New constraints on the planetary system around the young active star AU Mic

Two transiting warm Neptunes near mean-motion resonance

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ABSTRACT

AU Microscopii (AU Mic) is a young, active star whose transiting planet was recently detected. Here, we report our analysis of its TESS light curve, where we reveal the BY Draconis type quasi-periodic rotational modulation by starspots simultaneously to the flaring activity and planetary transits. We measured a flare occurrence rate in AU Mic of 6.35 flares per day for flares with amplitudes in the range of 0.06% < f < 1.5% of the star flux. We employed a Bayesian Markov chain Monte Carlo analysis to model the five transits of AU Mic b observed by TESS, improving the constraints on the planetary parameters. The measured planet-to-star effective radius ratio of Rp/R* = 0.0496 ± 0.0007 implies a physical radius of 4.07 ± 0.17 R⊕ and a planet density of 1.4 ± 0.4 g cm−3, confirming that AU Mic b is a Neptune-size moderately inflated planet. While a single feature possibly due to a second planet was previously reported in the former TESS data, we report the detection of two additional transit-like events in the new TESS observations of July 2020. This represents substantial evidence for a second planet (AU Mic c) in the system. We analyzed its three available transits and obtained an orbital period of 18.859019 ± 0.000016 d and a planetary radius of 3.24 ± 0.16 R⊕, which defines AU Mic c as a warm Neptune-size planet with an expected mass in the range of 2.2 M⊕ < M < 25.0 M⊕, estimated from the population of exoplanets of similar sizes. The two planets in the AU Mic system are in near 9:4 mean-motion resonance. We show that this configuration is dynamically stable and should produce transit-timing variations (TTV). Our non-detection of significant TTV in AU Mic b suggests an upper limit for the mass of AU Mic c of < 7 M⊕, indicating that this planet is also likely to be inflated. As a young multi-planet system with at least two transiting planets, AU Mic becomes a key system for the study of atmospheres of infant planets and of planet-planet and planet-disk dynamics at the early stages of planetary evolution.

Key words. planetary systems – stars: individual: AU Mic – stars: activity – techniques: photometric

1. Introduction

Young planetary systems present an opportunity to observe planets in the early stages of planetary formation when gravitational interactions have not significantly changed the initial configuration of the system. AU Microscopii (AU Mic) is a particularly interesting young system, with an estimated age of 22 ± 3 Myr (Manajek & Bell 2014), which is located at a distance of only 9.7248 ± 0.0046 pc (Gaia Collaboration 2018). Table 1 summarizes the star parameters of AU Mic that are relevant for this work. The AU Mic host is an M1 star with a spatially resolved edge-on debris disk (Kalas et al. 2004) and at least one transiting planet, AU Mic b (Plavchan et al. 2020). This Neptune-size planet is in a 8.5-d prograde orbit aligned with the stellar rotation axis (Martioli et al. 2020; Hirano et al. 2020; Palle et al. 2020). While Plavchan et al. (2020) only reported an upper limit on the mass of AU Mic b, Klein et al. (2021) measured 17.1±4.7 M⊕ thanks to infrared observations secured with the SPIRou spectroplanimeter (Donati et al. 2020). Plavchan et al. (2020) has also reported the detection of an isolated transit event of a second possible candidate planet, hereafter referred to as AU Mic c.

The notion that AU Mic could be a host for several planets is not a surprising one. Indeed, the occurrence rate of planets with a radius between 0.5 R⊕ and 4.0 R⊕ and a period between 0.5 and 256 d is estimated as 8.4+1.1−1.4 planets per M dwarf (Hsu et al. 2020), although the occurrence rate of more massive planets in M dwarfs decreases significantly with mass (e.g., Bonfils et al. 2013). Moreover, provided the fact that AU Mic has an edge-on debris disk and that AU Mic b is a transiting planet with an aligned orbit, the chances that other planets also reside in co-planar orbits increase and, therefore, possible close-in additional planets are also likely to transit the star.

AU Mic is a magnetically active star with strong flaring activity (Robinson et al. 2001). Its surface is largely filled by starspots, producing a BY Draconis-type light curve with a quasi-periodic rotational modulation and a period of 4.863 ± 0.010 d (Plavchan et al. 2020). As in other active stars, the strong flaring and magnetic activity of AU Mic makes it more difficult to detect planetary transits in a photometric time series, especially for
small planets where the occurrence rate is higher. In this work, we present an analysis of the Transiting Exoplanet Satellite (TESS) data of AU Mic, including the new observations obtained in July 2020, where we implement a multi-flare model combined with the starspot model, improving the constraints on the planetary parameters from transit modeling and allowing for the detection of two additional transits of the second candidate planet AU Mic c.

