ± 2.2</td>
</tr>
<tr>
<td>( M_P^d )</td>
<td>Planet mass (M$_\oplus$)</td>
<td>7.9 ± 1.6</td>
</tr>
<tr>
<td>( \rho_P^c )</td>
<td>Planet density (g cm$^{-3}$)</td>
<td>7.5$^{+1.1}_{-2.9}$</td>
</tr>
<tr>
<td>( \rho_P^d )</td>
<td>Planet density (g cm$^{-3}$)</td>
<td>8.1$^{+2.9}_{-2.6}$</td>
</tr>
<tr>
<td>( F )</td>
<td>Insolation (F$_\oplus$)</td>
<td>247$^{+182}_{-52}$</td>
</tr>
<tr>
<td>( T_{eq} )</td>
<td>Equilibrium temperature (K)</td>
<td>1103$^{+163}_{-64}$</td>
</tr>
<tr>
<td>( \Lambda )</td>
<td>Restricted Jeans escape parameter</td>
<td>29 – 31</td>
</tr>
</tbody>
</table>

\[ Notes. \ (a) (BJD - 2454833) \text{ days.} \ (b) Fixed. \ (c) Derived using a Gaussian process regression method. \ (d) Derived using the floating chunk offset technique. \ (e) Assuming isotropic re-radiation, and a Bond albedo of zero. \ (f) From transit modelling. \ (g) Defined in Fossati et al. (2017a). \]
\( \Lambda \), which is defined as  
\[
\Lambda = \frac{GM_{p}m_{H}}{k_{B}T_{eq}R_{p}},
\]
where \( G \) is the gravitational constant, \( m_{H} \) is the hydrogen mass, and \( k_{B} \) is the Boltzmann constant. When \( \Lambda \approx 20 - 40 \), depending on the system parameters, a planet with an hydrogen-dominated atmosphere will lie in the boil-off regime (Fossati et al. 2017a). Considering the two derived planetary masses for K2-216b, \( \Lambda \) ranges between 29 and 31. Assuming that the planet originally accreted a hydrogen-dominated atmosphere, following the boil-off phase, the planet will have a \( \Lambda \) value of about 20 (to be conservative). This value corresponds to a planetary radius of \( R_{p} \) (see Fig. 4 in [Rogers et al. 2011]). We estimated the stellar XUV flux starting from the \( \log(R_{\alpha}/R_{\odot}) \) value derived from the spectra. We converted the measured \( \log(R_{\alpha}/R_{\odot}) \) value into \( \text{Ca}n \ H \ & K \) line core emission flux at 1 AU employing the equations listed in Fossati et al. (2017b), obtaining 18 \( \text{erg cm}^{-2} \text{s}^{-1} \). From this value, and using the relations given by Linsky et al. (2013, 2014), we obtained a stellar Ly \( \alpha \) flux at 1 AU of 20 \( \text{erg cm}^{-2} \text{s}^{-1} \) and an XUV flux at the planetary orbit of approximately 19,000 \( \text{erg cm}^{-2} \text{s}^{-1} \). Using this value and the planet parameters in the upper atmosphere code leads to mass-loss rates of \( 6 - 9 \times 10^{-12} \text{M}_{\oplus} \text{year}^{-1} \). This implies that the planet must have lost between 0.07 and 0.13% of its mass in one Gyr. Our estimated age of the system in Sect. 4.2 has very large uncertainties, but during a 5 Gyr main-sequence life-time of the host star the planet would have lost between 0.35 and 0.65% of its mass, which is significantly larger than the predicted initial hydrogen-dominated envelope mass of 0.1%. In addition, the above mass-loss predictions should be considered to be lower limits, since the young star was significantly more active than taken into account above. Thus, even considering the large uncertainties in age, we conclude that K2-216b likely has completely lost its primordial, hydrogen-dominated atmosphere, and is one of the largest planets found to have lost its atmosphere (see Fig. 7 in Van Eylen et al. 2017).

8. Summary

In this paper, we confirm the discovery of the super-Earth K2-216b (EPIC 220481411b) in a 2.17 day orbit transiting a moderately active K5V star at a distance of 115 ± 20 pc. We derive the mass of planet b using two different methods: (i) a Gaussian process regression based on both the radial velocity and the photometric time series, and (ii) the “floating chunk offset” technique, based on RV measurements observed close in time (4 days) with the assumption that the orbital period of the planet is much less than the rotational period of the star. The results are in very good agreement with each other: \( M_{p} \approx 7.4 \pm 2.2 \text{M}_{\oplus} \) from the GP regression, and \( M_{p} \approx 7.9 \pm 1.6 \text{M}_{\oplus} \) from the FCO technique. The density is consistent with a rocky composition of primarily iron and magnesium silicate, although the uncertainties allow a range of planetary compositions. With a size of \( 1.8^{+0.2}_{-0.1} \text{R}_{\oplus} \), this planet falls within, or just below, the gap of the large uncertainties in age, we conclude that K2-216b likely has lost its atmosphere.

