A super-Earth and two sub-Neptunes transiting the nearby and quiet M dwarf TOI-270

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Supplementary Information:
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On Bayesian statistics, Nested Sampling and Gaussian Processes

Here, we briefly outline the key concepts of Bayesian statistics, Nested Sampling and Gaussian Processes, which we extensively use for all analyses. Following Bayes’ theorem, the ‘posterior’ $P(\theta|M, D)$ is the degree of belief about the model $M$ and its parameters $\theta$, which is updated based on data $D$. It is given by:

$$P(\theta|M, D) = \frac{P(D|\theta, M)P(\theta|M)}{P(D|M)}.$$  \hspace{1cm} (1)

Therein, the ‘likelihood’ $P(D|\theta, M)$ is the probability of observing the data given the model and parameters. The ‘prior’ $P(\theta|M)$ limits and informs the model parameters. The last term, $P(D|M)$, is the ‘Bayesian evidence’,

$$P(D|M) = \int P(D|\theta, M)P(\theta|M)d\theta.$$ \hspace{1cm} (2)

and quantifies the degree of belief about the model itself given the data (marginalised over all parameters). Comparing different physical models, which is often desired in exoplanet studies, relies on the estimation of the Bayesian evidence, $P(D|M)$.

Nested Sampling \cite{1} is designed to directly compute the Bayesian evidence – making it distinct from Markov Chain Monte Carlo (MCMC) approaches, which bypass this step. For example, this enables the robust comparison of models with different numbers of exoplanets \cite{2}, circular versus eccentric orbits, or TTVs versus no TTVs. With Nested Sampling we draw samples from the prior volume (of the model parameter space) with hard likelihood thresholds. Successively, samples with the smallest likelihood get rejected, until the posterior distribution is found.

For modelling correlated noise in the data, we employ a Gaussian Process (GP) jointly with our transit model fit. A GP uses different kernels and metrics to evaluate the correlation between data points. The squared distance $r^2$ between data points $x_i$ and $x_j$ is evaluated for any metric M as

$$r^2 = (x_i - x_j)^T M^{-1} (x_i - x_j).$$ \hspace{1cm} (3)

We choose our GP with a series approximation of a ‘Matern 3/2’ kernel $k(r)$ using the \texttt{celerite} implementation \cite{3}:

$$k(r) = \sigma^2 \left[ (1 + 1/\epsilon)e^{-(1-\epsilon)\sqrt{r}/\rho} - (1 - 1/\epsilon)e^{-(1+\epsilon)\sqrt{r}/\rho} \right].$$ \hspace{1cm} (4)

This kernel has two hyperparameters that are fitted for: the amplitude $\sigma$, and the time scale $\rho$ of the correlations. In this expression used by \texttt{celerite}, $\epsilon$ controls the quality of the series approximation and is set to 0.01; in the limit $\epsilon \to 0$ it becomes the Matern-3/2 function. This kernel can describe variations with a smooth, characteristic length scale together with rougher (i.e. more stochastic) features.

Orbital dynamics

To investigate the dynamical stability of the TOI-270 system for a range of planet masses, we utilised the Mercury Integrator Package written by \cite{4}. The 4-body integrations were carried out for a duration of $10^8$ simulation years, equivalent to $1.1 \times 10^8$ orbits of the inner planet and $3.2 \times 10^7$ orbits of the outer planet. To ensure a sufficient time resolution, we adopt the criteria of \cite{5} and choose a time resolution of 0.05 days. Regarding the initial orbital conditions of the planets, we assume zero eccentricity, a periastron argument of $\omega = 90^\circ$, and specify the time of inferior conjunction using the $T_0$ values for each of the planets shown in Table 1. The planet masses are adopted from the predicted values. We conduct a series of dynamical simulations that vary the mean anomaly (starting locations) for each of the planets. This technique explores the orbital parameter space that determines dynamical stability as a function of various system parameters \cite{6,7}. Assuming initial circular orbits, we find that the system is exceedingly stable with eccentricities remaining below 0.4% (Supplementary Fig. \cite{5}). Gradually raising the assumed masses, we find that the system remains stable up to ten times the original mass estimates. In the range of 10–30 times the original masses, instability in the system becomes inevitable with planets either being ejected from the system or colliding with the host star.

