Dynamical masses of two infant giant planets

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Dynamical masses of two infant giant planets

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Current theories of planetary evolution predict that infant giant planets have large radii and very low densities before they slowly contract to reach their final size after about several hundred million years ^{1,2}. These theoretical expectations remain untested to date, despite the increasing number of exoplanetary discoveries, as the detection and characterisation of very young planets is extremely challenging due to the intense stellar activity of their host stars ^{3,4}. However, the recent discoveries of young planetary transiting systems allow to place initial constraints on evolutionary models^{5–9}. With an estimated age of 20 million years, V1298 Tau is one of the youngest solar-type stars known to host transiting planets: it harbours a multiple system composed of two Neptune-sized, one Saturn-sized, and one Jupiter-sized planets ^{10,11}. Here we report the dynamical masses of two of the four planets. We find that planet b, with an orbital period of 24 days, has a mass of 0.60 Jupiter masses and a density similar to the giant planets of the Solar System and other known giant exoplanets with significantly older ages ^{12,13}. Planet e, with an orbital period of 40 days, has a mass of 1.21 Jupiter masses and a density larger than most giant exoplanets. This is unexpected for planets at such a young age

and suggests that some giant planets might evolve and contract faster than anticipated, thus challenging current models of planetary evolution.

V1298 Tau is a very young K1 dwarf star with a mass of $1.170 \pm 0.060 M_{\odot}$, a radius of $1.278 \pm 0.070 R_{\odot}$, an effective temperature of 5050 ± 100 K, and solar metallicity (see Table 1). It is the physical companion of the G2 star HD 284154. Based on their position in color-magnitude diagrams, isochrone fitting, rotation period, lithium abundance, and X-ray emission, the pair belongs to the Group 29 stellar association¹⁴ and has an age of 20 ± 10 Myr.

V1298 Tau was observed by Kepler’s “Second Light” K2 mission^{15,16} during its campaign 4. The analysis of the K2 data, covering 71 days of continuous observations, revealed the presence of four transiting planets orbiting in the system¹¹. The three inner planets (b, c, and d) were determined to have orbital periods of 24.1396 ± 0.0018 , 8.24958 ± 0.00072 and 12.4032 ± 0.0015 days, and radii of $0.916^{+0.052}_{-0.047}$, $0.499^{+0.032}_{-0.029}$, and $0.572^{+0.040}_{-0.035} R_{\text{Jup}}$ (i.e. Jupiter radii). The fourth planet, e, was identified with only a single transit event, with a radius of $0.780^{+0.075}_{-0.064} R_{\text{Jup}}$ and orbital period estimated to be between 40 and 120 days. A previous study constrained the mass of V1298 Tau b to be smaller than $2.2 M_{\text{Jup}}$ ¹⁷ (i.e. Jupiter masses).

To measure the planetary masses, we performed an intensive spectroscopic campaign collecting more than 260 radial velocity (RV) measurements of V1298 Tau, using the high spectral resolution spectrographs HARPS-N¹⁸, CARMENES¹⁹, SES²⁰, and HERMES²¹ between April 2019 and April 2020. The relative radial velocities were obtained through two standard different techniques, depending on the instrument: matching each individual spectrum of V1298 Tau to a template constructed from all observed spectra of our target²² for HARPS-N and CARMENES, and a Gaussian fit to the function resulting from cross-correlating the spectra of V1298 Tau against a binary mask²³ for SES and HERMES. The derived RVs have a median internal uncertainty of 9 m s^{-1} for HARPS-N, 24 m s^{-1} for CARMENES, 117 m s^{-1} for SES, and 50 m s^{-1} for HERMES. The combination of data coming from all four spectrographs has proven convenient for monitoring the stellar activity, which has a semi-amplitude of about 250 m s^{-1} , as expected, given the young age

and rapid rotation of the star. However, the different wavelength coverage of each instrument and the varying response of V1298 Tau’s activity in the blue and red wavelengths – due to the different contrast of active regions at different wavelengths – introduced an additional complexity to the analysis of the RVs²⁴. We approached this issue by allowing different amplitudes in the stellar model for the instruments with different spectral ranges.

Young stars show large variations in flux and in RV due to magnetic activity. In V1298 Tau these variations are much larger than those expected for any of the planetary-induced signals. These variations have also a higher frequency than those induced by the planetary orbits due to the relatively fast stellar rotation. To better monitor the changes caused by stellar activity, we performed contemporaneous *V*-band photometry with a cadence of 1 observation every 8 hours using the Las Cumbres Observatory (LCOGT) network²⁵. We obtained 250 measurements with a typical precision of 10 parts per thousand (ppt). The data showed variations of up to 60 ppt, almost twice as large as those found in the K2 data. This is not surprising for a spot-dominated photosphere, as the Kepler passband is more extended towards red wavelengths, where the spot contrast is smaller. During the 2019–2020 campaign, our photometric data showed a rotation-induced signal at a period of 2.9104 ± 0.0019 days, slightly different from the period measured during the 2015 K2 campaign (2.869 ± 0.013 days). This difference could be attributed to differential rotation.

To mitigate the effects of activity on the RV data of V1298 Tau, we opted for a global model combining the K2 photometry, RV, and one contemporaneous activity proxy²⁶. For this particular purpose we used the LCOGT photometry as our proxy, as we could obtain a better observing cadence than for any of the spectroscopic indicators. The model uses the K2 photometry to constrain the planetary orbital periods, phases and radii, the LCOGT photometry and the RVs to constrain the timescales and amplitudes of the activity variations during our observing campaign, and the RVs to measure the masses of the planets. To model the activity components, we relied on a Gaussian processes (GP) regression^{27,28}. Given the complexity of the activity variations, we tested several GP kernels. More details can be found in the supplementary material. To take advantage of the sampling of the photometric follow-up, we shared several hyperparameters between the RV

and LCOGT time series. We added four Keplerian components to the RV model, representing the planets. The analysis considered a zero-point value and a noise term (jitter) for each dataset as free parameters to be optimised simultaneously, with the exception of the K2 data. For the K2 data we opted to manually include the white-noise component given in the discovery paper²⁹. To sample the posterior distribution and obtain the statistical significance of the model we relied on a Markov chain Monte Carlo (MCMC) procedure, using `emcee`³⁰.

We obtained significant measurements of the RV semi-amplitudes induced by planet b of $38 \pm 12 \text{ m s}^{-1}$, and by planet e of $65 \pm 16 \text{ m s}^{-1}$. For planets c and d, we can only set upper limits of 26 m s^{-1} and 24 m s^{-1} with a 99.7% confidence, respectively. Planet e was originally detected with a single transit, insufficient for the accurate measurement of its orbital period¹¹. Using the RV data, we obtained the detection at a period of $40.2 \pm 1.0 \text{ d}$, on the short end of the range expected from the transit duration²⁹. If this period is correct, the K2 mission missed transits right before and after its campaign by just a few days. We measured the orbital eccentricities for planets b and e to be 0.13 ± 0.07 and 0.12 ± 0.07 respectively. Figure 1 shows the phase folded curves of the RV signals attributed to planets b and e. The analysis of the RV and photometry during the 2019–2020 campaign yielded a stellar rotation period of $2.9104 \pm 0.0019 \text{ days}$, with a semi-amplitude in RV of about 250 m s^{-1} , and of 5% of the flux in the *V*-band photometry. Our analysis of the K2 data yielded orbital periods, times of transit, and relative radii consistent with the discovery paper¹⁰. Table S1 in the methods section shows the complete summary of our results, including all the alternative methods that we tested. We note that the determination of the period of planet e comes almost exclusively from the spectroscopic analysis. If the attribution of the ~ 40 -day period to V1298 Tau e is correct, the new TESS observations of V1298 Tau (Sectors 43 and 44, September – October 2021) should detect at least one transit of the planet.

We derived the masses of the planets b and e to be $0.60 \pm 0.20 M_{\text{Jup}}$ and $1.21 \pm 0.40 M_{\text{Jup}}$, respectively, placing both in the category of warm Jupiters. For the same planets we derived radii of $0.872 \pm 0.058 R_{\text{Jup}}$ and $0.725 \pm 0.075 R_{\text{Jup}}$, respectively, compatible with previous measurements¹⁰. From these measurements we derive densities of $1.11 \pm 0.46 \text{ g cm}^{-3}$ and $3.9 \pm 2.0 \text{ g}$

cm^{-3} , respectively. The density obtained for V1298 Tau b is consistent with that of Jupiter and makes this young planet resemble the current giant planets of the Solar System. For planet e we obtain a higher, but less precise, density. If this result were confirmed, it could be one of the densest giant planets known to date, similar to HATS-17 b¹² and Kepler-539 b¹³. For the two smaller planets, c and d, we calculated 3σ upper limits on their masses of $0.27 M_{\text{Jup}}$ and $0.32 M_{\text{Jup}}$, respectively, which set upper limits to the densities of 4.4 g cm^{-3} and 2.8 g cm^{-3} , respectively. The combination of the masses of all the pairs in the system are Hill-stable³¹. Table 2 shows the final planetary parameters adopted for the system.