Acknowledgements. We thank the NOT, TNG, ESO, Subaru, and TCS staff members for their support during the observations. Based on observations obtained with (a) the Nordic Optical Telescope (NOT), operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos and in the Instituto de Astrofísica de Canarias (IAC), programmes 53-016, 54-027, and 54-211; (b) with the Italian Telescopio Nazionale Galileo (TNG) operated at the ORM (IAC) on the island of La Palma by the INAF Fundacón Galileo Galilei; (c) the 3.6-m ESO telescope at La Silla Observatory, programmes 094.C-0891 and 0100.C-0808; (d) the Telescopio Carlos Sánchez (TCS) installed at IAC’s Observatorio del Teide, Tenerife; (e) the Subaru Telescope, operated by the National Astronomical Observatory of Japan; (f) NESSI, funded by the NASA Exoplanet Exploration Program and the NASA Ames Research Center. NESSI was built at the Ames Research Center by Steve B. Howell, Nic Scott, Elliott P. Horch, and Emmett Quigley; (g) the K2/Kepler mission. Funding for the K2/Kepler mission is provided by the NASA Science Mission Directorate. The K2 data presented in this paper were downloaded from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX13AC07G and by other grants and contracts. This work has made use of SME package, which benefits from the continuing development work by J. Valenti and N. Piskunov and we gratefully acknowledge their continued support. This work has made use of the VALD database, operated at Uppsala University, the Institute of Astronomy RAS in Moscow, and the University of Vienna (Kupka et al. 2000; Ryabchikova et al. 2015). C.M.P. and M.F. gratefully acknowledge the support of the Swedish National Space Board. DK and LF acknowledge the Australian Forschungs-förderungsgesellschaft FFG project “TAPAS4CHEOPS” PP65939. SziCs, APH, and HR acknowledge the support of the DFG priority program SPP 1992 “Exploring the Diversity of Extrasolar Planets (HA 3279/12-1, PA255/18-1, PA525/19-1, PA525/20-1 and RA 714/14-1).” Funding for the Stellar Astrophysics Centre is provided by The Danish National Research Foundation (Grant agreement no.: DNRF106).

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Fig. 8: Mass-radius diagram of all small exoplanets ($R_p \leq 2 R_\oplus$, and $M_p \leq 30 M_\oplus$) with a measured mass and radius to a precision better than 20% as listed in the NASA Exoplanet Archive. K2-216b is marked with a red square. The colours of the planets indicates the insolation in units of $F_\odot$. Earth and Venus are plotted in red filled circles for comparison. The solid lines are theoretical mass-radius curves (Zeng et al. 2016), from top to bottom: 100% H$_2$O (blue solid line), a mixture of 50% H$_2$O and 50% MgSiO$_3$ (cyan dashed line), 100% MgSiO$_3$ (green solid line), a mixture of 75% MgSiO$_3$ and 25% Fe (magenta dashed line), a mixture of 50% MgSiO$_3$ and 50% Fe (brown solid line), a mixture of 25% MgSiO$_3$ and 75% Fe (red dashed line), and 100% Fe (orange solid line).
Appendix A: Table radial velocity measurements

Appendix B: Figures
Table A.1: FIES, HARPS, and HARPS-N radial velocity measurements of K2-216.

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<th>GP(^c)</th>
<th>FCO(^d)</th>
<th>BIS(^e)</th>
<th>FWHM(^f)</th>
<th>(\log (R_\text{HK})(\gamma))</th>
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Notes. \(^{a}\) Time stamps are given in barycentric Julian day in barycentric dynamical time. \(^{b}\) The FIES RV measurements are relative, while the HARPS and HARPS-N measurements are absolute. \(^{c}\) Included RVs in the Gaussian process regression model. \(^{d}\) The division of “chunks” in the floating chunk offset (FCO) technique radial velocity model. The model excluded the isolated RVs in the empty entries. \(^{e}\) Bisector inverse slope (BIS) of the cross-correlation function (CCF). \(^{f}\) Full-width at half maximum of the CCF. \(^{g}\) A dimensionless ratio of the emission in the Ca\(\text{ii}\)H\& K line cores to that in two nearby continuum bandpasses on either side of the lines. \(^{h}\) Systematic instrumental offset derived from the Gaussian regression. \(^{i}\) Not used in any of the RV models due to S/N < 20.
Fig. B.1: From top to bottom: Generalised Lomb-Scargle periodograms of the K2 light curve, the radial velocity measurements (RV), bisector inverse slope (BIS), full-width at half maximum of the correlation function (FWHM), and the activity index log ($R'_{HK}$) where the last four are extracted from the HARPS and HARPS-N data. The stellar period is marked with the vertical dashed blue line, and the planet orbital period with the vertical dashed red line. The false-alarm probability (FAP) is marked at the 1% level.
Fig. B.2: The output $K$ amplitude as a function of input $K$ amplitude using the floating chunk offset technique.

Fig. B.3: The floating chunk offset-periodogram over the range 0.5 – 10 days ($\chi^2$ versus period). The y-axis is flipped so that a minimum appears as a peak, much like a standard periodogram. The best fit is at the planet period of 2.17 days.