Independently, to explore the system’s stability in the context of non-circular orbits we computed the Mean Exponential Growth factor of Nearby Orbits, $Y(t)$ (MEGNO, \cite{8,9,10}). This chaos index evaluates the stability of the bodies’ trajectories after small perturbations. Each body’s six-dimensional displacement vector, $\delta_i$, (position and velocity) is a dynamical variable from its ‘shadow particle’ (a particle with slightly perturbed initial conditions). We obtained differential equations for each $\delta_i$ by applying a variational principle to the trajectories of the original bodies. Next, the MEGNO was computed from the vari-
lations as:

\[ Y(t) = \frac{2}{t} \int_0^t \frac{||\delta(s)||}{||\delta(s)||} s ds \]  

(5)

along with its time-average mean value

\[ \langle Y(t) \rangle = \frac{1}{t} \int_0^t Y(s) ds. \]  

(6)

The time-weighting factor amplifies any stochastic behaviour, which allows the detection of hyperbolic regions in the time interval \((0, t)\). \(\langle Y(t) \rangle\) enables to distinguish between chaotic and quasi-periodic trajectories: if \(\langle Y(t) \rangle \rightarrow \infty\) for \(t \rightarrow \infty\) the system is chaotic; while if \(\langle Y(t) \rangle \rightarrow 2\) for \(t \rightarrow \infty\) the motion is quasi-periodic. With this technique we evaluate the upper limits of the eccentricities, and constructed a set of three two-dimensional MEGNO-maps (Supplementary Fig. 3). We use the MEGNO implementation with the N-body integrator REBOUND [11][12]. The integration time is set to \(10^6\) times the orbital period of the outermost planet, TOI-270 d. The time-step was set as \(5\%\) of the period of the innermost planet, TOI-270 b, and the simulation was stopped when \(\langle Y(t) \rangle > 10\). We run three independent simulations to analyse the upper limits of the eccentricities for pairs of planets, while keeping the third planet’s orbit circular in each case. All other planet parameters are fixed to the values in Table 1. The size of each MEGNO-map is \(100 \times 100\) pixels, meaning we explore the eccentricity space for each planet pair up to \(10,000\) times. The results suggest that low eccentricities of 0.05 for all planets are possible. The most restrictive eccentricity is detected for the middle planet TOI-270 c, with an upper-limit of 0.05. Planets b and d could reach eccentricities up to 0.1.

In a closely-packed system like TOI-270, tidal interactions between the star and the planets additionally influence the evolution of the orbits. However, the timescale for each parameter differs; for example, the semi-major axis evolves the slowest, while the obliquity and the planetary rotational period can change fast. We explore the tidal evolution using the ‘constant time-lag model’, where the bodies are a weakly viscous fluid [13]. The mathematical description is given in [14] [15] [16] [17] and summarised by [18], who implemented it first in their code MERCURY-T and later in POSIDONIUS [19]. We use both codes to verify our findings. TOI-270 b likely is Earth-like/rocky, therefore we assume the product of the potential Love number of degree 2 and a time-lag corresponding to Earth’s value of \(k_2,\oplus \Delta \tau_\oplus = 213\) s [20]. TOI-270 c and TOI-270 d likely are rocky/icy planets (taking into account [21] and [22]) with a dissipation higher than Earth’s, thus we assume \(5 \times k_2,\oplus \Delta \tau_\oplus [18][23]\). We also assume that the fluid Love number and the potential Love number of degree 2 are equal. The rotational period of the host body is uncertain: from photometric and spectral observations we expect an old-slow rotator, but it is possible (yet unlikely) that is a young-fast rotator. We hence run our simulations for three different rotational periods: \(P_{*,\text{rot}} = 2,50, 100\) days. First, we explore the evolution of the obliquity and rotational period from different initial conditions: initial planetary rotational periods of 10 h, 100 h and 1,000 h, and an initial obliquity of 15°, 50° and 75°. The rest of the planet parameters are fixed to the values in Table 1, and we assumed eccentricities of 0.05 for all the planets (upper limits from the stability analysis above). The results for different stellar rotation periods are comparable. For the slow rotator as an example, we find that the evolution to pseudo-rotational state occurs over a short time-scale of \(10^4\)–\(10^5\) yr for all planets, with the outer planet being the slowest to reach this state. Since TOI-270 is much older than this time-scale, we conclude that our planets are likely well aligned with the host star. However, other events which are not studied here, such as magnetic breaks or rotational deformation, might alter this state. The resulting rotational periods are \(P_{(b,c,d),\text{rot}} = 76\) h, 133 h, and 281 h, respectively.