Core accretion models of evolution of planetary systems predict planets of $\sim 20 \text{ Myr}$ to be at the early stages of their contraction phase, showing very large radii and low densities^{1,32–34}. Our results indicate that V1298 Tau b and e deviate from this picture. Figure 2 shows the position of the planets orbiting V1298 Tau in a mass-radius diagram compared to the known population of exoplanets. Similar to the case of AU Mic b⁹ – the only other exoplanet of similar age with a mass measurement – the mass-radius relation of the planets orbiting V1298 Tau resembles that of the planets of our Solar System and of the general population of known transiting exoplanets. However, in contrast to the case of AU Mic b, the planets V1298 Tau b and e seem incompatible with the expected population derived from these models of evolution of planetary systems. Figure 3 shows the planets orbiting V1298 Tau with the expected population of exoplanets orbiting a $1 M_{\odot}$ star at the ages of 20 Myr and 5 Gyr (simulation NG76³⁵ using the Bern model¹) and with the mass-radius tracks coming from other different models^{32,33}. These planets should not reach this mass-radius configuration until hundreds of Myr later². Considering their densities, it is not expected that the planets orbiting V1298 Tau will contract significantly in the future due to evaporation³⁶. Our result suggests that some giant planets might reach a mass-radius configuration compatible with the known mature population of exoplanets during their first 20 Myr of age.

An alternative explanation to the characteristics of V1298 Tau b and e could be offered by an extreme enrichment in heavy elements compared to giant planets of the Solar System and the general population of transiting exoplanets³⁷. A fraction of heavy elements of 40–60% and 60–80% of

the total mass of planets b and e would partially reconcile our results with the core-accretion evolutionary models^{1,32,33}. These enrichment would correspond to 3-20 times the fraction of heavy elements of Jupiter for V1298 Tau b, and 5-25 times for V1298 Tau e. Such high metallicities are not expected for planets orbiting stars with solar metallicity. Figure 3 shows the planets orbiting V1298 Tau with the mass-radius tracks derived for core-heavy exoplanets at the ages of 20 Myr and the age of the Solar System. The models for core-heavy exoplanets predict the planets will keep contracting, moving them to a region of the parameter space in which there are no known field exoplanets. If giant planets which such high metallicities could exist, and this scenario was correct, it would suggest that the two planets formed further away from their host star, possibly at separations of several astronomical units, consistent with those observed in protoplanetary disks imaged by ALMA³⁸, and experienced large-scale migration and accretion of planetesimals³⁹. Previous studies have shown that Neptune-sized exoplanets can be found in short orbits at the age of 10 Myr⁵. The original discovery of V1298 Tau b⁴⁰ also pointed in the same direction for planets with Jupiter-radii. We can now confirm that planets with masses similar to Jupiter can reach close-in orbits in the first 20 Myr.

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Author Contribution A.S.M. wrote the main text of the manuscript. A.S.M, V.J.S.B., J.I.G.H and M.R.Z.O wrote the methods section of the manuscript. A.S.M. and M.D. performed the radial velocity analysis. N.L., A.S., V. J. S. B., G. M., R. R., S. B., C.C.G., A.S.M., M.D., P. J. A. and M. W. coordinated the acquisition of the radial velocities. V. J. S. B., F.M., E.P., H.P. and E.E.B coordinated the acquisition of the photometry. A.S.M., B.T.P., F.F.B and T.G. performed the extraction of radial velocities. F.M. performed the extraction of the photometry. V.J.S.B., M.R.Z.O., J.I.G.H., C.d.B., H.M.T., D.S.A., N.L. and E.L.M. determined the stellar properties of V1298 Tau and HD 284154. R.C., A.M., D.T. contributed to the discussion on planetary evolution. R.R.L, A.S., M.R.Z.O., V.J.S.B and G.L. organised the collaboration between the different teams. M.D., A.S., S.B., G.M., S.D., R.C., L.M., V.D., D.L., F.M., D.T., A.M. are members of the GAPS consortium. P.J.A., J.A.C, A.Q., A.R. and I.R are members of the CARMENES consortium. L.M. participated in the discussion of stellar activity. T.G., K.G.S. and M.W. are members of the STELLA consortium. All authors were given the opportunity to review the results and comment on the manuscript.

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Figure 1: **Phase folded plots of the RV signals for the two planets of the V1298 Tau planetary system with significant mass measurements.** *Left panel:* Phase-folded representation of the best-fitting circular orbit (red line) for V1298 Tau b. *Right panel:* Same for V1298 Tau e. For a better visualisation, only HARPS and CARMENES data have been included. In all cases, 1σ error bars (internal RV uncertainties) of the measurements are shown.

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Figure 2: **Planets of V1298 Tau in the context of the known planets.** Histogram of the masses and radii of known planets for which the two parameters are determined with a precision better than 33%. The planets orbiting V1298 Tau are highlighted in teal symbols, with their 1σ error bars. The left-pointing arrows show the upper limits for the masses of V1298 Tau c and d. Jupiter and Saturn have been added for comparison. The planets at orbital periods larger than 12 days are shown with dark-grey symbols.

Figure 3: **Planets of V1298 Tau in the context of the models of evolution of exoplanets.** *Left panel:* Masses and radii of the planets orbiting V1298 Tau compared to the expected planetary population orbiting a star with solar mass and metallicity at 20 Myr and 5 Gyr³⁵. Core-heavy planets have been highlighted. *Center panel:* Masses and radii of the planets orbiting V1298 Tau compared to the mass radius-tracks from Fortney et al. for planets with light and heavy-cores ($50 - 100 M_{\oplus}$)³². *Right panel:* Masses and radii of the planets orbiting V1298 Tau compared to the mass radius-tracks by Baraffe et al. for planets with light and enriched cores ($Z \sim 0.5 - 0.9$)³³. All panels show the histogram of the known population of exoplanets, and the positions of Jupiter and Saturn, as reference points.

Table 1: **Stellar parameters of V1298 Tau and its wide companion HD 284154**

Parameter	V1298 Tau	HD 284154	Reference
RA [h m s]	04 05 19.59	04 05 14.35	41
DEC [$^{\circ}$ ' '']	+20 09 25.6	+20 08 21.5	41
Parallax [mas]	9.214 ± 0.05	9.202 ± 0.060	41
Distance [pc]	108.5 ± 0.7	108.7 ± 0.7	41
Spectral Type	K1	G2	42, 43
V [mag]	10.12 ± 0.05	8.51 ± 0.02	44
G [mag]	10.0702 ± 0.0007	8.3561 ± 0.0005	41
J [mag]	8.687 ± 0.023	7.287 ± 0.020	45
K [mag]	8.094 ± 0.021	6.947 ± 0.026	45
U [km s $^{-1}$]	-12.63 ± 0.03	-12.90 ± 0.64	This work
V [km s $^{-1}$]	-6.32 ± 0.06	-6.32 ± 0.10	This work
W [km s $^{-1}$]	-9.19 ± 0.06	-9.49 ± 0.28	This work
Age [Myr]	20 ± 10	20 ± 10	This work
Luminosity [$L_{\odot}$]	0.954 ± 0.040	4.138 ± 0.040^1	This work
Effective temperature [K]	5050 ± 100	5700 ± 100	This work
Mass [$M_{\odot}$]	1.170 ± 0.060	1.28 ± 0.06^2	This work
Radius [$R_{\odot}$]	1.278 ± 0.070	1.477 ± 0.082^2	This work
Rotation period [d]	2.91 ± 0.05		This work
Fe/H [dex]	0.10 ± 0.15	0.05 ± 0.15	This work

1: Corresponds to the binary system.

2: Measurement for each individual component assuming an equal-mass binary.

Table 2: **Planetary parameters for the V1298 Tau system.** Upper and lower limits show the 99.7% confidence interval. T0 given in BJD - 2450000.

