A very eccentric brown dwarf coplanar to a warm Jupiter and a hot super Earth

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In transiting planetary systems, where planetary sizes are accurately determined from transit observations, the presence of transit timing variations (TTVs), especially when combined with radial velocity (RV) data, provides powerful constraints on masses and orbital eccentricities. Together, these measurements offer crucial insights into system architecture, formation mechanisms, and dynamical evolution. We present long-term RV and transit/TTV monitoring of the active and young star (age ∼1 Gyr) TOI-201, revealing an exceptional multi-planet system composed of a hot super-Earth (SE) transiting every 5.8 days, a warm Jupiter (WJ) on a 53-day orbit, and an eccentric (e = 0.622) low-mass brown dwarf (BD) on an approximately 8-year orbit, with an estimated mass of $M_{BD} \sim 16$ Jupiter masses. The BD is the longest-period transiting object ever characterized via RVs, and the only one known to be coplanar with inner planets. The architecture of this system suggests that the SE was formed isolated and in the innermost region of the gaseous disc. On the other hand, the orbital configuration of the outer companions suggests a nearly in-situ formation of both objects, with the WJ forming in a dense inner disc. Alternatively, the BD might have formed farther out and migrated inward, while inflating its eccentricity due to interactions with the disc.

TOI-201 is a young (age ∼ 1 Gyr) F-type main-sequence star with a V -band optical brightness of 9.1 magnitudes, located 112 pc from the Sun (see Methods section 'Stellar parameters'). This star is known to harbor a transiting warm Jupiter (WJ; TOI-201 b) with a 53-day orbital period, which was discovered in 2019 by the Transiting Exoplanets Survey Satellite1 (TESS[1]). The planet was initially characterized using ground-based spectroscopic data and was one of the first so-called WJs detected by TESS [2]. TOI-201 is also among the few systems that were observed in more than 30 TESS sectors, 17 of which were not yet available in the discovery paper (refer to the Methods section 'TESS photometric data'). Building on this expanded light curve dataset, we are now able not only to refine the physical and orbital parameters of TOI-201 b , but also to validate a new 5.8-day periodic transit signal induced by an inner super-Earth (SE), hereafter named TOI-201 c (refer to Methods section 'super-Earth confirmation'). Furthermore, a single long-duration transit event was detected in Sector 64 (April 2023). Ground-based spectroscopic observations (see Methods section 'High-resolution spectroscopic data') in the context of the Warm gIaNts with tEss (WINE) collaboration[3], along with archival radial velocity (RV) data, reveal that this mono-transit event is due to an eccentric long-period Brown Dwarf (BD), TOI-201 d . This is consistent both with SPHERE high-contrast imaging observations, which fully rule out the presence of stellar binary companions within ∼ 5 arcsec (see details in Methods section

