Two massive rocky planets transiting a K-dwarf 6.5 parsecs away

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HD 219134 is a K-dwarf star at a distance of 6.5 parsecs around which several low-mass planets were recently discovered1-2. The Spitzer Space Telescope detected a transit of the innermost of these planets, HD 219134 b, whose mass and radius (4.5 ± 0.03M⊙ and 1.6 ± 0.05R⊕ respectively) are consistent with a rocky composition1. Here, we report new high-precision time-series photometry of the star acquired with Spitzer revealing that the second innermost planet of the system, HD 219134 c, is also transiting. A global analysis of the Spitzer transit light curves and the most up-to-date HARPS-N velocity data set yields mass and radius estimations of 4.74 ± 0.19M⊕ and 1.602 ± 0.055R⊕ for HD 219134 b, and of 4.36 ± 0.22M⊕ and 1.511 ± 0.047R⊕ for HD 219134 c. These values suggest rocky compositions for both planets. Thanks to the proximity and the small size of their host star (0.775 ± 0.005R⋆)3, these two transiting exoplanets — the nearest to the Earth yet found — are well suited for a detailed characterization (for example, precision of a few per cent on mass and radius, and constraints on the atmospheric properties) that could give important constraints on the nature and formation mechanism of the ubiquitous short-period planets of a few Earth masses.

The detection1 of a transit of HD 219134 b, combined with the assumption that the system’s planets originated in a common protoplanetary disk, translated into significantly improved transit probabilities for the other planets orbiting the star, especially for HD 219134 c. Using a Monte Carlo approach4, and assuming a standard deviation for the orbital inclinations of the system’s planets of 2.2°, the corresponding value for the Solar System, we calculated an after-priori transit probability of 21% for HD 219134 c, significantly greater than its a priori geometric transit probability of 5.4%. We therefore intensified our radial velocity (RV) monitoring of HD 219134 c with the HARP-S-N spectrograph5 in the second semester of 2015. Our analysis of the extended HARPS-N dataset (see Methods) and assuming or not a transit represented by an eclipse model10. We compared the different models using the Bayesian information criterion (BIC)11 as a proxy for the marginal likelihood of the models tested. The presence of a transit was decisively favoured (Bayes factor12 > 1,000) for all three time-series (Fig. 1, Supplementary Table 1). This confirmed the transiting nature of HD 219134 b and revealed that of HD 219134 c. After selection of the most likely models, we performed individual MCMC analysis of each transit light curve, including the initial HD 219134 b transit light curve1, to obtain consistent transit parameters for the two transits of planet b (14 April 2015 and 16 March 2016) and of planet c (26 March and 29 April 2016).

We determined a stellar mass of 0.81 ± 0.03M⊙ with the stellar evolution modelling code CLES13, using as inputs the radius and effective temperature as measured previously1, and the metallicity © 2017 Macmillan Publishers Limited, part of Springer Nature. All rights reserved.
as derived from spectroscopic analysis\(^1\) (see Table 1). We varied the internal physics for convection efficiency, possible core extramixing and initial helium abundance. The error budget includes the associated uncertainties on the input parameters but is dominated by the uncertainty on the initial helium abundance when modeling stellar evolution. The uncertainties on convection and extramixing parameters have relatively low contributions. Only old stellar ages were obtained (11.0 \(\pm\) 2.2 Gyr), consistent with the long magnetic cycle and the slow rotation inferred for this star\(^4\). This old age is also consistent with previous works\(^{15-17}\) that favoured an age between 6 and 11 Gyr. Compared with this broad age range, our smaller uncertainty can be attributed to the highly precise stellar radius and temperature constrained by interferometry\(^3\) (Table 1) that we used as inputs to our stellar evolution modelling, unlike these previous works.