Parameter	<i>V1298 Tau b</i>	<i>V1298 Tau c</i>	<i>V1298 Tau d</i>	<i>V1298 Tau e</i>
P_{orb} [d]	24.1399 ± 0.0015	8.24894 ± 0.00083	12.4058 ± 0.0018	40.2 ± 1.0
T_0 [d]	7067.0486 ± 0.0015	7064.2805 ± 0.0041	7072.3897 ± 0.0030	7096.6226 ± 0.0031
a [au]	0.1718 ± 0.0029	0.0840 ± 0.0013	0.1102 ± 0.0018	0.241 ± 0.064
R_p/R_*	0.0699 ± 0.0025	0.0372 ± 0.0017	0.0464 ± 0.0020	0.0583 ± 0.0040
R_p [R_{Jup}]	0.872 ± 0.058	0.464 ± 0.035	0.578 ± 0.043	0.725 ± 0.075
Incl. [$^\circ$]	> 88.7	> 87.5	> 88.3	> 89.0
K_{RV} [m s^{-1}]	38 ± 12	< 26	< 24	65 ± 16
e	0.134 ± 0.075	< 0.30	< 0.21	0.122 ± 0.079
m [M_{Jup}]	0.60 ± 0.20	< 0.27	< 0.32	1.21 ± 0.40
ρ [g cm^{-3}]	1.11 ± 0.46	< 4.4	< 2.8	3.9 ± 2.0

Methods

1 DATA

HARPS-N and CARMENES RVs HARPS-N¹⁸ is a fibre-fed high resolution échelle spectrographs installed at the 3.6 m Telescopio Nazionale Galileo of the Roque de los Muchachos Observatory (La Palma, Spain). It has a resolving power of 115 000 over a spectral range of 360–690 nm and is contained in a temperature- and pressure-controlled vacuum vessel to avoid spectral drifts due to temperature and air pressure variations. It is equipped with its own pipeline, providing extracted and wavelength-calibrated spectra, as well as RV measurements and other data products, such as cross-correlation functions and the bisector of their line profiles. We obtained 132 observations between 2019 and 2020: 72 of those measurements under Spanish time and the remaining 60 in the context of the GAPS programme^{45,46}, a long-term, multi-purpose, observational programme aimed to characterise the global architectural properties of exoplanetary systems. On-source integration times were typically set to 900s. Using the HARPS-N data, we obtained the S_{MW} ⁴⁷, $H\alpha$ ⁴⁸, NaI ⁴⁹ and TiO ⁵⁰ chromospheric indicators.

The CARMENES instrument consists of a visual (VIS) and near-infrared (NIR) spectrographs covering 520–960 nm and 960–1710 nm with a spectral resolution of 94 600 and 80 400, respectively¹⁹. It is located at the 3.5 m Zeiss telescope at the Centro Astronómico Hispano Alemán (Almería, Spain). We extracted the spectra with the CARACAL pipeline, based on flat-relative optimal extraction⁵¹. The wavelength calibration that was performed by combining hollow cathode lamps (U-Ar, U-Ne, and Th-Ne) and Fabry-Pérot etalons. The instrument drift during the nights is tracked with the Fabry-Pérot in the simultaneous calibration fibre. For our analysis, we rely only on the visual channel data. We obtained 35 observations between 2019 and 2020.

RVs for HARPS-N and CARMENES were obtained using SERVAL²⁴. This software builds a high signal-to-noise template by co-adding all the existing observations and then performs a maximum likelihood fit of each observed spectrum against the template yielding a measure of the Doppler shift and its uncertainty. We obtained typical RV precisions of 9 and 24 m s⁻¹ for HARPS and

CARMENES measurements.

SES RVs The STELLA échelle spectrograph (SES) is a high resolution spectrograph installed at the 1.2m STELLA telescope at the Teide Observatory (Tenerife, Spain) . It has a resolving power of 55 000 over a wavelength range of 390–870 nm²⁰. RVs were obtained by the automatic reduction pipeline, by cross-correlating the spectra with a synthetic stellar template with a temperature of 5000K. We obtained 61 epochs spread across 3 months, during the winter of 2019–2020, with the goal of following the activity variations of V1298 Tau. We obtained a typical RV precision of 117 m s⁻¹ per observation.

HERMES RVs The High-Efficiency and high-Resolution Mercator Échelle Spectrograph (HERMES) is a installed at the 1.2m Mercator telescope at the Roque de los Muchachos Observatory (La Palma, Spain)²¹. The spectra were automatically processed by the HERMES pipeline, but later we derived our own RV measurements by cross-correlating the spectra with a K1 synthetic template taken from the HARPS-N reduction pipeline. This made the effective wavelength range used for the RV calculation similar to the HARPS-N wavelength range. We obtained 35 measurements during 18 individual winter nights in 2019–2020, with the goal of monitoring the shape of the activity variations. We obtained a typical RV precision of 55 m s⁻¹ per observation.

LCO V-band photometry We observed V1298 Tau with the 40 cm telescopes of the Las Cumbres Observatory (LCOGT)²⁵. The 40 cm telescopes are equipped with a 3k×2k SBIG CCD camera with a pixel scale of 0.571 arcsec providing a field of view of 29.2×19.5 arcmin.

We observed V1298Tau in the *V*-band every 8h over 4 months, during the winter of 2019–2020. The raw images were reduced by LCO’s pipeline BANZAI and aperture photometry was performed on the calibrated images using *AstroImageJ*⁵². For each night, we selected a fixed circular aperture in *AstroImageJ* and performed aperture photometry on the target and 5 reference stars of similar brightness. We obtained 250 *V*-band measurements with a typical precision of 0.5% in relative flux.

K2 photometry As complementary data to the spectroscopic dataset, we downloaded the available photometric light curve obtained by the Kepler Space Telescope *K2* mission¹⁶ from the Mikulski Archive for Space Telescopes (MAST). This photometric dataset was taken in the long cadence mode, characterised by 30-min integration time. We adopted the EVEREST 2.0⁵³ light curve, which corrects for K2 systematics using a variant of the pixel-level decorrelation method⁵⁴. This time-series covers a time-span of about 71d (one Kepler quarter) from 2015 February 8 to 2015 April 20, which corresponds to the K2 Campaign 4.

FIES spectroscopy We took a single exposure of 2100s of HD 284154 with the high-resolution ($R \approx 67\,000$) FIES spectrograph at the 2.6m-NOT telescope of the Roque de los Muchachos Observatory (La Palma, Spain). Observations made on 18 August 2020.

2 Stellar parameters of V1298 Tau

Membership to Group 29 V1298 Tau is the low-mass companion of the warmer, G0-type star HD 284154 at a projected separation of 97.7 arcsec (or 10600 AU at the distance of the system). The pair belongs to the recently identified Group 29⁵⁵, which is a young, sparse association of coeval stars in the Taurus region, all of which share very similar proper motions and distances based on the Tycho-Gaia astrometric catalog (TGAS)^{56,57}. Using updated trigonometric parallaxes and other astrometric determinations provided by the Gaia Data Release 2⁴⁰, we confirm that both V1298 Tau ($\mu_\alpha \cos\delta = 5.23 \pm 0.13$, $\mu_\delta = -16.08 \pm 0.05$ mas a⁻¹, $d = 108.6 \pm 0.7$ pc) and HD 284154 ($\mu_\alpha \cos\delta = 5.04 \pm 0.12$, $\mu_\delta = -16.32 \pm 0.05$ mas a⁻¹, $d = 108.6 \pm 0.7$ pc) are proper motion companions located at a distance that is compatible with that of the Group. The Galactic velocities U, V, W of V1298 Tau and HD 284154 completely overlap with the distribution of the space motions of Group 29 members, thus providing additional support to the membership of V1298 Tau and HD 284154 in this association.

Effective temperature, surface gravity and metallicity of V1298 Tau We derived the stellar parameters and metallicity of V1298 Tau using the high-resolution HARPS-N spectra. The extracted, blaze-corrected 2D spectra were corrected for barycentric velocity (varying from +10.8 to

-30.4 km s^{-1}) and for RV (varying from $+14.4$ to $+15.7 \text{ km s}^{-1}$) and normalised to unity order by order with a third-order polynomial using our own IDL-based automated code⁵⁸. All orders of all spectra were co-added and merged with a wavelength step of $0.01 \text{ \AA}$ per pixel. The resulting 1D spectrum depicted in Figure ED 2 shows a signal-to-noise ratio of $\sim 107, 222, 284, 412$ and 391 at $4200, 4800, 5400, 6000$, and $6600 \text{ \AA}$, respectively.

Using the same automated code, we normalised and combined the HARPS-N spectra from our RoPES RV program⁵⁹ of three other stars (HD 220256, HD 20165 and ϵ Eri) with similar spectral types to be used as comparison stars. We compared the HARPS-N spectra of these templates with that of V1298 Tau to derive the projected rotation velocity of V1298 Tau. To reduce the computing load we restricted the calculation to the spectral range $5355\text{--}5525 \text{ \AA}$ and performed a Markov Chain Monte Carlo (MCMC) simulation with 5000 chains implemented in EMCEE. The mean stellar projected rotation velocity of V1298 Tau obtained from the three templates is $23.8 \pm 0.5 \text{ km s}^{-1}$.