Once the planets reach a pseudo-rotational state, tidal heating keeps acting while the orbits are eccentric, and decreases towards zero with circularisation. To explore the circularisation we ran another suite of simulations, performing integrations up to \(10^8\) yr. We find that after this time the eccentricities shrink by 94–98% from their initial values, meaning from 0.05 to < 0.002 for all planets. Since our planetary system is likely much older, this suggests the orbits are in a near-circular configuration. While the orbits are still eccentric, the tidal heating is about 250–350 W m\(^{-2}\) for planet TOI-270 b, 500–600 W m\(^{-2}\) for planet c, and 10 W m\(^{-2}\) for planet d. After \(10^8\) years, the tidal contribution decreased down to \(\sim 1.5\) W m\(^{-2}\), \(\sim 1.0\) W m\(^{-2}\), and \(\sim 0.02\) W m\(^{-2}\) for planets b, c, and d, respectively.

Finally, we investigate if the TOI-270 system remains stable when there is a fourth planet, which is located in the terrestrial-like habitable zone between 0.1–0.28 AU [24][25]. We again simulate this scenario using MEGNO (as described above) for a 5-body system, and a range of orbital distances and masses of the fourth planet (100 values between 0.1–0.3 AU, and 100 values between 1–100 M\(_\oplus\)), while freezing all other parameters. We find that the system is fully stable for the range of masses and semi-major axes in question.
Supplementary Figure 1: Archival images and TESS image for TOI-270 from 1983 to 2018. The red plus shows the current position of TOI-270 in comparison. The regions mark the TESS aperture masks used in Sector 3 (red), 4 (purple) and 5 (blue). At the given spatial resolution, we see no background sources at the target’s current sky location.
Supplementary Figure 2: Follow-up lightcurves for TOI-270 (see also Supplementary Table 1). Red lines show 20 lightcurves generated from randomly drawn posterior samples from the best-fit *allesfitter* model.
Supplementary Figure 3: Sensitivity of VLT/NaCo images to nearby companions, as a function of separation. 

Inset: 4” square image, centered on the target. No visual companions appear in this image, or anywhere within the field of view. Note that two point spread function artefacts appear 750 mas north and south of the host. These artefacts originate from the structure of the point spread function due to the target’s brightness, and are not visual companions.
Supplementary Figure 4: Posterior probability distributions for all astrophysical parameters of the `allesfitter` nested sampling fit of TOI-270. The figure also highlights the correlation (or absence thereof) between all parameters. Vertical dashed lines show the median and 68% credible interval.
Supplementary Figure 5: Dynamical analysis based on the Mercury Integrator, showing the planets’ eccentricities over a range of masses (the predicted mass multiplied by a factor). The system is stable with eccentricities remaining below 0.05 for masses up to ten times the predicted mass. For masses 10–30 times higher, the system achieves stability but the interaction between planets begins to drive high eccentricities. At ~30 times the original masses, the system would be chaotic.

Supplementary Figure 6: Dynamical analysis based on MEGNO-maps. The configurations are as follow: Left, free eccentricities $e_b$ and $e_c$ in the range of 0 to 0.3, while $e_d=0$. Middle, free $e_b$ and $e_d$, while $e_c=0$. Right, free $e_c$ and $e_d$, while $e_b=0$. All other planetary parameters are fixed. In all cases: $\langle Y(t) \rangle \rightarrow 2$ for quasi-periodic orbits and $\langle Y(t) \rangle \rightarrow 5$ for chaotic systems. This shows that the system is stable for a range of low eccentricities.
Supplementary Figure 7: A recovery test for injected transits of small planets in the terrestrial-like habitable zone of TOI-270 (corresponding to periods of 18–85 days). While larger transiting planets could have been found in the available TESS data, the regime of small exoplanets with period beyond ~30 days remains open for future transit searches.
## Supplementary Table 1: Observation Log

### Discovery photometry

| TOI-270 | Date (UTC) | Telescope | Filter | Exposure time (sec) | Nr. of exposures | Duration (min) | Transit coverage | Aperture radius (arcsec) | FWHM (arcsec) |
|---------|------------|-----------|--------|---------------------|-----------------|---------------|------------------|--------------------------|-------------|
| b       | 2018-09-20 | TESS      | TESS   | 120                 | 46874           | –             | –               | 30–60"                  | –           |
| c       | 2018-12-11 | –         | –      | –                   | –               | –             | –               | –                       | –           |