2. TESS light curve

AU Mic was observed by TESS (Ricker et al. 2015) in Sector 1 from 2018-Jul.-25 to 2018-Aug.-22, in cycle 1, camera 1. Then it was observed again in Sector 27 from 2020-Jul.-04 to 2020-Jul.-30, in cycle 3, camera 1. The second visit was observed as part of the TESS Guest Investigator Programs G03263 (PI: P. Plavchan), G03141 (PI: E. Newton), and G03273 (PI: L. Vega) in fast mode with a time sampling of 20 s compared to the 2 min time sampling of the first visit. We obtained the de-trended photometric time series from the Mikulski Archive for Space Telescopes (MAST) using the MAST astroquery tool. Figure 1 shows the AU Mic PDCSAP\(^1\) flux in units of electrons-per-second (e\(^{-}\)s\(^{-1}\)) as a function of time given in TESS Barycentric Julian Date (TTBJD = BJD – 2,457,000.0) for the two visits. Plavchan et al. (2020) have analyzed the same TESS data from the first visit only, and in the present paper we report for the first time an analysis including the more recent 2020 TESS data. The predicted times of the transits of AU Mic b and c as calculated from our ephemerides (see Sects. 5 and 6) are marked with vertical lines.

3. Starspots

As illustrated in Fig. 1, the TESS light curve of AU Mic shows a typical BY Draconis type of quasi-periodic variation due to starspots modulated by stellar rotation. The starspots evolve and, therefore, this modulation cannot be accurately modeled by a single periodic function. Thus, we treat this quasi-periodic modulation as a baseline “continuum” signal, where we model it by fitting a piece-wise fourth-order polynomial with iterative sigma-clipping. This approach works well when the ranges are carefully selected and inspected as follows. First, we can be certain that the polynomial function is a sufficiently accurate approximation for the local baseline variation within each range. Then we avoid the edges of the ranges to include either a transit or a flare event. Finally, we avoid the inclusion of large gaps (when TESS did not deliver data) within the same range. The edges for all selected ranges are represented by the blue vertical dashed lines in Fig. 1.

This starspot model is removed from the data to model flares and planetary transits as explained in Sects. 4–6, which are further removed from the original data to fit the starspot modulation again. We repeat this procedure iteratively until the standard deviation of residuals is not improved by more than 1%. We typically meet this criterion upon three to five iterations. The final starspot model is also shown in Fig. 1. In Appendix A, we present an independent measurement of the rotational period of AU Mic from the starspot modulation in the 2018 TESS data.

4. Flares

AU Mic is an active young star with intense flaring activity. We carry out an analysis of the flares in the TESS data to improve the constraints on the transit events. We consider the starspot-subtracted residuals as shown in Fig. 2. The flares are typically clusters of points lying above the noise level. First we detect peaks as possible candidate flares using the scipy.signal.find_peaks\(^3\) routine, where it finds local maxima via a simple comparison of neighbouring values. We set a minimum peak amplitude of 2.5σ and a minimum horizontal distance between peaks of about ~100 min. Some flares in AU Mic are quite complex, while other flares occur before a previously initiated flare has ended. Therefore, we visually inspected all detected peaks to identify any possible additional peaks that have been missed by the find-peaks algorithm. After a few iterations, we identified a total of 324 flares in the whole TESS time series.

The times and amplitudes of detected peaks were adopted as initial values for the basis of performing a least-squares fit using the multi-flare model of Davenport et al. (2014), where each flare is represented by a two-phase model with a polynomial rise and an exponential decay. Figure 3 shows, as an example, the residual light curve and fit flares model for three days of flaring activity in AU Mic in both TESS visits. For each flare in the model, we fit the flare amplitude (\(F_{\text{max}}\)), the full width at half maximum (FWHM), and the time of maximum \(t_{\text{peak}}\). The fit parameters for all flares are presented in Appendix B.

The total continuous monitoring time of AU Mic performed by TESS was estimated as 49.75 d, where we have discounted the large gaps in the data. We detected a total of 324 flares, from which 316 have fit amplitudes above \(F_{\text{max}} > 1\)σ, for \(\sigma = 161.5\) e\(^{-}\)s\(^{-1}\). Thus, the AU Mic global occurrence rate of flares with amplitude above \(F_{\text{max}} > 0.06\%\) of the median stellar flux (279544 e\(^{-}\)s\(^{-1}\)) is estimated as 6.35 flares per day or about 1 flare every 3.8 h. Figure 4 shows the distribution of flares as function of flare amplitudes. We fit an exponential to the measured distribution and obtained an empirical model for the occurrence rate as function of flare amplitude of \(F_{\text{max}} = 0.17e^{-4.0f_{\text{max}}}d^{-4}\), with \(F_{\text{max}}\) in units of 10\(^{-5}\) e\(^{-}\)s\(^{-1}\). We notice that the strong flares, which are more important energetically, have a much lower occurrence rate and therefore a low statistical significance in our analysis. Thus, this empirical relationship is only expected to hold for flares above the detection limit imposed by the noise and for flares with a statistically significant number of events observed.