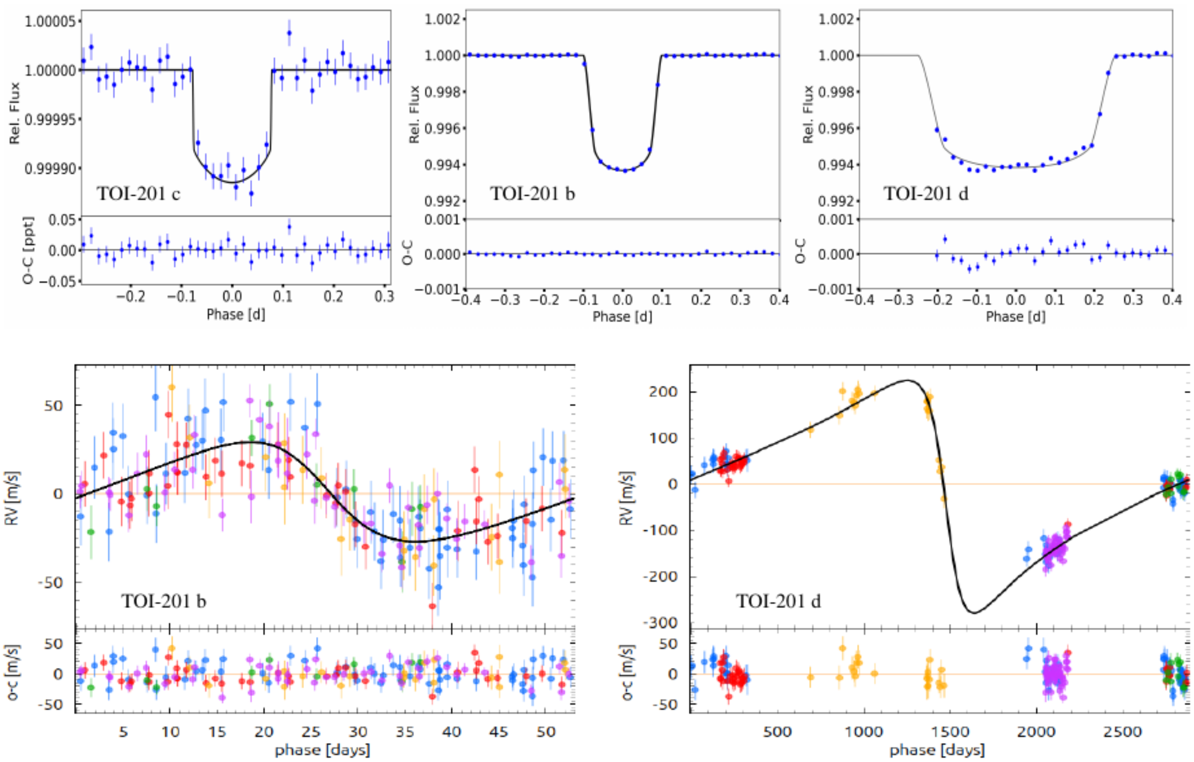

Figure 1. Upper row: Phase folded transits of TOI-201 c, as obtained with 34 different sectors (left panel), TOI-201 b , including 16 transits (middle panel), and the mono-transit event of TOI-201 d , in Sector 64 (right panel). The blue dots correspond to 20-minute phase-bins, and the black solid line to the best transit model. Lower row: Phase folded RV curve of TOI-201, as induced by planets b and d (left and right panels, respectively). The blue, red, green, orange, and magenta dots correspond to FEROS, HARPS, CORALIE, CHIRON and PLATOSPEC data, respectively. The solid line corresponds to the best-fitting model.

'VLT/SPHERE high-contrast imaging'), and with transit time variations (TTVs) observed for the WJ.

We performed a joint analysis of TESS photometry and high-precision RVs from five different facilities (see details in Methods section 'High-resolution spectroscopy') using a self-consistent N-body model, which takes into account the mutual gravitational interaction between the WJ and the BD. This was necessary since the BD induces notable TTVs on the WJ (refer to the Methods section 'Joint RV and transit N-body orbital fitting analysis'). The inner SE was modeled independently using a Keplerian orbital fit to the TESS light curves, as it is sufficiently distant from the massive companions to avoid detectable dynamical interactions on observable timescales. Moreover, its RV signal remains below the level of the observed stochastic RV noise (usually referred to as 'stellar jitter'). As a result, we could determine its radius with high precision, but only place an upper limit on its mass of ~ 33 Earth masses ($M_{\oplus}$) at the 1σ significance level (see Methods section 'super-Earth confirmation'). Figure 1 shows all the phase-folded transits and RVs, along with their best-fitting models, while the main properties obtained for the planets and the BD are listed in Table 1. The radius of TOI-201 c is well below the radius valley that separates the population of SEs, small rocky planets, from sub-Neptunes, which are expected to retain a significant fraction of water or gas in their envelopes[4]. We compared the resulting planet radius with interior models with different masses and compositions (see Methods section 'Interior models'), finding that TOI-201 c is consistent with being rock-dominated, with no significant amount of water on its surface, and with a mass between $\sim 3\,M_{\oplus}$, for a pure silicate rock composition, and $\sim 9\,M_{\oplus}$ for 100% iron composition (Extended Data Fig. 1).