### Follow-up photometry

| TOI-270 | Date (UTC) | Telescope | Filter | Exposure time (sec) | Nr. of exposures | Duration (min) | Transit coverage | Aperture radius (arcsec) | FWHM (arcsec) | ∆ ln Z § |
|---------|------------|-----------|--------|---------------------|-----------------|---------------|------------------|--------------------------|-------------|----------|
| b       | 2018-12-18 | PEST      | Rc     | 120                 | 189             | 449           | Full             | 7.38                     | 4.10         | < 0      |
|         | 2018-12-25 | LCO-CTIO  | i'     | 20                  | 113             | 113           | Ingr.+66%        | 7.78                     | 4.30         | < 0      |
|         | 2018-12-27 | SS0-T17   | Clear  | 60                  | 120             | 151           | Full             | 6.30                     | 2.10         | N/A ‡    |
|         | 2018-12-28 | PEST      | V      | 120                 | 174             | 404           | Full             | 7.38                     | 4.00         | < 0      |
|         | 2019-01-11 | LCO-CTIO  | i'     | 14                  | 221             | 200           | Full             | 8.94                     | 2.10         | < 0      |
|         | 2019-01-14 | LCO-SSO   | i'     | 15                  | 178             | 161           | Full             | 7.00                     | 1.74         | 6.8 §    |
|         | 2019-01-24 | LCO-SSO   | g'     | 40                  | 136             | 184           | Full             | 4.23                     | 2.14         | < 0      |
|         | 2019-01-27 | LCO-SAAO  | g'     | 70                  | 119             | 218           | Full             | 7.78                     | 2.28         | < 0      |
| c       | 2018-12-15 | TS        | z'     | 10                  | 698             | 242           | Full             | 4.48                     | 2.48         | 11.3 §   |
|         | 2018-12-16 | LCO       | i'     | 90                  | 88              | 180           | Full             | 5.83                     | –           | 19.2 §   |
|         | 2018-12-27 | LCO-SSO   | i'     | 11                  | 207             | 216           | Full             | 7.78                     | 2.95         | 19.3 §   |
|         | 2019-01-13 | PEST      | V      | 120                 | 143             | 335           | Egr.+90%         | 7.38                     | 4.60         | 1.6      |
|         | 2019-01-13 | MKO       | g'     | 128                 | 82              | 247           | Full             | 9.20                     | 3.00         | 5.2 §    |
|         | 2019-01-13 | Myers     | B      | 180                 | 70              | 300           | Full             | 4.14                     | 4.00         | 7.1 §    |
| d       | 2018-12-27 | TS        | z'     | 10                  | 848             | 301           | Full             | 4.48                     | 2.31         | 4.3 §    |
|         | 2019-01-19 | LCO-SAAO  | i'     | 11                  | 182             | 156           | Ingr.+77%        | 5.44                     | 1.91         | 6.3 §    |
|         | 2019-02-23 | LCO-CTIO  | g'     | 70                  | 123             | 203           | Full             | 5.83                     | 2.76         | 6.3 §    |

### Reconnaissance spectroscopy

| TOI-270 | Date (UTC) | Telescope | Resolution | Wavelengths |
|---------|------------|-----------|------------|-------------|
|         | 2018-12-22 | FIRE      | 6000       | 8000 – 25000 Å |
|         | 2019-01-23 | ANU       | 23000      | 3900 – 6700 Å |

### High-resolution imaging

| TOI-270 | Date (UTC) | Telescope | Filter | Exposure time (sec) | Nr. of exposures | FWHM (mas) |
|---------|------------|-----------|--------|---------------------|-----------------|------------|
| –       | 2019-01-25 | NaCo      | Ks     | 20                  | 9               | 90         |

Telescopes:
- LCO-SSO: Las Cumbres Observatory - Siding Spring (1 m) [26]
- LCO-CTIO: Las Cumbres Observatory - Cerro Tololo Interamerican Observatory (1 m) [26]
- LCO-SAAO: Las Cumbres Observatory - South African Astronomical Observatory (1 m) [26]
- TS: TRAPPIST-South (0.6 m) [27]
- SSO-T17: Siding Spring Observatory - T17 (0.4 m)
- PEST: The Perth Exoplanet Survey Telescope (0.3 m)
- Myers: Myers-Siding Spring (0.4 m)
- MKO: Mt. Kent Observatory CDK700 (0.7 m)
- FIRE: Magellan Folded-port InfraRed Echellette (6.5 m) [28]
- ANU: Australia National University Echelle spectrograph (2.3 m); spectrum reduced following [29]
- NaCo: VLT NAOS-CONICA (8.2 m) [30][31]

†Observations not included, as deep exposures were used to study faint neighbouring stars and exclude possible blended eclipsing binaries.