To estimate the stellar parameters of V1298 Tau (T_{eff} and $\log g$, and metallicity, $[\text{Fe}/\text{H}]^a$), we used three different codes, which allowed us to check the consistency of the results. First, we used the FERRE code⁶⁰ with a grid of synthetic spectra⁶¹ with a micro-turbulence velocity fixed at $\xi_{\text{mic}} = 1.5 \text{ km s}^{-1}$ to fit the HARPS-N spectrum of V1298 Tau, providing $T_{\text{eff}}/\log g/A(\text{Fe}) = 5010/4.48/7.20$ (note that the canonical solar Fe abundance is $A_{\odot}(\text{Fe}) = 7.50$ ⁶²). For comparison, we also analysed the HARPS-N spectrum of the star ϵ Eri and the Kurucz solar ATLAS spectrum⁶³, both broadened with a rotation profile of 24 km s^{-1} , obtaining $T_{\text{eff}}/\log g/A(\text{Fe}) = 5085/4.91/7.24$ and $= 5912/4.74/7.31$, respectively. FERRE uses a running mean filter to normalise both synthetic and observed spectra and fits a wide spectral range of the HARPS-N spectrum ($4500\text{--}6800 \text{ \AA}$), masking out the Balmer and NaID lines, which for the young V1298 Tau star could show their cores in emission. Taking the analysis of the Solar ATLAS as the solar reference, this method #1 gives $[\text{Fe}/\text{H}] = -0.11$ as the metallicity of V1298 Tau. We suspect that slightly low metallicity is related to the relatively high microturbulence adopted for the grid of synthetic spectra⁶¹. The

^a $A(X) = \log[N(X)/N(\text{H})] + 12$ and $[\text{Fe}/\text{H}] = A(\text{X}) - A_{\odot}(\text{X})$ with $X = \text{Fe}$

expected microturbulent velocity should be $\xi_{\text{mic}} = 0.85 \text{ km s}^{-1}$ ⁶⁴, so this may be the reason why the derived metallicity with this method appears to be slightly lower than the solar value.

Second, we used the STEPARSYN code (Tabernero et al. 2021, in preparation), a Bayesian code that uses a synthetic grid of small spectral regions of $3 \text{ \AA}$ around 95 Fe lines with a fixed $\xi_{\text{mic}} = 0.85 \text{ km s}^{-1}$. The result of this second method is $5041/4.24/7.62$ a metallicity $[\text{Fe}/\text{H}] = +0.16$.

Third, we implemented a Bayesian python code that compares the observed spectrum with a synthetic spectrum in the spectral range $5350\text{--}5850\text{\AA}$ (see Figure ED 1). We performed a Markov Chain Monte Carlo (MCMC) simulation with 5000 chains implemented in EMCEE³⁰. We use a small $3 \times 3 \times 3$ grid of synthetic spectra with values $T_{\text{eff}}/\log g/\text{A}(\text{Fe})$ of $4750\text{--}5250/3.5\text{--}4.5/7.0\text{--}8.0$ and steps of $250 \text{ K} / 0.5 \text{ dex} / 0.5 \text{ dex}$, computed with the SYNPLE code, assuming a microturbulence $\xi_{\text{mic}} = 0.85 \text{ km s}^{-1}$, and ATLAS9 model atmospheres with solar α -element abundances ($[\alpha/\text{Fe}]=0$ ⁶⁵), and the same linelist as in method #1. This method #3 delivered $T_{\text{eff}}/\log g/\text{A}(\text{Fe}) = 5071/4.25/7.44$ and a metallicity $[\text{Fe}/\text{H}] = +0.07$ for V1289 Tau.

Taking into account the slightly different results from the three different methods we adopted the values $T_{\text{eff}}/\log g/[\text{Fe}/\text{H}] = 5050 \pm 100/4.25 \pm 0.20/+0.10 \pm 0.15$ for V1298 Tau. Finally, we checked the derived effective temperature by applying the implementation of the InfraRed Flux Method (IRFM⁶⁶). Using the available photometry in the infrared bands JHK_S from the Two Micron All-Sky Survey (2MASS⁶⁷) and the Johnson V magnitude from the AAVSO Photometric All-Sky Survey (APASS⁶⁸), and adopting $E(B - V) = 0.061$ from the dust maps⁶⁹ corrected⁷⁰ using the distance of 108 pc to V1298 Tau ⁴⁰, we applied the IRFM to obtain a $T_{\text{IRFM}} = 5047 \pm 66 \text{ K}$, in agreement with the spectroscopic value. Assuming an extinction $E(B - V) = 0.024 \pm 0.015$ ¹¹, we got $T_{\text{IRFM}} = 4947 \pm 67 \text{ K}$, and $4928 \pm 67 \text{ K}$ for $E(B - V) = 0$.

Effective temperature, surface gravity and metallicity of HD 284154 HD 284154 is resolved as a double-lined spectroscopic binary (see Figure ED 3), which has been identified as a wide binary of V1298 Tau⁵⁷. Using the FIES spectrum, we estimated a RV difference of $\delta RV = 43.6 \pm 1.0 \text{ km s}^{-1}$ between the two stellar components, an identical stellar rotation of $V_{\text{rot}} =$

$10 \pm 1 \text{ km s}^{-1}$ derived from the double-peaked cross-correlation function (CCF) of the observed FIES spectrum cross-correlated with a mask of isolated and relatively strong Fe lines. Assuming both binary components have the same mass (see below), the center-of-mass RV is $+14.8 \pm 0.7 \text{ km s}^{-1}$, perfectly compatible with the center-of-mass RV of V1298 Tau.

We applied method #3 to derive the stellar parameters and metallicity of both stellar components of HD 284154. We assumed both stars have the same luminosity and origin and therefore the same stellar mass and metallicity. We then generated a grid of synthetic spectra in the parameter range $T_{\text{eff}}/\log g/\text{A}(\text{Fe})$ of $5500 - 6000/3.5 - 4.5/7.0 - 8.0$ and steps of $250 \text{ K} / 0.5 \text{ dex} / 0.5 \text{ dex}$, with a fixed $\xi_{\text{mic}} = 0.95 \text{ km s}^{-1}$, and adding the fluxes of each component separated by $\delta RV = 43.6 \text{ km s}^{-1}$ (see Figure ED). We obtained $T_{\text{eff}}/\log g/[\text{Fe}/\text{H}] = 5700 \pm 100/4.35 \pm 0.20/+0.05 \pm 0.15$ for HD 284154.

Lithium abundance We used the MOOG code⁷¹ and ATLAS9 model atmospheres to derive the lithium abundances of V1298 Tau and HD 284154 (see Figure ED 4), with the approximation of local thermodynamical equilibrium (LTE). We applied the non-LTE corrections⁷² to get a Li abundance of $\text{A}(\text{Li}) = 3.43 \pm 0.15$ and 3.24 ± 0.15 , for V1298 Tau and HD 284154, respectively, roughly consistent with the solar meteoritic value⁶².

Masses, radii and luminosities We determined the bolometric luminosity of both V1298 Tau and HD 284154 by transforming the observed magnitudes into bolometric magnitudes using *Gaia* distances and colour-bolometric corrections⁷³. We confirmed that the obtained values (shown in Table 1) are fully compatible at the $1-\sigma$ level with those derived from the integration of the photometric spectral energy distributions using the Virtual Observatory Spectral Energy Distribution Analyzer⁷⁴ (VOSA) tool for the stellar effective temperatures. The radius of each star was then obtained from the Stefan-Boltzmann equation; we split the luminosity of HD 284154 in two identical parts to account for its nearly equal mass binary nature and arbitrarily augmented the error in the luminosity determination of each component by a factor of two. Masses were obtained from the comparison of the derived effective temperatures and bolometric luminosities with various stellar evolutionary models available in the literature^{75–77}. All models are consistent within the error bars.

Uncertainties in the mass determination account for the temperature and luminosity uncertainties and also for the dispersion of the results from the different models including models with slightly different metallic composition. We obtain mass and radius estimates of $1.170 \pm 0.060 M_{\odot}$ and $1.278 \pm 0.070 R_{\odot}$ for V1298 Tau, and $1.28 \pm 0.06 R_{\odot}$ and $1.477 \pm 0.082 R_{\odot}$ for each of the stars of HD 284154. All values are provided in Table 1. We additionally inferred the stellar parameters for V1298 Tau and HD 284154 from stellar evolution models using a Bayesian inference method⁷⁸. This Bayesian analysis makes use of the PARSEC v1.2S library of stellar evolution models⁷⁷. It takes the absolute G magnitude, the colour $G_{BP}-G_{RP}$, and [Fe/H] from *Gaia* DR2⁴⁰, returning theoretical predictions for other stellar parameters. We have assumed solar metallicity with [Fe/H]=0.00 $\pm$ 0.20. For HD 284154 it was assumed that this binary (whose Gaia photometry was corrected by adding 0.7526 mag) is in the pre-main sequence phase due to the expected youth of the association. For V1298 Tau we obtained a Log L of $-0.040 \pm 0.009 L_{\odot}$, an effective temperature of 4929 ± 32 K, a mass of $1.17 \pm 0.03 M_{\odot}$, a radius of 1.310 ± 0.027 and a log g of 4.271 ± 0.028 . For HD 284154 we obtained a Log L of $0.299 \pm 0.009 L_{\odot}$, an effective temperature of 5699 ± 55 K, a mass of $1.263 \pm 0.013 M_{\odot}$, a radius of 1.45 ± 0.04 and a log g of 4.218 ± 0.020 .