For TOI-201 b , we confirmed that it is a prototypical WJ (see Fig. 2 and Extended Data Fig. 2) in a mildly eccentric orbit ($e = 0.280 \pm 0.002$), and we refined its orbital parameters. By comparing its measured radius with different MESA[5] models (see Methods section 'Interior models'), we found that TOI-201 b is consistent with a rocky core with a mass between $\sim 14 - 28\,M_{\oplus}$, surrounded by a gaseous envelope with the same metal fraction as the parent star (Extended Data Fig. 3). This corresponds to a planet metallicity of $Z_{\rm p} = 0.13^{+0.04}_{-0.03}$, thus to a planet heavy-element enrichment of $Z_{\rm p}/Z_{\star} = 5.0^{+1.5}_{-1.2}$. These values are consistent

Table 1. Physical and orbital parameters of the inner planets and the BD.

Parameter	TOI-201 d	TOI-201 b	TOI-201 c
Period (d)	$5.849240^{+0.000005}_{-0.000006}$	$52.97804^{+0.00004}_{-0.00002}$	$2881.15^{+0.02}_{-0.01}$
Semi-major axis (au)	$0.0677^{+0.0012}_{-0.0012}$	$0.3001^{+0.0031}_{-0.0031}$	$4.33^{+0.06}_{-0.06}$
Radius	$1.436^{+0.045}_{-0.046}\,R_\oplus$	$1.01^{+0.03}_{-0.03}\,R_\mathrm{J}$	$0.99^{+0.03}_{-0.03}\,R_\mathrm{J}$
Eccentricity	$0.116^{+0.154}_{-0.084}$	$0.275^{+0.002}_{-0.002}$	$0.622^{+0.001}_{-0.001}$
Mass	$< 33\,M_\oplus$	$0.59^{+0.02}_{-0.02}\,M_\mathrm{J}$	$16.46^{+0.48}_{-0.48}\,M_\mathrm{J}$
Mean density (g cm^{-3})	< 61	0.71 ± 0.07	21.07 ± 1.78
Eq. temperature (K)	1337.6 ± 15.2	635.7 ± 10.4	167.8 ± 3.0
Orbital inclination (deg)	$87.54^{+0.68}_{-0.39}$	$88.855^{+0.001}_{-0.003}$	$89.855^{+0.001}_{-0.001}$

with those obtained with GASTLI[6] of $Z_\mathrm{p} = 0.08^{+0.08}_{-0.05}$ and $Z_\mathrm{p}/Z_\star = 3.1^{+3.1}_{-1.9}$. On the other hand, for TOI-201 d we obtained $M_\mathrm{p} = 16.46^{+0.34}_{-0.34}$ Jupiter masses (M_J) and $R_\mathrm{p} = 0.99^{+0.03}_{-0.03}$ Jupiter radii (R_J), placing this object within the BD mass regime, slightly above the deuterium-burning limit[7], and consistent with models with low initial deuterium fraction (Extended Data Fig. 3). In particular, TOI-201 d is the farthest transiting substellar companion ($P = 2881.15^{+0.02}_{-0.01}$ days and $e = 0.622^{+0.001}_{-0.001}$) ever characterized with RV-follow up (see Figure 2). TOI-201 is also the only known planetary system hosting a distant BD which is coplanar to inner planets, in this case a WJ and a SE.