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\(^1\) https://astroquery.readthedocs.io/en/latest/mast.html

\(^2\) Pre-search Data Conditioning SAP.

\(^3\) https://docs.scipy.org/doc/scipy/reference/generated/scipy.signal.find_peaks.html
Fig. 1. TESS light curve of AU Mic. Top panel: data for the first visit (from 2018-Jul-25 to 2018-Aug-22). Bottom panel: data for the second visit (from 2020-Jul-04 to 2020-Jul-30). Black points are the PDCSAP flux and vertical solid lines show the times of planetary transits, as obtained in our analysis, for AU Mic b (in orange) and AU Mic c (in green). Blue vertical dashed lines show the knots of selected ranges for the piece-wise polynomial fit and the red line shows the starspot model.

in the TESS data, that is, those with amplitudes in the range of \(0.06\% < f_{\text{max}} < 1.5\%\) of the star flux.

The transit duration of AU Mic b calculated by Plavchan et al. (2020) is about 3.5 h with transit depth of 0.26%. Therefore, considering that a transit observation of AU Mic b requires an out-of-transit baseline of about 2 h, it is most likely that any transit observation in AU Mic should be affected in some way by flare events. This shows the importance of modeling flares adequately to improve the constraints on the planetary parameters obtained by the transits.

5. Transits of AU Mic b

Three transits of AU Mic b occurred during the first TESS visit, but only two have been observed due to a communication problem with the spacecraft during the second transit (see Plavchan et al. 2020). For the second visit, three other transits were expected, and indeed we were able to identify all of them. To analyze these five transits together, we start with the parameters of AU Mic b from Plavchan et al. (2020), referred to as “prior values” in Table 2, to remove the transit signal from the TESS light curve before fitting the starspot and flare models. Our transit model is calculated using the BATMAN toolkit by Kreidberg (2015), where we assume a circular orbit \((e = 0)\). This assumption is in agreement with Plavchan et al. (2020), who did not detect any significant eccentricity from their analysis of the transits only, where the eccentricity would be slightly constrained by the duration of the transit. We adopt as priors the quadratic limb-darkening coefficients (LDC) from Claret (2018) with an arbitrary error of 0.1, where we obtained the values calculated for the photometric system of TESS and those matching the closest stellar parameters to those of AU Mic (see Table 1).
The transits of AU Mic b, flares, and starspots are fit simultaneously using the non-linear least squares optimization (OLS) fit tool `scipy.optimize.leastsq`. As explained in Sect. 3 this procedure is run iteratively, where we first obtain an independent fit for each component of the model and then we set these values as initial guess to run an OLS analysis with all free parameters in the three components of the model. Then we consider the data in the ranges around the transits of AU Mic b to sample the posterior distributions of the transit parameters using the emcee Markov chain Monte Carlo (MCMC) package (Foreman-Mackey et al. 2013). The chain is set with 100 walkers and 30,000 MCMC steps of which we discard the first 5000. The MCMC samples are presented in Fig. C.1, which show the chains reaching stability before the first 5000 discarded steps. The posterior distributions are illustrated in Fig. C.3. The best-fit values of the transit parameters are calculated as the medians of the posterior distribution with error bars defined by the 34% on each side of the median, all presented in Table 2.

Figure 5 shows the results of our analysis for each transit range separately, and the bottom right panel shows the flux normalized by the starspot and flare models for all transits together, and our best fit model along with the previous model of Plavchan et al. (2020) for comparison. The dispersion of residuals are 358, 433, 633, 566, and 588 ppm, for each respective epoch. The global dispersion is 573 ppm. Notice that our measured parameters of AU Mic b agree within 3σ with the previous measurements by Plavchan et al. (2020) but with improved accuracy. Our measured planet-to-star radius ratio is slightly larger than that measured by Plavchan et al. (2020; see lower, right panel of Fig. 5). However, as described in Sect. 7, our derived effective
Table 2. Transit fit parameters for planet AU Mic b obtained in our analysis from a simultaneous fit of the five transits observed by TESS as illustrated in Figs. 5 and C.3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior value</th>
<th>MCMC fit value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of conjunction, $T_0$ [TBJD]</td>
<td>1330.38957 $\pm$ 0.00015</td>
<td>1330.39051 ± 0.00015</td>
</tr>
<tr>
<td>Orbital period, $P$ [d]</td>
<td>8.46321 $\pm$ 0.00004</td>
<td>8.463000 ± 0.000002</td>
</tr>
<tr>
<td>Normalized semi-major axis, $a/R_*$</td>
<td>$19.1^{+1.5}_{-1.6}$</td>
<td>$19.1^{+0.2}_{-0.1}$</td>
</tr>
<tr>
<td>Orbital inclination, $i$ [degree]</td>
<td>89.5$^{+0.4}_{-0.4}$</td>
<td>89.5$^{+0.4}_{-0.4}$</td>
</tr>
<tr>
<td>Planet-to-star radius ratio, $R_p/R_*$</td>
<td>0.0514 $\pm$ 0.0013</td>
<td>0.0526$^{+0.0003}_{-0.0002}$</td>
</tr>
<tr>
<td>Linear limb dark. coeff., $u_0$</td>
<td>$N(0.23, 0.1)$</td>
<td>0.13 $\pm$ 0.03</td>
</tr>
<tr>
<td>Quadratic limb dark. coeff., $u_1$</td>
<td>$N(0.38, 0.1)$</td>
<td>0.58 $\pm$ 0.06</td>
</tr>
</tbody>
</table>