Age estimation Figure ED 5 shows that the photometric sequence of Group 29 is compatible with the isochrones of 10-30 Myr. This photometric sequence of Group 29 is sub-luminous compared to that of the Upper Scorpius association, and is very similar to that of the Beta Pic moving group. This suggests that the Group 29 and, hence, the V1298 Tau system, is older than the USco association (5-11 Myr¹⁰) and has a similar age to Beta Pic (20 ± 10 Myr⁷⁹). The rotation period of V1298 Tau (2.865 ± 0.012 d¹¹) points in a similar direction. It fits perfectly with stars with similar spectral types of very young associations such as Rho Ophiuchus, Taurus, Upper Scorpius and the Taurus foreground population⁸⁰, with ages in the range of 1–30 Myr, but rotates faster than stars of similar spectral types in open clusters such as the Pleiades (~ 110 Myr⁸¹) or Praesepe (600-800 Myr⁸²). The lithium content of V1298 Tau allows also constraining its age, since this element is destroyed in low-mass stars on timescales of tens of million years. Comparing the equivalent width of the lithium line of V1298 Tau (400 mÅ) with that of stars in open clusters and young moving groups of different ages⁸³, we can conclude that the lithium content of V1298 Tau is compatible

with an age of 1–20 Myr, and is larger than in stars in open clusters such as IC 2391 and IC 2602, with estimated ages of 35–50 Myr⁸⁴. V1298 Tau exhibits an X-ray emission of $4.58^{+1.71}_{-1.44} 10^{30}$ erg.s⁻¹⁸⁵, compatible with a stronger activity than the stars in the Pleiades^{86,87}, and has a UV excess (NUV–J = 8.15 ± 0.05 mag), characteristic of stars younger than ~ 100 Myr⁸⁸. In addition, employing the same Bayesian inference method used in previous section⁷⁸, we also obtained estimates for the ages of V1298 Tau and HD 28415 of 9 ± 2 Myr and 13 ± 4 Myr, respectively. Using all previous results, we can constraints the age of V1298 Tau to be 20 ± 10 Myr.

3 Modelling

We fit simultaneously the K2 photometry, LCO photometry and RV time-series. We model the activity signals in RV and the LCO photometry using Gaussian Processes (GP) with `celerite`⁸⁹. We used a variation of the *rotation* kernel described in the original `celerite` article:

$$k(\tau) = \frac{A^2}{2+C} \left[e^{-\tau/L_1} \left(\cos\left(\frac{2 \cdot \pi \tau}{P_{\text{rot}}}\right) + (1+C) \right) + \Delta^2 \cdot e^{-\tau/L_2} \left(\cos\left(\frac{4 \cdot \pi \tau}{P_{\text{rot}}}\right) + (1+C) \right) \right] + (\sigma^2(t) + \sigma_j^2) \cdot \delta_\tau \quad (1)$$

where A represents the covariance amplitude, P_{rot} is the rotation period, L_1 and L_2 represent the timescale of the coherence of the periodicity at the rotation period and its first harmonic, Δ represents the scaling in amplitude of the variability at the first harmonic of the rotation period, and C the balance between the periodic and the non-periodic components. The equation also includes a term of uncorrelated noise (σ), independent for every instrument, added quadratically to the diagonal of the covariance matrix to account for all un-modelled noise components, such as uncorrected activity or instrumental instabilities. δ_τ is the Kronecker delta function, and τ represents an interval between two measurements, $t - t'$. This kernel behaves similar to the classical quasi-periodic kernel²⁸, with an explicit mode at the first harmonic of the rotation period (PQP2 from now on). A simpler version of this kernel was successfully used to model the variations of Proxima Centauri to the level of the instrumental precision²⁶. To model the activity variations in the K2 photometry we used a combination of two simple harmonic oscillators (SHO) centred at the rotation period of the star and its first harmonic. This kernel has been shown to appropriately model the photo-

metric variations of V1298 Tau¹¹. The SHO kernel is described in equation 23 of the `celerite` article⁸⁹. To better constrain the behaviour of the GP in its description of the activity-induced RV variations, some of the hyper-parameters are shared between the GP of the LCO photometry and the RV²⁶. The period and timescales of coherence of the variability are shared parameters, while the amplitudes and mix factors are independent. As activity signals are known to have a chromatic dependence^{24,26}, we split the dataset by instruments and gave independent amplitudes of the activity signals to each instrument. The K2 observations were obtained in 2017, while the LCO and RV data was obtained during 2019 and 2020. As the activity is not expected to remain stable after such a long time, we used two groups of hyper-parameters for the two different observing campaigns. We measure the final planetary parameters by fitting transits of the K2 lightcurve using the `pytransit` package⁹⁰ and Keplerian orbits implemented with `Radvel`⁹¹ in the RVs.

To sample the posterior distribution of the model we relied on `emcee`³⁰, combining a differential evolution algorithm^{92,93} and a differential evolution algorithm with a snooker move⁹⁴, with a probability of 80% and 20%, respectively, to be used in each iteration. We initialised a number of independent chains equal to four times the number of free parameters, and ran the sampler for 1 000 000 iterations. Every 10 000 iterations we computed the auto-correlation time of the posterior. We stopped earlier if the number of steps was larger than 50 times the auto-correlation timescale, and the timescale changed less than 1% from the previous measurement. The burn-in period is later defined as 20 times the auto-correlation timescale. Then we estimate the Bayesian evidence of the model ($\text{Ln}Z$) using the posterior distribution⁹⁵.

We significantly detected the signals corresponding to planets b and e and derived upper limits for the amplitudes of the signals corresponding to planets c and d. This was our most significant model, with a measured $\text{Ln}Z$ of -4477 . To confirm our results we repeated the analysis described above using the combination of two simple harmonic oscillators (SHO) to model the RV and LCO variations. We obtained a similar result, with larger amplitude for planet b and smaller uncertainties, but less significant ($\text{Ln}Z$ of -4547). We also attempted to confirm the results using the Quasi-Periodic GP Kernel²⁸ to model the activity variations in the RV and LCO data, implemented

using *George*⁹⁶. Previous studies have found it effective to study young stars⁹⁷. In this case we obtain lower amplitudes for the signals attributed to planets *b* and *e*, and higher for planet *c*. This was the least favoured of the models we tested ($\text{Ln}Z$ of -4553). For the most favoured model (PQP2) we tested the difference between having 4 planetary components in the RV, 2 planetary components (*b* and *e*) and no planetary components. We found that a model with 2 Keplerian components in the RV is 30 times more likely than a model with no planetary signals. The model with 4 Keplerian components is less significant than the model with 2 Keplerian components, which is not surprising considering we could not detect the RV signals of planets *c* and *d*.

As the results coming from the different GP models are slightly different, we performed simulations to test the accuracy of the amplitude measurements in this particular case. To do that we subtracted the detected planetary signals from the RV to create an "activity-only" dataset. Following the same procedure as with our original RV dataset, we tested that all the models recovered amplitudes consistent with zero at the periods of the planets. Later we injected planetary signals at different amplitudes to study the behaviour of every model. The results were very similar to what we had already found. The PQP2 kernel recovered the amplitudes of the signals corresponding to planets *b* and *e* within a 5% accuracy for amplitudes larger than $20 \text{ m} \cdot \text{s}^{-1}$. The model showed a tendency to underestimate the amplitudes of planets *c* and *d* by a 20 % margin for amplitudes smaller than $20 \text{ m} \cdot \text{s}^{-1}$. The combination of two SHO kernels consistently overestimated the amplitude of planet *b*, while underestimating the amplitudes of the three remaining signals. The QP accurately recovered the amplitudes of planets *c* and *d*, and it strongly underestimated the amplitudes of the signals corresponding to planets *b* and *e*, sometimes by a 50% margin. This is not a fully unexpected behaviour, as the more flexible GP Kernels have a higher rate of false negatives⁹⁸. Figure ED 6 shows the comparison between the injected and recovered planetary amplitudes using the three GP kernels. The PQP2 kernel provided the best consistent results for all the tested combinations.

To further test our results we opted for a different approach based on the correlation of the RVs with the photometric data. In spot-dominated stars, the activity-induced RV variations are correlated

with the gradient of the flux²⁶. This correlation can be used to detrend the data from stellar activity. As we do not have simultaneous, but contemporaneous, photometry, we calculated the gradient from the model of the photometry. Figure ED 10 shows how the RV data (from HARPS-N and CARMENES) compare to the gradient of the V-band flux. We modelled the rotation using a third order polynomial against the derivative of the flux. A first attempt left some residual power at the first harmonic of the rotation period, which led us to include a sinusoidal component at that period. Our activity model is then defined as:

$$RV_{Rot} = C1 \cdot \frac{dFlux}{dt} + C2 \cdot \left(\frac{dFlux}{dt} \right)^2 + C3 \cdot \left(\frac{dFlux}{dt} \right)^3 + A_{Rot} \cdot \sin\left(4 \cdot \pi \frac{(t - T0)}{P_{Rot}}\right) \quad (2)$$

where T0 was parametrised as $JD_0 + P_{Rot} \cdot \phi$, with $JD_0 = 2458791.627$.