We then performed a global MCMC analysis of all our data (HARPS-N RVs plus Spitzer photometry, including the initial HD 219134 b transit light curve\(^3\)), to get the strongest constraints on the parameters of the short-period planets orbiting HD 219134 (see Methods). A circular orbit was assumed for HD 219134 b, its proximity to the star resulting in a computed tidal circularization timescale\(^18\) of 80 Myr when assuming a tidal quality factor\(^19\) of 100, corresponding to the maximum value derived for terrestrial planets and satellites of the Solar System\(^1,19\). The same computation for planet c resulted in a tidal circularization timescale of 2.5 Gyr, so we conservatively left its orbital eccentricity free in our analysis.

Table 1 presents the resulting values and error bars for the system parameters, while Fig. 1 shows the light curves corrected for the systematics and the best-fit transit models.

As HD 219134 is a well-characterized, bright and nearby star, the detection of the transits of its two inner planets makes possible the first detailed characterization and comparative study of two massive rocky planets orbiting the same star. Notably, an intense RV and photometric follow-up could improve the precision on the planets' masses and radii down to the 3% and 1% levels (currently 4.5% and 3%), respectively, thanks to very well-constrained values of the stellar mass and radius (see Methods). Assuming rocky compositions for both planets, which is consistent with our measurements (Fig. 2, ref. \(^2\)), and applying a semi-empirical mass–radius relation based on the Earth's seismic model\(^21\), we infer core mass fractions (CMF) of 0.09\(^{+0.16}_{-0.06}\) and 0.26 \(\pm\) 0.17 for planets b and c, respectively. These CMF values have to be compared to a CMF of 0.33 for the Earth\(^21\). At this stage, we can thus only conclude that our current dataset marginally favours a CMF smaller than the Earth's for planet b.

With the improved precisions on the planets' masses and radii mentioned above, the errors on their CMF would drop to 5–6%, making possible much stronger inferences on their compositions. Still, these inferences would rely on the assumptions that both planets have negligible volatile contents and atmospheric extents, as larger CMFs combined with significant volatile contents and/or extended hydrogen-dominated atmospheres could result in the same measured masses and radii\(^20,22\). Fortunately, the host star is small and bright enough to make it possible to constrain the atmospheric extents and compositions of the planets by (transit transmission) spectroscopy with the Hubble Space Telescope (HST), and, possibly, by occultation emission spectroscopy with the James Webb Space Telescope (JWST) which is due to launch in 2018 (see Methods).

The theories of formation of short-period planets of a few Earth masses fall into two main classes, one assuming a formation far from the star, outside the snow line, followed by a significant inwards migration by gravitational interaction with the gas disk\(^23\), and the other assuming in situ formation\(^24,25\). The latter requires the establishment of a very high surface density of dust grains in the inner protoplanetary disk. The grains then coagulate to form roughly centimetre-sized ‘pebbles’. These are caught by gas drag and migrate inwards to the inner edge of the gas disk, where they accumulate, and eventually form close-in planets by gravitational instability or core accretion\(^26,27\). The two classes of models predict different planetary compositions, the former and latter favouring, respectively, volatile-rich and volatile-poor compositions\(^28\). Very strong constraints on the planets’ compositions could thus help to discriminate their origins. However, the large irradiation received by the planets during the ~11 Gyr since their formations could make this discrimination a challenging task even in that case, as it could have significantly altered their initial structures and compositions.

The transiting nature of both HD 219134 b and c increases the probability that planets d and f also transit. Using the formalism of previous work\(^1\), we compute posterior transit probabilities of 13.1% and 8.1% for planets f and d, respectively, significantly greater than

\(\text{Figure 1} \mid \text{Spitzer transit photometry of the planets HD 219134 b and c. Spitzer/IRAC 4.5-\mu m time-series photometry for HD 219134, corrected for the instrumental effects, unbinned (cyan dots) and binned per 7.2 min = 0.01 d (black circles with error bars, each error bar being the standard deviation for the bin). For each light curve, the best-fit transit model is superimposed in red. The left and right panels show the transits of, respectively, HD 219134 b and HD 219134 c. The photometry is folded on the orbital period of the planets (0 = inferior conjunction).\)
Table 1 | Parameters of HD 219134 and its four inner planets.