Fig. 3. TESS residual light curve of AU Mic between TBJD = 1344.3 and TBJD = 1347.3 (top panel) and between TBJD = 2050.8 and TBJD = 2053.8 (bottom panel). Blue circles show the flux after subtracting the starspot model, brown line shows the multi-flare best fit model. Green points show the residuals with an arbitrary offset for better visualization. The dispersion of residuals are 107 e$^{-}$ s$^{-1}$ and 178 e$^{-}$ s$^{-1}$ for data presented in top panel and bottom panel, respectively.

Fig. 4. Number of flares normalized by the total observed time of 49.75 d as function of flare amplitude. Dashed line shows the fit to an exponential decay as shown in the legend, where variable $x$ represents the flare amplitude.

Fig. 5. Number of flares normalized by the total observed time of 49.75 d as function of flare amplitude. Dashed line shows the fit to an exponential decay as shown in the legend, where variable $x$ represents the flare amplitude.
Fig. 5. Each panel shows the range around one of the three transits of AU Mic b observed by TESS. The top part of each panel shows the TESS data (blue circles) and the best-fit model for each component, as indicated in the legend. The bottom part in each panel shows the TESS data normalized by the starspot and flare model (blue points) and the best-fit transit model (red line). Vertical dashed lines show the central time of each transit. Bottom right panel: phase-folded light curve for all the data from the five transits (light blue points) and the binned data (dark blue points) with a bin size of 0.005 d, our best fit model (red line), and the previous fit model of Plavchan et al. (2020) for comparison (orange dashed line). The residuals (green points) are displayed with an arbitrary offset.

\[ R_p / R_\star = N(0.04, 0.01) \]  

The orbital inclination is considered with an uniform prior distribution of \( i = U(85^\circ, 90^\circ) \) and the limb darkening coefficients are fixed to the literature values presented in Table 1. In Appendix D, we present the results for this independent analysis of each transit. The posterior of all the transit parameters agree within 3\( \sigma \) (see Table D.1), and the dispersion of residuals improves when we adopted the fit period of \( P = N(18.86, 0.01) \) d as prior, which supports our hypothesis that these three events were caused by the transits of the same planet AU Mic c. Finally, we perform a joint analysis of the three transits simultaneously, where we adopt the same priors as in the independent analysis above, except for the limb darkening coefficients, where we adopted a normal prior with the literature values and an arbitrary error of 1.0. We call attention to the fact that the limb darkening coefficients obtained in Sect. 5 could have been used as priors since both planets are transiting the same star. However, the two planets may transit the stellar disk in different regions, and since AU Mic is largely filled by starspots, the limb darkening may also be affected by the different temperatures of the transited regions in the photosphere. Table 3 presents the priors and fit parameters, while Fig. 6 shows the TESS data for the three transits and the best-fit model obtained from our analysis. As in Sect. 5, the MCMC samples and posterior distributions are illustrated in Figs. C.2 and C.4.

7. Discussion

We combine the transit parameters of AU Mic b and c presented in Tables 2 and 3 with the star parameters from Table 1 to calculate a number of derived parameters, which are presented in Table 4.

The planet-to-star radius ratio obtained in Sects. 5 and 6 are likely overestimated due to the presence of spots covering a significant fraction of the stellar photosphere. This is because the
Table 3. Transit fit parameters for planet AU Mic c obtained in our analysis from a simultaneous fit of the three transits observed by TESS as illustrated in Figs. 6 and C.4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior value</th>
<th>MCMC fit value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of conjunction, $T_0$ [TBJD]</td>
<td>$N(1342.23, 0.01)$</td>
<td>1342.2223 ± 0.0005</td>
</tr>
<tr>
<td>Orbital period, $P$ [d]</td>
<td>$N(18.86, 0.01)$</td>
<td>18.859019$^{+0.000016}_{-0.000015}$</td>
</tr>
<tr>
<td>Normalized semi-major axis, $a/R_*$</td>
<td>$U(31.5, 1.4)$</td>
<td>29 ± 3</td>
</tr>
<tr>
<td>Orbital inclination, $i$ [degree]</td>
<td>$U(85, 90)$</td>
<td>89.0$^{+0.5}_{-0.01}$</td>
</tr>
<tr>
<td>Planet-to-star radius ratio, $R_p/R_*$</td>
<td>$N(0.04, 0.01)$</td>
<td>0.0418$^{+0.0012}_{-0.0010}$</td>
</tr>
<tr>
<td>Linear limb dark. coef., $u_0$</td>
<td>$N(0.23, 1.0)$</td>
<td>0.0$^{+0.2}_{-0.3}$</td>
</tr>
<tr>
<td>Quadratic limb dark. coef., $u_1$</td>
<td>$N(0.38, 1.0)$</td>
<td>1.2$^{+0.3}_{-0.3}$</td>
</tr>
</tbody>
</table>