§Only observations with a Bayes factor ∆ ln Z > 3 (strong evidence for a signal) are used for the global analysis.
might arise from systematics related to the satellite orbit (  \sim 34 \text{ in TESS Sectors 3–4 short-cadence data}. The search is performed on the Supplementary Table 4: Threshold crossing events with a signal-to-noise ratio SNR \geq \text{parameters}

eccentricity and/or free TTVs. A Bayes factor

Supplementary Table 2: A comparison of various models with different degrees of freedom. The Null Hypothesis, a circular model without TTVs, is compared against more complicated models allowing for free eccentricity and/or free TTVs. A Bayes factor >3 would mean strong Bayesian evidence for a model \[32\]. We thus find no strong Bayesian evidence for eccentricity nor TTVs.

| Facility, date | \( q_1 \) | \( q_2 \) | \( u_1 \) | \( u_2 \) | \( \ln \sigma_{\text{white}} \) | GP ln \( \sigma \) | GP ln \( \rho \) |
|---------------|---------|---------|---------|---------|-----------------|-------------|-------------|
| TESS, 2018-12-16 | 0.29 \pm 0.24 | 0.45 \pm 0.26 | 0.48 \pm 0.16 | 0.05 \pm 0.24 | -6.6243 \pm 0.0034 | -8.712 \pm 0.087 | -1.97 \pm 0.25 |
| LCO, 2018-12-25 | 0.51 \pm 0.31 | 0.64 \pm 0.29 | 0.93 \pm 0.45 | -0.01 \pm 0.40 | -6.407 \pm 0.069 | -10.5 \pm 0.32 | 0.3 \pm 1.5 |
| LCO CTO, 2019-02-23 | 0.44 \pm 0.31 | 0.48 \pm 0.30 | 0.55 \pm 0.35 | 0.02 \pm 0.018 | -6.245 \pm 0.048 | -10.4 \pm 0.32 | 0.22 \pm 0.038 |
| LCO CTO, 2019-02-27 | 0.37 \pm 0.34 | 0.43 \pm 0.30 | 0.75 \pm 0.35 | -0.06 \pm 0.042 | -6.472 \pm 0.064 | -2.06 \pm 0.054 | 1.19 \pm 0.051 |
| LCO CTO, 2019-02-28 | 0.44 \pm 0.31 | 0.46 \pm 0.32 | 0.52 \pm 0.51 | 0.05 \pm 0.077 | -6.01 \pm 0.063 | -2.19 \pm 0.55 | 0.67 \pm 0.063 |
| LCO CTO, 2019-02-29 | 0.45 \pm 0.32 | 0.40 \pm 0.31 | 0.49 \pm 0.38 | 0.11 \pm 0.03 | -5.93 \pm 0.074 | -11.0 \pm 0.5 | 0.11 \pm 0.086 |
| LCO CTO, 2019-03-14 | 0.59 \pm 0.31 | 0.55 \pm 0.32 | 0.73 \pm 0.49 | -0.07 \pm 0.045 | -6.489 \pm 0.056 | -11.1 \pm 0.24 | 0.037 \pm 0.036 |
| MK-OPT, 2019-03-13 | 0.59 \pm 0.31 | 0.53 \pm 0.38 | 0.74 \pm 0.48 | -0.04 \pm 0.34 | -6.112 \pm 0.084 | -0.46 \pm 0.55 | 1.983 \pm 0.02 |
| Myers, 2019-09-13 | 0.52 \pm 0.3 | 0.48 \pm 0.31 | 0.61 \pm 0.51 | 0.02 \pm 0.40 | -5.303 \pm 0.088 | -10.2 \pm 2.7 | 2.00 \pm 0.10 |
| ASP DSR, 2019-09-13 | 0.50 \pm 0.3 | 0.49 \pm 0.3 | 0.59 \pm 0.3 | 0.01 \pm 0.07 | -5.572 \pm 0.054 | -10.7 \pm 2.4 | 1.11 \pm 0.15 |
| Trappist, 2019-12-15 | 0.25 \pm 0.3 | 0.38 \pm 0.24 | 0.32 \pm 0.2 | 0.10 \pm 0.02 | -5.827 \pm 0.027 | -4.04 \pm 0.33 | -1.028 \pm 0.035 |
| Trappist, 2019-12-27 | 0.17 \pm 0.18 | 0.38 \pm 0.25 | 0.28 \pm 0.19 | 0.07 \pm 0.09 | -5.604 \pm 0.025 | -3.82 \pm 0.06 | -1.067 \pm 0.037 |