Using this model we recovered a very similar solution as with the mixture of two SHO kernels, although with much larger residuals. We detected the presence of the planets V1298 Tau b and e, and measured upper limits for the amplitudes of planets c and d. We measure the amplitude of planet e to be much larger than what was found with the GP models, which might be caused by the Keplerian model absorbing some unmodelled activity.

Table ED 1 shows the parameters used in the fit, the datasets involved in fitting every parameter, the priors and the results obtained for the different models tested. Figure ED 7 shows the RV data with the best fit model for the planetary parameters, and a weighted average model for the activity component. Figure ED 8 shows the best fit to the contemporary photometry and Figure ED 9 shows the best fit to the K2 observations.

Lessons learned and limitations We found that the signal phase folded to the rotation period shows clearly the two modes of oscillation that our favoured GP Kernel describes. The amplitude of the rotation signal is 8 times larger than the amplitude measured for the signal related to V1298 Tau b, and 5 times larger than the signal related to planet e. Figure ED 11 shows the huge RV amplitude difference between the stellar variability and the planetary detected signals. In young exoplanets field the stellar activity signals engulf those signals related to the planets and therefore

similarly large observational efforts with precise RV measurements will be required.

We found that not all GP Kernels behaved the same at all timescales in our dataset. The classic QP Kernel handles short-period signals quite well. However for longer period signals it seems to absorb a significant part of the Keplerian components, causing a clear underestimation of the measured amplitudes. The mixture of SHO kernels had the opposite behaviour. It *underfits* the activity component, leaving larger residuals and causing an overestimation of (some of) the Keplerian amplitudes. We found that our Kernel of choice (PQP2) provides better description of the activity variations of V1298 Tau and a more accurate determination of the Keplerian amplitudes.

It is important to remain cautious about the mass determined for the planet V1298 Tau e. The original detection did not constrain the orbital period, which is derived purely from the RV information. We studied the S_{MW} index⁴⁷, $H\alpha$ index⁴⁸, NaI index⁴⁹ and TiO⁵⁰ chromospheric indicators following a very similar procedure as with the RV data, not finding any significant periodicity (aside from the rotation) at periods shorter than 150 days, which favours the planetary hypothesis. However, disentangling planetary signals from stellar activity in RV in young stars such as V1298 Tau is a very challenging task. Without the confirmation of its orbital period by transit photometry it is very difficult to completely exclude a stellar origin (or contribution) to the signal.

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Code availability The SERVAl template-matching radial velocity measurement tool, Celerite, George, EMCEE, RADVEL, PyTransit, AstroImageJ, SYNPLE, StePar, FERRE and MOOG are easily accessible open source projects. Additional software available upon request.

Data availability The RV, LCOGT and K2 data is available at <https://cloud.iac.es/index.php/s/jto2dxfHRF2Aw2B>. The public high-resolution spectroscopic raw data used in the study can be freely downloaded from the corresponding facility archives. Proprietary raw data are available from A.S.M on reasonable request.

Extended Data Figure 1: Best synthetic spectral fit of the HARPS-N spectrum of V1298 Tau. The interpolated SYNPLE synthetic spectrum without rotational broadening computed for the derived best-fit stellar parameters and metallicity (top panel), the broadened spectrum with a rotational velocity of 24 km s^{-1} (middle panel) and the observed HARPS-N 1D spectrum of V1298 Tau (black line) together with the best-fit synthetic spectrum (purple line) are displayed in the spectral range 5350–5850 Å (bottom panel).

Extended Data Figure 2: HARPS-N spectrum of V1298 Tau. normalised HARPS-N 1D spectrum of V1298 Tau, corrected for barycentric velocity and RV, coadded and merged with a wavelength step of 0.01 Å/pixel, with a signal-to-noise ratio of ~ 320 at 5800 Å.

Extended Data Figure 3: Best synthetic spectral fit to the NOT FIES spectrum of HD 284154. The interpolated SYNPLE synthetic spectra without broadening computed for the derived best-fit stellar parameters and metallicity (top panel), the synthetic spectra separated by $RV \sim 43.6 \text{ km s}^{-1}$ with a rotational velocity of 10 km s^{-1} (middle panel) and the observed FIES 1D spectrum of HD 284154 (black line) together with the best-fit synthetic double-lined spectrum (purple line) are displayed in the spectral range 5350–5850 Å (bottom panel).

Extended Data Figure 4: The Lithium spectral region of V1298 Tau and HD 284154.

Spectral region of the lithium doublet around $6708 \text{ \AA}$ of the solar ATLAS spectrum broadened with a rotation profile of 24 km s^{-1} (top panel), the HARPS-N spectrum of V1298 Tau (middle panel), and the FIES spectrum of the double-lined spectroscopic binary HD 284154 (bottom panel), together with the best-fit MOOG synthetic spectra.

Extended Data Figure 5: Position of V1298 Tau and HD 284154 in the colour-magnitude and Hertzsprung-Russel diagrams. *Left panel:* Colour-magnitude diagram of V1298 Tau and HD 284154A and B (separate components) and the other group 29 members along with various PARSEC isochrones⁷⁷. The 20-Myr isochrone nicely reproduces the sequence of stars with colours $G - K_s < 3.5$ mag while the 10- and 30-Myr isochrones provide acceptable upper and lower envelopes to the observed dispersion of the Group 29 sequence. *Right panel:* Location of V1298 Tau (red) and HD 284154 (blue) in the Hertzsprung-Russel diagram. HD 284154 is decomposed into two equal mass and equal luminosity stars. The tracks for masses between 1.0 and 1.9 $M_{\odot}$ are also shown and are labeled with the mass value in solar units. Note that the luminosity axis is in logarithmic scale. The error bar in luminosity is of the size of the symbol.

Extended Data Figure 6: Accuracy of the recovered planetary amplitudes of the different methods. Recovered planetary amplitude against injected planetary amplitude in the simulated datasets

Extended Data Figure 7: RV time series with the best model fit of V1298 Tau. *Top left panel:* Full time series with the best fit model combining stellar activity and planetary signals. The stellar activity model represented is a weighted average of the models used for the different spectral ranges. *Top right panel:* Zoom on the intensive observational campaign. *Bottom left panel:* Planetary RV component, after subtracting the stellar induced signal. *Bottom right panel:* Zoom to the intensive observational campaign.

Extended Data Figure 8: LCO V-band photometry. *Left panel:* Time series of the LCO V-band photometry with the best fit obtained from the global analysis. *Right panel:* Zoom to a well-sampled section.

Extended Data Figure 9: K2 photometry. Time series of the K2 photometry with the best fit obtained from the global analysis. *Top left panel:* K2 data with the full fit. *Top right panel:* Data detrended from stellar activity with the best fit to the transits. *Bottom panels:* Phase folded plots of the transits of the four planets.

Extended Data Figure 10: Correlation between the RV and the derivative of the V-band flux.

RV measurements plotted against the derivative of the V-band flux as measured in the LCO data.

Extended Data Figure 11: Comparison between the activity induced RV signal and the planetary signals. RV data folded in phase with the stellar rotation period (left panel) and the V1298 Tau b and V1298 Tau e planetary signals (middle and right panels). For the planetary signals only HARPS and CARMENES data have been plotted.

Extended Data Table 1: Parameters and priors for the combined model. The column "Dataset" shows between which datasets the parameter is shared during the optimisation. All T0s are expressed in BJD - 2450000. Datasets: 1 - K2; 2 - LCO; 3 - HARPS-N RV; 4 - CARMENES RV; 5 - SES RV; 6 - HERMES RV. ¹The correlation model ($4p_{Corr}$) uses a different amount of data.