Fig. 6. Each panel shows the range around one of the three transits of AU Mic b observed by TESS. Details are the same as in Fig. 5, but here we present the results for the three TESS transits of AU Mic c. The dispersion of residuals are 370, 646, 609 ppm, for each respective epoch. The global dispersion is 609 ppm.

observed transit depth is likely smaller than the nominal depth that would be obtained for a completely unspotted photosphere. Therefore, an effective planet-to-star radius ratio can be obtained by applying a correction factor to the observed transit depth as in Eq. (1) of Rackham et al. (2018), that is,

$$\left(\frac{R_p}{R_*}\right)_{\text{eff}}^2 = \left[1 - f_{\text{spot}} \left(1 - \frac{F_{\text{spot}}}{F_{\text{phot}}}\right)\right] \frac{R_p}{R_*}_{\text{obs}}^2$$

for $f_{\text{spot}}$ being the spot filling factor estimated at 20% based on magnetic activity (Klein et al. 2021) and $F_{\text{spot}}/F_{\text{phot}}$ being the flux fraction between the spots and the photosphere. The latter can be estimated assuming a blackbody flux for each of the two components, where the photospheric temperature is $T_{\text{phot}} = 3700$ K and the spots’ temperature is estimated at 86% of the photospheric value in M1 stars (Rackham et al. 2018). The latter is in agreement with spectropolarimetric measurements of AU Mic by Berdyugina (2011). Our estimation for the spot-to-photosphere flux fraction integrated over the TESS band pass (between 60 and 1000 nm) is $F_{\text{spot}}/F_{\text{phot}} \sim 46\%$. Therefore, the effective radius for both transiting planets in the AU Mic system should be given by $R_{\text{eff}} = 0.94 R_{\text{obs}}$ that is, about 6% smaller than the measured radius.

In addition to the correction above, there is an uncertainty in the planet radius due to the rotational modulation by starspots and other photospheric heterogeneities, which implies a variable baseline flux. To account for this additional uncertainty, we considered the amplitude of the photospheric modulation in the AU Mic TESS light curve, which is about 5%. This variability propagates an uncertainty on the order of $\sqrt{0.05}$ to the planet radius measurements, which is included in the uncertainty values reported in Table 4.

Klein et al. (2021) recently measured a semi-amplitude of the radial velocity of the reflex motion caused by AU Mic b of $K_b = 8.5^{+0.3}_{-0.2}$ m s$^{-1}$, providing an important constraint on the mass of this planet. We recalculated the planet density based on our radius measurement and obtained $\rho_b = 1.4 \pm 0.4$ g cm$^{-3}$. 

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To estimate a plausible mass range for AU Mic, we considered a population of transiting exoplanets\footnote{Exoplanet parameters compiled from exoplanet.eu} with radii within 1σ of the measured radius of AU Mic c, as presented in Fig. 7. The median and median absolute deviation of the mass of exoplanets in this population is $0.043 \pm 0.036 \ M_{\text{Jup}}$. Therefore, the mass of AU Mic c is likely to lie in the range of $0.007 \ M_{\text{Jup}} < M_c < 0.079 \ M_{\text{Jup}}$, implying a planet density in the range of $0.4 \ g \ cm^{-3} < \rho_c < 4.1 \ g \ cm^{-3}$. Several different scenarios are possible for the internal structure of this planet depending on its mass. We estimate the semi-amplitude of the induced radial velocity caused by AU Mic c in the star motion to be in the range of $0.8 \ m s^{-1} < K_c < 9.5 \ m s^{-1}$. A number of world-class spectrometers can currently achieve the necessary precision to detect such reflex motion. However, the intense stellar activity in AU Mic may represent a challenge for such measurement.

In order to analyze the stability of the orbital solution (Table 4), we performed a global frequency analysis (Laskar 1990, 1993) in the vicinity of the best fit, in the same way as achieved for other planetary systems (e.g., Correia et al. 2005, 2010). The system is integrated on a regular 2D mesh of initial conditions, with varying semi-major axis and eccentricity of planet c, while the other parameters are retained at their nominal values. We used the symplectic integrator SABA1064 of Farrés et al. (2013), with a step size of $5 \times 10^{-3}$ yr and general relativity corrections. Each initial condition is integrated over 5 kyr, and a stability indicator is computed to be the variation in the measured mean motion over the two consecutive 2.5 kyr intervals of time (for more details see Crouzet et al. 2010). For regular motion, there is no significant variation in the mean motion along the trajectory, while it can vary significantly for chaotic trajectories.