Supplementary Table 3: Nuisance parameters of the fit to individual observations, which are later fixed to their median values in the global analysis. These include the limb darkening parameters \( q_1 \) and \( q_2 \) in the parametrization suggested by \[33\] (for comparability also translated into the quadratic limb darkening parameters \( u_1 \) and \( u_2 \)); the natural logarithm of the white noise scaling \( \sigma_{\text{white}} \); and the hyperparameters of the GP Matern-3/2, namely the natural logarithms of the amplitude \( \sigma \) and characteristic time scale \( \rho \).

| TLS# | SNR | Depth (mmag) | Period (d) | First epoch (BJD) | Note |
|------|-----|-------------|------------|-------------------|------|
| 1    | 85.8| 3.9 | 5.65986    | 2458389.50438    | planet c |
| 2    | 54.1| 3.1 | 11.38025   | 2458389.67737    | planet d |
| 3    | 21.1| 0.9 | 3.36014    | 2458387.09273    | planet b |
| 4    | 8.3 | 0.2 | 5.53073    | 2458388.19620    | shallow and too wide |
| 5    | 6.5 | 0.6 | 13.90082   | 2458395.07980    | falls in noisy regions† |

Supplementary Table 4: Threshold crossing events with a signal-to-noise ratio SNR \geq 5 detected with transit least squares \[34\] in TESS Sectors 3–4 short-cadence data. The search is performed on the PDC-SAP lightcurves, which were additionally detrended using a Gaussian process. † Note that this signal might arise from systematics related to the satellite orbit (\sim 13.7 days).
References

[1] Skilling, J. Nested Sampling. In Fischer, R., Preuss, R. & Toussaint, U. V. (eds.) American Institute of Physics Conference Series, vol. 735, 395–405 (2004).

[2] Hall, R. D., Thompson, S. J., Handley, W. & Queloz, D. On the Feasibility of Intense Radial Velocity Surveys for Earth-Twin Discoveries. Mon. Not. R. Astron. Soc. 479, 2968–2987 (2018).

[3] Foreman-Mackey, D., Agol, E., Ambikasaran, S. & Angus, R. celerite: Scalable 1D Gaussian Processes in C++, Python, and Julia. Astrophysics Source Code Library (2017).

[4] Chambers, J. E. A hybrid symplectic integrator that permits close encounters between massive bodies. Mon. Not. R. Astron. Soc. 304, 793–799 (1999).

[5] Duncan, M. J., Levison, H. F. & Lee, M. H. A Multiple Time Step Symplectic Algorithm for Integrating Close Encounters. Astron. J. 116, 2067–2077 (1998).

[6] Kane, S. R. Stability of Earth-mass Planets in the Kepler-68 System. Astrophys. J., Letters 814, L9 (2015).

[7] Kane, S. R. Resolving Close Encounters: Stability in the HD 5319 and HD 7924 Planetary Systems. Astrophys. J. 830, 105 (2016).

[8] Cincotta, P. & Simó, C. Conditional Entropy. Celestial Mechanics and Dynamical Astronomy 73, 195–209 (1999).

[9] Cincotta, P. M. & Simó, C. Simple tools to study global dynamics in non-axisymmetric galactic potentials - I. Astronomy and Astrophysics Supplement Series 147, 205–228 (2000).

[10] Cincotta, P. M., Giordano, C. M. & Simó, C. Phase space structure of multi-dimensional systems by means of the mean exponential growth factor of nearby orbits. Physica D Nonlinear Phenomena 182, 151–178 (2003).

[11] Rein, H. & Liu, S.-F. REBOUND: an open-source multi-purpose N-body code for collisional dynamics. Astron. Astrophys. 537, A128 (2012).