| Parameters | Value |
|------------|-------|
| Star       | HD 219134 |
| Mass ($M_\odot$) | 0.81 ± 0.03 |
| Radius ($R_\odot$) | 0.778 ± 0.005 |
| Effective temperature (K) | 4,699 ± 16 |
| [Fe/H] (dex) | +0.11 ± 0.04 |
| Age (Gyr) | 11.0 ± 2.2 |
| Density ($\rho_\odot$) | 1.729 ± 0.073 |
| Log surface gravity (dex) | 4.567 ± 0.018 |
| Luminosity ($L_\odot$) | 0.2646 ± 0.0050 |

For the solar reference, we used the abundances obtained by ref. 36.

The stellar mass was derived by stellar evolution modelling, and the planetary parameters result from a combined MCMC analysis of the most recent HARPS-N RV dataset and of the Spitzer transit photometry, including the three new transit light curves presented here. From our stellar evolution modelling; †from ref. 1; ‡assuming a null Bond albedo; ‡upper limit for f and d (edge-on orbit); ¶lower limit for planets f and d (radius computed with composition model of ref. 20 for a pure iron composition; ‡‡computed by Monte Carlo simulations using the formalism of previous work).
letters

As the atmospheric abundance cannot be directly measured from spectroscopy, we computed evolutionary tracks with various initial helium abundances, \(Y_0\), for a quasi-primalordial value (\(Y_0 = 0.25\)), a protostellar value (\(Y_0 = 0.27\)) and values obtained from the general trend observed for the chemical evolution of galaxies (up to \(Y_0 \approx 0.30\)).

Limb-darkening coefficients. As in previous work\(^1\), we assumed a quadratic law\(^2\) to represent the limb darkening and its impact on the shape of the transit light curves\(^3\). Values for the two quadratic limb-darkening coefficients \(u_1\) and \(u_2\) were interpolated at each step of the Markov chains from the tables of ref. \(^3\). For the Spitzer 4.5-μm bandpass, based on the step's values for the stellar effective temperature \(T_{\text{eff}}\), metallicity [Fe/H], microturbulence speed \(\xi_\text{turb}\), and surface gravity logarithm \(\log g\). The marginal posterior PDFs of \(u_1\) and \(u_2\) have as median ± standard deviation, respectively, 0.0812 ± 0.0005 and 0.1498 ± 0.0013.

Individual analysis of the Spitzer light curves. For each of the four Spitzer photometric time-series, we used the adaptive MCMC code presented in previous work\(^1\) and references therein to explore a large range of models, each consisting of a baseline model aiming to represent the photometric variations of instrumental origins, added — or not — to the eclipse model of ref. \(^1\). To represent the transit of planet b (light curves of 14 April 2015 and 15 March 2016) or c (light curves of 26 March and 29 April 2019), the tested baseline models (see previous work\(^1\) and references therein) consisted of polynomial functions of different external parameters (time, width and position of the stellar image in the Spitzer images, and logarithm of time; see Supplementary Table 1), multiplied — or not — by a numerical position model computed at each step of the Markov chains from the tables of ref. \(^3\). For the Spitzer 4.5-μm bandpass, based on the step's values for the stellar effective temperature \(T_{\text{eff}}\), metallicity [Fe/H], microturbulence speed \(\xi_\text{turb}\), and surface gravity logarithm \(\log g\). The marginal posterior PDFs of \(u_1\) and \(u_2\) have as median ± standard deviation, respectively, 0.0812 ± 0.0005 and 0.1498 ± 0.0013.

For each light curve, we then performed a longer MCMC analysis comprising five Markov chains of 100,000 steps, similar in detail to the global analysis described below. These individual analyses resulted in consistent transit parameters for the two transits of planet b (14 April 2015\(^\text{a}\) and 16 Mar 2016\(^\text{a}\)) and of planet c (26 March and 29 April 2016). The selection of a model with transit for the four light curves and the consistency of the fitted transit parameters with the ones expected for the transits of the planets b and c detected by RV\(^\text{1}\) allowed us to firmly conclude the transiting nature of HD 219134 c and to confirm that of HD 219134 b.