Parameter	Dataset	Priors	$4p_{PQP2}$	$4p_{Damped}$	$4p_{QP}$	$4p_{Corr}$
<i>Planets</i>						
T0 b [d]	1,3,4,5,6	$\mathcal{N}(7067.0488, 1)$	$7067.0486^{+0.0015}_{-0.0017}$	$7067.0484^{+0.0018}_{-0.002}$	$7067.0486^{+0.0018}_{-0.0021}$	$7067.0486^{+0.0014}_{-0.0015}$
P b [d]	1,3,4,5,6	$\mathcal{N}(24.1396, 1)$	$24.1399^{+0.0015}_{-0.0016}$	$24.14^{+0.0015}_{-0.0014}$	$24.1396^{+0.0016}_{-0.0016}$	$24.1395^{+0.0016}_{-0.0015}$
R_p/R_* b	1	$\mathcal{U}(0, 0.2)$	$0.0699^{+0.0027}_{-0.0025}$	$0.0702^{+0.0027}_{-0.0024}$	$0.07^{+0.0029}_{-0.0027}$	$0.0704^{+0.0024}_{-0.0025}$
Imp b	1	$\mathcal{U}(0, 1)$	$0.37^{+0.12}_{-0.21}$	$0.4^{+0.09}_{-0.18}$	$0.37^{+0.11}_{-0.2}$	$0.41^{+0.08}_{-0.15}$
K b [m s^{-1}]	3,4,5,6	$\mathcal{U}(0, 200)$	38^{+13}_{-12}	$49.1^{+8.5}_{-8.9}$	20^{+11}_{-8}	48^{+18}_{-15}
$\sqrt{e} \cdot \cos \omega$ b	1,3,4,5,6	$\mathcal{U}(-1, 1)$	$0.32^{+0.13}_{-0.16}$	$0.32^{+0.1}_{-0.25}$	$-0.12^{+0.28}_{-0.3}$	$-0.14^{+0.5}_{-0.34}$
$\sqrt{e} \cdot \sin \omega$ b	1,3,4,5,6	$\mathcal{U}(-1, 1)$	$0.04^{+0.15}_{-0.18}$	$-0.0^{+0.15}_{-0.18}$	$0.04^{+0.15}_{-0.19}$	$-0.01^{+0.16}_{-0.14}$
T0 c [d]	1,3,4,5,6	$\mathcal{N}(7064.2797, 1)$	$7064.2806^{+0.0039}_{-0.0048}$	$7064.2805^{+0.0038}_{-0.0043}$	$7064.2795^{+0.0044}_{-0.0057}$	$7064.2797^{+0.0039}_{-0.0046}$
P c [d]	1,3,4,5,6	$\mathcal{N}(8.24958, 1)$	$8.2491^{+0.001}_{-0.0009}$	$8.24899^{+0.00093}_{-0.00082}$	$8.2495^{+0.0015}_{-0.0012}$	$8.2492^{+0.001}_{-0.0009}$
R_p/R_* c	1	$\mathcal{U}(0, 0.2)$	$0.0372^{+0.0019}_{-0.0017}$	$0.0372^{+0.002}_{-0.0019}$	$0.0355^{+0.0021}_{-0.0023}$	$0.0369^{+0.0018}_{-0.0018}$

Continued on next page

Extended Data Table 1 – Continued from previous page

Imp c	1	$\mathcal{U}(0, 1)$	$0.26^{+0.16}_{-0.16}$	$0.25^{+0.16}_{-0.17}$	$0.22^{+0.19}_{-0.15}$	$0.12^{+0.2}_{-0.08}$
K c [m s ⁻¹]	3,4,5,6	$\mathcal{U}(0, 200)$	$5.6^{+5.7}_{-4.0}$	$5.3^{+5.7}_{-3.7}$	$9.9^{+4.7}_{-4.9}$	$11.8^{+8.1}_{-6.7}$
$\sqrt{e} \cdot \cos \omega$ c	1,3,4,5,6	$\mathcal{U}(-1, 1)$	$0.05^{+0.26}_{-0.26}$	$0.03^{+0.25}_{-0.27}$	$0.21^{+0.18}_{-0.28}$	$0.0^{+0.26}_{-0.26}$
$\sqrt{e} \cdot \sin \omega$ c	1,3,4,5,6	$\mathcal{U}(-1, 1)$	$-0.13^{+0.18}_{-0.18}$	$-0.13^{+0.17}_{-0.19}$	$-0.14^{+0.17}_{-0.16}$	$-0.03^{+0.14}_{-0.18}$
T0 d [d]	1,3,4,5,6	$\mathcal{N}(7072.3913, 1)$	$7072.39^{+0.0039}_{-0.0035}$	$7072.3902^{+0.0047}_{-0.0038}$	$7072.3909^{+0.0033}_{-0.0036}$	$7072.3905^{+0.0043}_{-0.0033}$
P d [d]	1,3,4,5,6	$\mathcal{N}(12.4032, 1)$	$12.4052^{+0.0021}_{-0.0017}$	$12.4053^{+0.002}_{-0.0018}$	$12.4075^{+0.0013}_{-0.0017}$	$12.405^{+0.0022}_{-0.0017}$
R _p /R _* d	1	$\mathcal{U}(0, 0.2)$	$0.0464^{+0.002}_{-0.0022}$	$0.0463^{+0.0021}_{-0.0022}$	$0.0496^{+0.0021}_{-0.0022}$	$0.0461^{+0.0022}_{-0.0023}$
Imp d	1	$\mathcal{U}(0, 1)$	$0.17^{+0.15}_{-0.11}$	$0.17^{+0.15}_{-0.12}$	$0.13^{+0.13}_{-0.09}$	$0.13^{+0.14}_{-0.09}$
K d [m s ⁻¹]	3,4,5,6	$\mathcal{U}(0, 200)$	$6.2^{+7.5}_{-4.3}$	$2.6^{+3.6}_{-1.9}$	$5.1^{+4.9}_{-3.5}$	$3.8^{+5.2}_{-2.8}$
$\sqrt{e} \cdot \cos \omega$ d	1,3,4,5,6	$\mathcal{U}(-1, 1)$	$0.01^{+0.23}_{-0.23}$	$0.0^{+0.22}_{-0.2}$	$0.02^{+0.2}_{-0.21}$	$0.01^{+0.22}_{-0.22}$
$\sqrt{e} \cdot \sin \omega$ d	1,3,4,5,6	$\mathcal{U}(-1, 1)$	$-0.06^{+0.16}_{-0.13}$	$-0.05^{+0.15}_{-0.14}$	$-0.14^{+0.13}_{-0.11}$	$-0.01^{+0.16}_{-0.13}$
T0 e [d]	1,3,4,5,6	$\mathcal{N}(7096.6229, 1)$	$7096.6228^{+0.0034}_{-0.0032}$	$7096.6229^{+0.0034}_{-0.0033}$	$7096.6229^{+0.0039}_{-0.0034}$	$7096.6227^{+0.0032}_{-0.0029}$
Log P e [d]	1,3,4,5,6	$\mathcal{U}(35, 400)$	$3.693^{+0.024}_{-0.024}$	$3.65^{+0.044}_{-0.022}$	$3.817^{+0.167}_{-0.099}$	$3.694^{+0.022}_{-0.022}$
R _p /R _* e	1	$\mathcal{U}(0, 0.2)$	$0.0583^{+0.0048}_{-0.005}$	$0.0576^{+0.0047}_{-0.0048}$	$0.0587^{+0.0052}_{-0.0054}$	$0.0578^{+0.0048}_{-0.0044}$
Imp e	1	$\mathcal{U}(0, 1)$	$0.49^{+0.09}_{-0.17}$	$0.45^{+0.1}_{-0.17}$	$0.51^{+0.09}_{-0.2}$	$0.46^{+0.08}_{-0.19}$
K e [m s ⁻¹]	3,4,5,6	$\mathcal{U}(0, 200)$	65^{+16}_{-19}	$61.2^{+8.2}_{-8.2}$	48^{+15}_{-16}	84^{+10}_{-9}
$\sqrt{e} \cdot \cos \omega$ e	1,3,4,5,6	$\mathcal{U}(-1, 1)$	$0.21^{+0.18}_{-0.27}$	$0.24^{+0.15}_{-0.24}$	$0.09^{+0.29}_{-0.32}$	$0.22^{+0.16}_{-0.21}$
$\sqrt{e} \cdot \sin \omega$ e	1,3,4,5,6	$\mathcal{U}(-1, 1)$	$0.01^{+0.25}_{-0.27}$	$0.04^{+0.19}_{-0.24}$	$0.1^{+0.27}_{-0.3}$	$0.11^{+0.19}_{-0.23}$
<i>Activity</i>						
Ln A [ppt]	1	$\mathcal{U}(-10, 10)$	$2.76^{+0.28}_{-0.26}$	$2.87^{+0.35}_{-0.3}$	$2.91^{+0.64}_{-0.41}$	$2.89^{+0.57}_{-0.44}$
Ln A [ppt]	2	$\mathcal{U}(-10, 10)$	$3.32^{+0.2}_{-0.18}$	$3.29^{+0.28}_{-0.31}$	$3.51^{+0.27}_{-0.22}$	
Ln A RV [m s ⁻¹]	3	$\mathcal{U}(-10, 10)$	$5.54^{+0.21}_{-0.19}$	$5.26^{+0.23}_{-0.2}$	$5.45^{+0.12}_{-0.11}$	$4.04^{+0.21}_{-3.1}$
Ln A RV [m s ⁻¹]	4	$\mathcal{U}(-10, 10)$	$5.49^{+0.21}_{-0.22}$	$5.33^{+0.32}_{-0.38}$	$5.43^{+0.17}_{-0.17}$	$-0.9^{+4.42}_{-6.0}$
Ln A RV [m s ⁻¹]	5	$\mathcal{U}(-10, 10)$	$5.59^{+0.24}_{-0.21}$	$5.24^{+0.26}_{-0.24}$	$5.67^{+0.18}_{-0.16}$	$4.34^{+0.37}_{-2.56}$
Ln A RV [m s ⁻¹]	6	$\mathcal{U}(-10, 10)$	$6.01^{+0.26}_{-0.27}$	$5.74^{+0.3}_{-0.25}$	$5.99^{+0.21}_{-0.19}$	$-1.78^{+4.59}_{-5.26}$
P _{rot} 2015 [d]	1	$\mathcal{U}(2.75, 3.1)$	$2.869^{+0.013}_{-0.013}$	$2.869^{+0.013}_{-0.012}$	$2.867^{+0.013}_{-0.012}$	$2.869^{+0.013}_{-0.013}$
Log T _{Scale 1} 2015 [d]	1	$\mathcal{U}(-10, 10)$	$5.51^{+0.75}_{-0.75}$	$5.74^{+0.81}_{-0.76}$	$5.96^{+1.27}_{-1.03}$	$5.8^{+1.25}_{-1.02}$
Log T _{Scale 2} 2015 [d]	1	$\mathcal{U}(-10, 10)$	$0.75^{+0.22}_{-0.18}$	$0.73^{+0.2}_{-0.17}$	$0.69^{+0.22}_{-0.18}$	$0.76^{+0.21}_{-0.17}$
P _{rot} 2019 [d]	1	$\mathcal{U}(2.75, 3.1)$	$2.9104^{+0.0019}_{-0.002}$	$2.9104^{+0.002}_{-0.0017}$	$2.8946^{+0.0046}_{-0.0035}$	$2.9038^{+0.0071}_{-0.0035}$
Log T _{Scale 1} 2019 [d]	1	$\mathcal{U}(-10, 10)$	$5.44^{+0.42}_{-0.36}$	$4.35^{+0.79}_{-0.62}$	$3.35^{+0.08}_{-0.1}$	
Log T _{Scale 2} 2019 [d]	1	$\mathcal{U}(-10, 10)$	$4.91^{+0.49}_{-0.41}$	$5.8^{+0.67}_{-0.63}$		
Log Δ RV	3,4,5,6	$\mathcal{U}(-10, 10)$	$-0.16^{+0.22}_{-0.21}$	$-0.13^{+0.26}_{-0.24}$		