In Fig. 8, we show the wide vicinity of the nominal solution for two different configurations, one with $M_c = 25.0 \ M_\oplus$ (top) and another with $M_c = 2.2 \ M_\oplus$ (bottom), corresponding to the maximum and minimum masses of the outer planet, respectively.

The stability indicator is reported using a color index, where “red” represents the strongly chaotic trajectories and “dark-blue” shows the extremely stable ones. We observe that there are several islands of mean motion resonances nearby, however, the main difference is that when the mass of the outer planet is large, these resonances become unstable. The best fit nominal solution (vertical dotted line) is close to the 9:4 resonance, but outside, and so the nominal solution is in the stable zone for both mass choices. How-
Fig. 7. Mass-radius diagram of planets. Blue circles show the known transiting exoplanets compiled from exoplanet.eu. The orange point represents AU Mic b and the light green horizontal dashed and dotted lines represent the AU Mic c radius measurement and ±1σ uncertainties. Dark green point represents the median of planets with radius within 1σ of the measured radius of AU Mic c. Dashed orange line shows an iso-density line for the radius and mass of AU Mic b and the olive lines correspond to the iso-densities obtained for the radius of AU Mic c and for the lower limit (dotted), median value (dashed), and upper limit (dot-dashed) of the mass of AU Mic c, based on the exoplanet population with the same radii.

Table 5. Measurements of the transit-timing variation (TTV) for the transits of AU Mic b and c observed by TESS.

<table>
<thead>
<tr>
<th>Planet</th>
<th>epoch</th>
<th>$T_c$ (TBJD)</th>
<th>TTV (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>0</td>
<td>1330.39046 ± 0.00016</td>
<td>−32 ± 17</td>
</tr>
<tr>
<td>b</td>
<td>2</td>
<td>1347.31646 ± 0.00016</td>
<td>+39 ± 21</td>
</tr>
<tr>
<td>b</td>
<td>84</td>
<td>2041.28238 ± 0.00026</td>
<td>−41 ± 25</td>
</tr>
<tr>
<td>b</td>
<td>85</td>
<td>2049.74538 ± 0.00026</td>
<td>+31 ± 32</td>
</tr>
<tr>
<td>b</td>
<td>86</td>
<td>2058.20838 ± 0.00026</td>
<td>+27 ± 27</td>
</tr>
<tr>
<td>c</td>
<td>0</td>
<td>1342.22432 ± 0.00031</td>
<td>−13 ± 43</td>
</tr>
<tr>
<td>c</td>
<td>37</td>
<td>2040.00697 ± 0.00048</td>
<td>−81 ± 53</td>
</tr>
<tr>
<td>c</td>
<td>38</td>
<td>2058.86596 ± 0.00049</td>
<td>+92 ± 59</td>
</tr>
</tbody>
</table>

but they allow us to reduce the uncertainty in the mass of the outer planet. The non-detection of TTVs that are larger than one minute place the mass of the outer planet on the low side as the likelier assumption. In Fig. 9, we show the TTV corresponding to an outer companion with $M_c = 7.0 M_J$. This mass generates TTVs with an amplitude around one minute corresponding to our upper limit. The observation of additional transits should help to resolve the present ambiguity in the outer planet mass.

Furthermore, we calculated the habitable zone (HZ) for AU Mic using the equations and data from Kopparapu et al. (2014), which gives an optimistic lower limit (recent Venus) at 0.25 au, and an upper limit (early Mars) at 0.64 au, with the runaway greenhouse limits ($M_p = 1 M_J$) ranging between 0.32 and 0.61 au. AU Mic b and c being at an orbital distance of 0.0645 ± 0.0013 au and 0.1101 ± 0.0022 au are not in the HZ.

We estimate the equilibrium temperatures as in Heng & Demory (2013) assuming a uniform heat redistribution and an arbitrary geometric albedo of 0.1, which gives $T_{eq,b} = 593 ± 21 \text{ K}$ and $T_{eq,c} = 454 ± 16 \text{ K}$, for AU Mic b and c, respectively, showing that these warm Neptunes are indeed too hot to sustain water in liquid state. Moreover, the actual temperature for these planets could be much higher due to a possible greenhouse effect depending on their atmospheric composition and also due to an elevated internal temperature provided the young age of the system.