Global MCMC analysis. We performed a global MCMC analysis of the HARPS-N and Spitzer time-series to derive the strongest possible constraints on the parameters of the system. This global analysis consisted in five Markov chains of 100,000 steps. Their convergence was successfully checked with a statistical test\(^4\). Supplementary Table 2 presents the models selected by minimization of the BIC for each individual data set. The model assumed to represent the RVs was the same as for our transit ephemerides determination (see above).

Supplementary Table 2 also shows for each light curve the error correction factor (CF) representing both the over- or under-estimation of the white noise of each measurement and the presence of correlated (red) noise in the data (see previous work\(^1\) for details). The jump parameters of the MCMC (that is, the parameters randomly perturbed at each step of the Markov chains) were the following:

- The stellar mass, radius, effective temperature and metallicity [Fe/H].
- For these four parameters, normal prior PDFs based on the values given in Table 1 were assumed.
- For HD 219134 b and c, the planet/star area ratio \(dF = (R_p/R_\star)^2\) (where \(dF\) is delta flux), and the parameter \(b = (a \cos i)/R_\star\), where \(a\) is the orbital semi-major axis and \(i\) is the orbital inclination. \(b\) is the transit impact parameter in the case of circular orbit. For the other two planets, \(dF\) was fixed to an arbitrary value and \(b\) was fixed to zero, as no transit of these planets was expected to happen during the Spitzer observations.
- For the four planets, the orbital period \(P\), the time of inferior conjunction \(T_0\) (corresponding to the mid-transit time for transiting planets), the parameter \(K_0 = K_0(1-c^2)\) (where \(K_0\) is the RV semi-amplitude and \(c\) is the orbital eccentricity, and (except for HD 219134 b for which a circular orbit was assumed) the two parameters \(\sigma_{\cos i}\) and \(\sigma_{\sin i}\), where \(\omega\) is the argument of periastron.

At each step of the MCMC, orbital, physical and eventually transit (duration, impact parameter) parameters of the planets are computed from their jump parameters (see previous work\(^1\) and references therein).

Table 1 presents, for the four planets, the resulting median and 1σ errors of the resulting posterior PDFs for the most physically relevant parameters. Figure 1 shows, for the four Spitzer light curves, the best-fit transit models and the light curves divided by the best-fit baseline models. Supplementary Fig. 1 shows the raw Spitzer light curves and the corresponding best-fit global model (transit and baseline). Supplementary Fig. 2 shows the best-fit Keplerian RV models for the four planets.

In a final stage, we performed a global analysis of the Spitzer photometry alone, assuming a uniform prior PDF for the stellar radius to derive the value of the stellar density constrained only by the transit photometry\(^6\). For this analysis, we assumed the orbits of both planets b and c to be circular. It resulted in a stellar density of \(1.7030 \pm 0.0735\) \(\rho_\star\), in excellent agreement with the density of 1.719 ± 0.071 \(\rho_\star\) derived when using the a priori knowledge of the stellar radius. This test provides a further validation of the planetary origin of the transit signals.

Potential for future improvements in precision of radii and masses of planets b and c. Transit observations allow measurement of the planet/star area ratio \(dF = (R_p/R_\star)^2\). The derivative of this formula shows that the relative error on the orbital radius \(\sigma_{\sigma_R}/R_\star\) is proportional to the relative error on the stellar radius \(\sigma_{\sigma_\star}/R_\star\), and to half of the relative error on the transit depth, \(1/2(\sigma_{\sigma_d}/dF)\). Assuming that \(\sigma_{\sigma_\star}/R_\star\) and \(\sigma_{\sigma_d}/dF\) are uncorrelated, \(\sigma_{\sigma_d}/dF\) can thus be expressed as the quadratic sum:

\[
\left(\frac{\sigma_{\sigma_d}}{dF}\right)^2 = \left(\frac{\sigma_{\sigma_R}}{R_\star}\right)^2 + \left(\frac{\sigma_{\sigma_\star}}{R_\star}\right)^2
\]

Injecting the values and errors of \(R_\star\) and \(dF\) shown in Table 1 for planets b and c into Equation (1) results in relative errors of, respectively, 3.4% and 3.1%, in perfect agreement with the relative errors deduced from the MCMC.