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Extended Data Table 1 – Continued from previous page

Log Δ Phot	1,2	$\mathcal{U}(-10, 10)$	$-0.96^{+0.26}_{-0.28}$	$-1.08^{+0.31}_{-0.34}$	$-1.11^{+0.43}_{-0.64}$	$-1.08^{+0.44}_{-0.59}$
Log C RV [d]	3,4,5,6	$\mathcal{U}(-10, 10)$	$-4.8^{+3.3}_{-3.4}$			
Log C Phot [d]	2	$\mathcal{U}(-10, 10)$	$-5.9^{+3.0}_{-2.8}$			
Log ω RV	3,4,5,6	$\mathcal{U}(-10, 10)$			$-1.18^{+0.09}_{-0.09}$	
Log ω Phot	2	$\mathcal{U}(-10, 10)$			$-0.32^{+0.19}_{-0.18}$	
Phase Rot	3,4,5,6	$\mathcal{U}(0, 1)$				$0.6^{+0.33}_{-0.04}$
C1 [m·ppm ⁻¹]		$\mathcal{N}(0,100)$				$-149.52^{+2.75}_{-7.21}$
C2 [m ² ·ppm ⁻²]		$\mathcal{N}(0,100)$				$11.13^{+6.07}_{-4.3}$
C3 [m ³ ·ppm ⁻³]		$\mathcal{N}(0,100)$				$-9.57^{+2.56}_{-2.01}$
<i>Instrumental</i>						
F0 _{K2} [ppt]	1	$\mathcal{N}(0, 30)$	$0.02^{+0.23}_{-0.26}$	$0.01^{+0.25}_{-0.24}$	$0.02^{+0.27}_{-0.26}$	$0.01^{+0.23}_{-0.24}$
F0 _{LCO} [ppt]	1	$\mathcal{N}(0, 30)$	$1.4^{+8.9}_{-8.9}$	$1.7^{+0.58}_{-0.57}$	4^{+16}_{-15}	
V0 _{HARPS-N} RV [m s ⁻¹]	3	$\mathcal{N}(0, 100)$	-9^{+88}_{-86}	$-37.0^{+6.5}_{-6.7}$	-51^{+60}_{-57}	-76^{+21}_{-22}
V0 _{CARMENES} RV [m s ⁻¹]	4	$\mathcal{N}(0, 100)$	-16^{+89}_{-85}	-1^{+13}_{-12}	-46^{+70}_{-76}	-35^{+24}_{-24}
V0 _{SES} RV [m s ⁻¹]	5	$\mathcal{N}(0, 100)$	-14^{+87}_{-90}	-1^{+17}_{-18}	-56^{+99}_{-104}	-49^{+28}_{-27}
V0 _{HERMES} RV [m s ⁻¹]	6	$\mathcal{N}(0, 100)$	-15^{+92}_{-89}	-52^{+16}_{-17}	-87^{+147}_{-146}	-79^{+27}_{-30}
Ln Jit _{LCO} Flux [ppt]	2	$\mathcal{U}(-10, 10)$	$1.2^{+0.13}_{-0.14}$	$1.69^{+0.24}_{-0.4}$	$1.588^{+0.074}_{-0.089}$	
Ln Jit _{HARPS-N} RV [m s ⁻¹]	3	$\mathcal{U}(-10, 10)$	$3.36^{+0.14}_{-0.15}$	$3.81^{+0.14}_{-0.21}$	$3.04^{+0.15}_{-0.19}$	$4.16^{+0.12}_{-0.09}$
Ln Jit _{CARMENES} RV [m s ⁻¹]	4	$\mathcal{U}(-10, 10)$	$-2.8^{+4.5}_{-4.9}$	$1.5^{+2.8}_{-7.5}$	$-3.0^{+4.3}_{-4.7}$	$4.6^{+0.1}_{-0.2}$
Ln Jit _{SES} RV [m s ⁻¹]	5	$\mathcal{U}(-10, 10)$	$-2.9^{+4.7}_{-4.7}$	$-2.4^{+5.4}_{-5.1}$	$-3.3^{+4.7}_{-4.6}$	$0.2^{+4.1}_{-6.9}$
Ln Jit _{HERMES} RV [m s ⁻¹]	6	$\mathcal{U}(-10, 10)$	$-0.7^{+4.7}_{-6.6}$	$-1.5^{+5.0}_{-5.7}$	$1.1^{+3.0}_{-7.6}$	$4.8^{+0.2}_{-0.2}$
<i>Limb Darkening</i>						
Limb _L	1	$\mathcal{U}(0, 1)$	$0.35^{+0.15}_{-0.16}$	$0.34^{+0.16}_{-0.15}$	$0.44^{+0.16}_{-0.17}$	$0.37^{+0.17}_{-0.15}$
Limb _Q	1	$\mathcal{U}(0, 1)$	$0.63^{+0.25}_{-0.3}$	$0.63^{+0.24}_{-0.32}$	$0.53^{+0.3}_{-0.32}$	$0.58^{+0.26}_{-0.31}$
<i>Residuals</i>						
RMS O - C [m s ⁻¹]	3,4,5,6		47	66	48	98
RMS O - C [m s ⁻¹]	3,4		26	36	18	65
<i>Bayesian Evidence</i>						
LnZ			-4477	-4546	-4553	-3488 ¹

Figures

Figure 1

Phase folded plots of the RV signals for the two planets of the V1298 Tau planetary system with significant mass measurements. Left panel: Phase-folded representation of the best-fitting circular orbit (red line) for V1298 Tau b. Right panel: Same for V1298 Tau e. For a better visualisation, only HARPS and CARMENES data have been included. In all cases, 1σ error bars (internal RV uncertainties) of the measurements are shown.

Figure 2

Planets of V1298 Tau in the context of the known planets. Histogram of the masses and radii of known planets for which the two parameters are determined with a precision better than 33%. The planets orbiting V1298 Tau are highlighted in teal symbols, with their 1σ error bars. The left-pointing arrows show the upper limits for the masses of V1298 Tau c and d. Jupiter and Saturn have been added for comparison. The planets at orbital periods larger than 12 days are shown with dark-grey symbols.

Figure 3

Planets of V1298 Tau in the context of the models of evolution of exoplanets. Left panel: Masses and radii of the planets orbiting V1298 Tau compared to the expected planetary population orbiting a star with solar mass and metallicity at 20 Myr and 5 Gyr³⁵. Core-heavy planets have been highlighted. Center panel: Masses and radii of the planets orbiting V1298 Tau compared to the mass radius-tracks from Fortney et al. for planets with light and heavy-cores (50 – $100 M_{\oplus}$)³². Right panel: Masses and radii of the planets orbiting V1298 Tau compared to the mass radius-tracks by Baraffe et al. for planets with light and enriched cores ($Z \sim 0.5 - 0.9$)³³. All panels show the histogram of the known population of exoplanets, and the positions of Jupiter and Saturn, as reference points.