8. Conclusions

We presented an analysis of the photometric TESS observations of the active young M1 star AU Mic, where we model the rotational modulation by starspots, the flaring activity, and the planetary transits simultaneously. Our analysis delivered an estimation of the flare occurrence rate of 6.35 flares per day for flares with amplitudes in the range of $0.06\% < f_{max} < 1.5\%$ of the star flux. With such a flare rate it is important to model flaring activity to improve the constraints on the planetary parameters from transits. In our simple multi-flare model, we did not explore a detailed physical modeling of flares (e.g., as in Tilley et al. 2019) that could, in principle, be studied more extensively given the high quality and broad time coverage of these TESS observations. Our aim was to find an empirical description of flares that improves the constraints on the planetary parameters of AU Mic b and that increases the sensitivity for detecting and characterizing the second planet AU Mic c.
Our analysis of the five transits of AU Mic b provided measurements of the orbital period and time of conjunction, giving an improved epimetheus of $T_c = 2.458 \times 303.9051 \pm 0.00015 + E \times 8.463000 \pm 0.000002$ JD for an accurate prediction of the times of future transits. Our detection of two new transits in the recent TESS observations have provided substantial evidence to confirm the second planet, that is, AU Mic c. We analyzed the three transits and obtained consistent results for the planetary parameters, which supports our hypothesis that these transits come from the same planet. Our MCMC analysis provided a determination of the planetary parameters for AU Mic c, delivering an epimetheus of $T_c = 2.458 \times 342.2223 \pm 0.0005 + E \times 18.859019 \pm 0.000016$ JD for the times of transits with a transit duration of 4.5 ± 0.8 hours. The derived radius of 3.24 ± 0.16 $R_\oplus$ indicates that AU Mic c is a Neptune-like planet with an expected mass in the range of 2.2 $M_\oplus$ < $M_c$ < 25.0 $M_\oplus$, estimated from the population of exoplanets of a similar size.

AU Mic b and c with an orbital period of 8.46 d and 18.86 d are near the 9:4 mean-motion resonance. Such a configuration is stable and could cause significant TTV, which we do not detect with the current dataset. Still, that non-detection provides an upper limit to the mass of AU Mic c of $M_c < 7 M_\oplus$, implying an upper limit to the planet density of $\rho_c < 1.3$ g cm$^{-3}$. This suggests that both planets are likely inflated, as it should be expected for young planets (e.g., Helled et al. 2020). Therefore, these planets are interesting targets for atmospheric characterization by transmission spectroscopy.

The interactions between the planets coupled in a near 9:4 mean-motion resonance and the debris disk surrounding the star are to be the subject of subsequent studies. High-resolution images have revealed that the disk has a complex structure with small-sized substructures, such as “feature A” at a dozen astronomical units showing a “loop-like” morphology (Wisniewski et al. 2019). As for the case of β Pictoris, it has been shown that the planets can sculpt the disk morphology through the gravitational interaction between planets and the debris disk parents bodies at far distances (Lecavelier Des Etangs et al. 1996; Augereau et al. 2001), particularly through resonance mechanisms in young systems that are still evolving (Lecavelier Des Etangs 1998). The impact of the presence of AU Mic b and AU Mic c on the dust disk deserves future analysis.

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Appendix A: Star rotation

In this appendix, we present an independent measurement of the star rotation period of AU Mic.

Starspots in AU Mic have a life time sufficiently large that the overall spot pattern did not change significantly during the 2018 TESS observations in the first visit. As one can see in the bottom panel of Fig. 1, there has been a more significant change in the spot pattern during the second visit of TESS, where the amplitude of the cyclic flux variations decreases with time. For this reason, we did not include the second visit data to measure the rotation period. Flares and planetary transits are removed from the original data using the models computed in Sects. 4–6. We apply the phase dispersion minimization (PDM) method inspired by the work of Stellingwerf (1978), where we calculate the phase curve for several values of trial rotation periods ranging from $4.85 \text{ d}$ to $4.88 \text{ d}$ in steps of $0.0001 \text{ d}$. The rotation period of $P_r = 4.865 \text{ d}$ measured by Torres et al. (1972)...

Fig. A.1. Rotation period versus chi-square for the reduced light curve of AU Mic after removing flares and planetary transits. Red dashed line shows the minimum $\chi^2$ at $P = 4.862 \pm 0.032 \text{ d}$ obtained by a parabolic fit (green line).

Fig. A.2. Phased light curve of AU Mic using our measured rotation period of 4.862 d. Black points show the 2018 TESS (first visit only) fluxes after removing the flares and transits best fit models, and red line shows the best fit cubic spline model to the phased data.
was considered as initial guess to define our search range. For each trial period, we fit a cubic spline with 15 knots and calculate the chi-square by \( \chi^2 \) at \( P_t = 4.862 \pm 0.032 \) d, which is consistent but less accurate than the rotation period of 4.863 \( \pm 0.010 \) d obtained by Plavchan et al. (2020) from the same data set. The resulting phase curve and best fit model are presented in Fig. A.2. The final dispersion of residuals from the fit to the time series, that is, 99 \( \pm 0.032 \) km s\(^{-1}\), is consistent but less accurate than the rotation period of \( R_c = 0.75 \pm 0.03 \) R\(_\odot\) (White et al. 2015) and the rotation period of \( P_t = 4.862 \pm 0.032 \) d, we calculate the velocity at the equator as \( v_{eq} = 2\pi R_c / P_t = 7.8 \pm 0.3 \) km s\(^{-1}\). This gives a maximum value of the projected velocity of \( v_{eq} \sin (i_\star) < 8.1 \) km s\(^{-1}\), for \( i_\star \) being the inclination angle of the rotation axis of the star with respect to the line of sight.