[12] Rein, H. & Tamayo, D. WHFAST: a fast and unbiased implementation of a symplectic Wisdom-Holman integrator for long-term gravitational simulations. Mon. Not. R. Astron. Soc. 452, 376–388 (2015).

[13] Alexander, M. E. The Weak Friction Approximation and Tidal Evolution in Close Binary Systems. Astrophysics and Space Science 23, 459–510 (1973).

[14] Mignard, F. The Evolution of the Lunar Orbit Revisited. I. Moon and Planets 20, 301–315 (1979).

[15] Hut, P. Tidal evolution in close binary systems. Astron. Astrophys. 99, 126–140 (1981).

[16] Eggleton, P. P., Kiseleva, L. G. & Hut, P. The Equilibrium Tide Model for Tidal Friction. Astrophys. J. 499, 853–870 (1998).

[17] Leconte, J., Chabrier, G., Baraffe, I. & Levrard, B. Is tidal heating sufficient to explain bloated exoplanets? Consistent calculations accounting for finite initial eccentricity. Astron. Astrophys. 516, A64 (2010).

[18] Bolmont, E., Raymond, S. N., Leconte, J., Hersant, F. & Correia, A. C. M. Mercury-T: A new code to study tidally evolving multi-planet systems. Applications to Kepler-62. Astron. Astrophys. 583, A116 (2015).

[19] Blanco-Cuaresma, S. & Bolmont, E. What can the programming language Rust do for astrophysics? In Brescia, M., Djorgovski, S. G., Feigelson, E. D., Longo, G. & Cavuoti, S. (eds.) Astroinformatics, vol. 325 of IAU Symposium, 341–344 (2017).

[20] Neron de Surgy, O. & Laskar, J. On the long term evolution of the spin of the Earth. Astron. Astrophys. 318, 975–989 (1997).

[21] Fortney, J. J., Marley, M. S. & Barnes, J. W. Planetary Radii across Five Orders of Magnitude in Mass and Stellar Insolation: Application to Transits. Astrophys. J. 659, 1661–1672 (2007).

[22] Chen, J. & Kipping, D. Probabilistic Forecasting of the Masses and Radii of Other Worlds. Astrophys. J. 834, 17 (2017).

[23] McCarthy, C. & Castillo-Rogez, J. Planetary Ices Attenuation Properties, vol. 183 (2013).

[24] Kopparapu, R. K. et al. Habitable Zones around Main-sequence Stars: New Estimates. Astrophys. J. 765, 131 (2013).
[25] Kopparapu, R. K. et al. Habitable Zones around Main-sequence Stars: Dependence on Planetary Mass. Astrophys. J. 787, L29 (2014).

[26] Brown, T. M. et al. Las Cumbres Observatory Global Telescope Network. Publ. Astron. Soc. Pacific 125, 1031 (2013).

[27] Jehin, E. et al. TRAPPIST: TRAnsiting Planets and Planetesimals Small Telescope. The Messenger 145, 2–6 (2011).

[28] Simcoe, R. A. et al. FIRE: A Facility Class Near-Infrared Echelle Spectrometer for the Magellan Telescopes. Publ. Astron. Soc. Pacific 125, 270 (2013).

[29] Zhou, G. et al. The mass-radius relationship for very low mass stars: four new discoveries from the HATSouth Survey. Mon. Not. R. Astron. Soc. 437, 2831–2844 (2014). [1310.7591]

[30] Lenzen, R. et al. NAOS-CONICA first on sky results in a variety of observing modes. In Iye, M. & Moorwood, A. F. M. (eds.) Instrument Design and Performance for Optical/Infrared Ground-based Telescopes, vol. 4841 of Proc. SPIE, 944–952 (2003).

[31] Rousset, G. et al. NAOS, the first AO system of the VLT: on-sky performance. In Wizinowich, P. L. & Bonaccini, D. (eds.) Adaptive Optical System Technologies II, vol. 4839 of Proc. SPIE, 140–149 (2003).

[32] Kass, R. E. & Raftery, A. E. Bayes factors. Journal of the American Statistical Association 90, 773–795 (1995).

[33] Kipping, D. M. Efficient, uninformative sampling of limb darkening coefficients for two-parameter laws. Mon. Not. R. Astron. Soc. 435, 2152–2160 (2013). [1308.0009]

[34] Hippke, M. & Heller, R. Optimized transit detection algorithm to search for periodic transits of small planets. Astron. Astrophys. 623, A39 (2019).