Assuming an improvement of a factor ~5 of the precisions on the planets’ transit depths resulting from an intense photometric monitoring campaign of their transits with, for example, Spitzer (at least 50 transits observed for both planets), the formula above predicts relative errors <1% on the planets’ radii, thanks to the precision of 0.64% on the stellar radius.

Assuming a circular orbit and perfectly determined orbital period and inclination, the same approach shows that the relative error on the mass of a planet deduced from RV measurements can be expressed\(^4\) as the quadratic sum:

\[
\left(\frac{\sigma_{\sigma_M}}{M_\star}\right)^2 = \left(\frac{\sigma_{\sigma_R}}{R_\star}\right)^2 + \left(2\frac{\sigma_{\sigma_\star}}{M_\star}\right)^2
\]

Injecting the values and errors of \(M_\star\) and \(K_0\) shown in Table 1 for planets b and c into this equation results in relative errors of 4% and 5% for the masses of planet b and c, respectively, in perfect agreement with the relative errors \(\sigma_{\sigma_M}/M_\star\) deduced from the MCMC (Table 1). Considering the precision of 3.7% on the stellar mass, Equation (2) predicts precisions of ~3% for the planets’ masses, provided that there

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Figure 2 | Mass-radius relationship for small planets with precisions on the masses better than 20%. The solid lines are theoretical mass-radius curves from previous work\(^2\).
were improvements of a factor -2 for the precisions of the RV semi-amplitudes, which could be achieved after several years of an intensive RV monitoring campaign of the star (at least 2,000 new RV measurements).

Potential for atmospheric characterization of the planets with HST and JWST. HD 219134 is a relatively small star (0.778 ± 0.0055 R⊙) and is a very bright infrared source (K = 3.25). Both features make it an a priori favourable target for the atmospheric characterization of its two transit inner planets by eclipse transmission and emission spectroscopy45. To quantify this potential, we computed estimates for both planets for the amplitudes of the signals in transmission and emission under different assumptions. For transmission, we used the formula46:

\[ \Delta F_d = 2\pi D N H (R_H / R_p) \]

where \( \Delta F_d \) is the increase in transit depth at a wavelength corresponding to a strong atomic or molecular transition, \( R_H \) is the planet's radius, \( N_H \) is the effective atmospheric extent in atmospheric scale height for a strong transition, and \( H \) is the atmospheric scale height given by:

\[ H = k BT \mu m g \]

where \( k \) is Boltzmann's constant, \( T \) is the temperature of the upper atmosphere at the planet's terminator, \( \mu \) is the mean molecular mass, and \( g \) is the planet's surface gravity. For these order of magnitude computations, we equated the extended exospheres of hydrogen photoevaporated from their atmospheres to a strong atomic or molecular transition, \( R_H \) is the planet's radius, \( N_H \) is the effective atmospheric extent in atmospheric scale height for a strong transition, and \( H \) is the atmospheric scale height given by:

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Author contributions
M.G. led the HD 219134 b+c transit search with Spitzer, planned and analysed the Spitzer observations, performed the global analysis of the Spitzer and HARPS-N data, and wrote most of the manuscript. B.-O.D. performed an independent analysis of the Spitzer data to verify M.G.’s results. V.V.G. performed the stellar evolutionary modelling of the host star. A.C.C., D.C., D.L., C.L., E.M., F.M., M.M., F.A.P., G.P., D.Sa., D.Sé., A.S. and S.U. form the HARPS-N science team which managed the RV monitoring of the host star. A.C.C., D.C., D.L., C.L., E.M., F.M., M.M., F.A.P., G.P., D.Sa., D.Sé., A.S. and S.U. contribute to the writing of the manuscript.

Additional information
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Competing interests
The authors declare no competing financial interests.