### Appendix B: Flares fit parameters

#### Table B.1. Flares fit parameters.

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Appendix C: MCMC samples and posterior distributions

Fig. C.1. MCMC samples (black dots) used to calculate the posterior distributions of the transit parameters of AU Mic b. The red dots show the discarded samples corresponding to the first 5000 steps of the chain. The blue lines show the median calculated for bins of 1000 steps. Dashed lines show the 16- and 84-percentiles and the solid horizontal lines shows the medians of the valid samples.

Fig. C.2. Same Fig. C.1 for the MCMC samples of the transit parameters of AU Mic c.
Fig. C.3. Pairs plot showing the MCMC samples and posterior distributions for the transit parameters of AU Mic b as presented in Table 2. The contours mark the 1, 2, and 3σ regions of the distribution. The blue crosses indicate the best fit values for each parameter and the dashed vertical lines in the projected distributions show the median values and the 1σ uncertainty (34% on each side of the median).
Fig. C.4. Pairs plot showing the MCMC samples and posterior distributions for the transit parameters of AU Mic b as presented in Table 2. Details are the same as in Fig. C.3 for the analysis of the three transits of AU Mic c.
Appendix D: Independent fit to the transits of AU Mic c

This appendix presents the results obtained from an MCMC analysis (as in Sect. 5) performed on each transit of AU Mic c independently. Table D.1 shows the posterior of the transit parameters, where we present first the results using broad priors and then using the more restricted priors, as described in Sect. 6. We notice that the period and semi-major axis are not well constrained by the shape of the transits. As a consequence, when using broad priors, their posteriors turn out to have relatively large uncertainties. However, the posterior of all parameters agree within 3σ among the three events and they also agree with our derived period of \( P \sim 18.86 \text{ d} \). The fit parameters for the more constrained priors also agree within 3σ, and the dispersion of residuals are improved with respect to the unconstrained solution, which supports our hypothesis that these events are caused by the transits of the same planet, namely, AU Mic c.

Table D.1. Fit transit parameters for an independent analysis of each of the three transit-like events identified as AU Mic c in the TESS light curve.

<table>
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<tr>
<th>Event</th>
<th>( T_0 ) [TBJD]</th>
<th>( P ) [d]</th>
<th>( a/R_* )</th>
<th>( R_p/R_* )</th>
<th>( i_p ) [°]</th>
<th>( \sigma ) [ppm]</th>
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<td>1(( a ))</td>
<td>1342.22 ± 0.03</td>
<td>30 ± 6</td>
<td>40 ± 8</td>
<td>0.028 ± 0.006</td>
<td>89.28 ± 0.45</td>
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<td>1</td>
<td>1342.2247±0.0005</td>
<td>17+13−8</td>
<td>25+18−11</td>
<td>0.036+0.0014−0.0012</td>
<td>88.6+0.9−1.2</td>
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<tr>
<td>2</td>
<td>2040.0063±0.0004</td>
<td>23±7−5</td>
<td>27 ± 6</td>
<td>0.0420±0.0009</td>
<td>88.28+0.3−0.5</td>
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<tr>
<td>3</td>
<td>2058.8672 ± 0.0004</td>
<td>21±46−12</td>
<td>37±78−21</td>
<td>0.0359±0.0005−0.0005</td>
<td>89.35+0.52−1.03</td>
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<tr>
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<td>18.8574±0.0016−0.0008</td>
<td>31.3±0.4−0.8</td>
<td>0.0393±0.0005−0.0004</td>
<td>89.04+0.09−0.06</td>
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<tr>
<td>2</td>
<td>2040.0062 ± 0.0003</td>
<td>18.8588±0.0012−0.0014</td>
<td>23.8±1.5−1.3</td>
<td>0.0444 ± 0.0007</td>
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<tr>
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<td>0.0409 ± 0.0004</td>
<td>89.03±0.07−0.20</td>
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</table>

Notes. The first row shows the previous results for Event 1 by Plavchan et al. (2020), the three following rows show the best fit parameters from our MCMC analysis of each event adopting an orbital period with an uniform prior of \( P = \mathcal{U}(1, 500) \) d. The last three rows show the fit parameters using an orbital period with a normal prior of \( P = \mathcal{N}(18.85895, 0.00003) \) d, as described in the text. \( a \)Fit parameters for Event 1 obtained by Plavchan et al. (2020).