The orbital configuration of the TOI-201 planetary system is shown in Figure 2. Similarly, the current state of the WJ+BD system is depicted in Extended Data Figure 4 (a), where we note that the WJ has a rather large free eccentricity compared to the forced eccentricity, $e_\mathrm{WJ,free} > e_\mathrm{WJ,forced}$. Here, $e_\mathrm{WJ,forced}$ is the secular equilibrium eccentricity due to the BD, while $e_\mathrm{WJ,free}$ is the amplitude of the oscillating mode around the forced eccentricity[9]. We note that instabilities and chaotic events such as planet-planet scattering[10] would most likely have generated significant mutual inclinations[11], which means that any instability is not expected to have taken place after the formation of the system, due to its co-planarity. This implies that the eccentricity of the WJ was acquired through less violent mechanisms. We can envision two possibilities for the assembly of this system (see Figure 3). One is that the BD formed close to its current orbit early on, either as a fragment in a massive disc[12] or alongside multiple fragments of which it was the only survivor, thus acquiring its high eccentricity[13] (Panel A, I). Had it also acquired some mutual inclination with the remaining disc inside its orbit, the latter must have realigned with the BD[14–16] to ensure co-planarity between the BD, the WJ and the inner SE (Panel A, II). Such eccentric massive companion would truncate[17, 18] and excite an eccentricity in the disc[19] (Panel A, III), hindering planet formation since the material budget would be limited and the

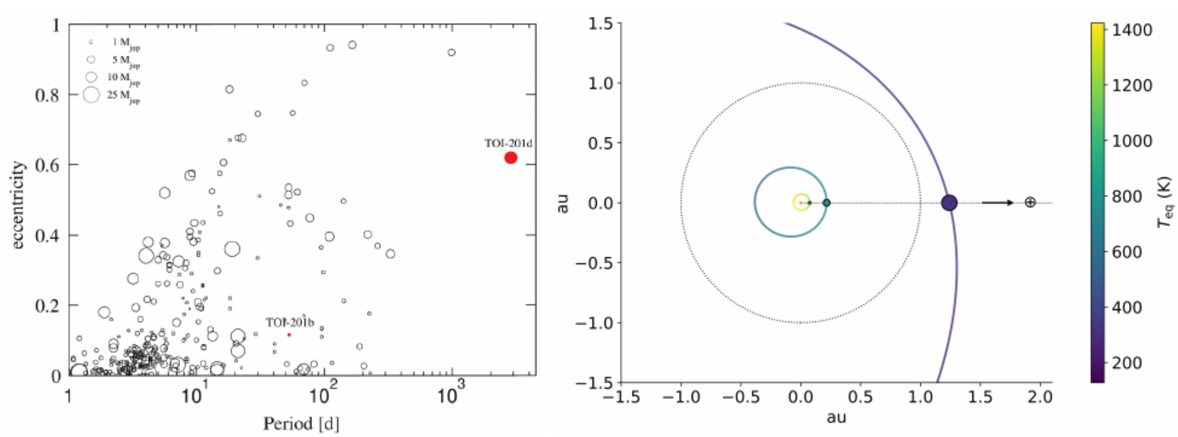

Figure 2. *Left panel:* Eccentricity vs. orbital period for known transiting giants ($0.3 < M_\mathrm{p}/M_\mathrm{J} < 30$) with eccentricity and mass precision better than 20%, including TOI-201 b and TOI-201 d (red circles). For visual clarity, the symbol sizes scale with the square root of the planet mass. Data retrieved from the NASA Exoplanet Archive (as of May 2025), and complemented with the low-mass BD compilation in ref.[8] *Right panel*: Orbital configuration of the TOI-201 system. The solid lines represent the orbit of the three planets, with the color scale corresponding to different equilibrium temperature. For comparison a circular orbit at 1 AU (Earth) is also shown (dotted line).

growth in an eccentric disc can be challenging[20–24]. Both these issues point to an initially dense inner disc with a large enough solid budget and whose self-gravity drives a fast pericenter precession to decouple the disc-BD secular interactions, allowing it to remain (initially) relatively circular[25]. The other possibility is that the BD formed farther out and even less eccentric (Panel B, I) , and that it migrated inward while getting its eccentricity pumped (Panel B, II), due to interactions with the gas[26] (an eccentricity pumping of the BD via Kozai-Lidov cycles[27,28] induced by a close companion is excluded by the SPHERE observations; see Extended Data Fig. 4), and reaching its current state (Panel B, III). This scenario would alleviate the issues posed by a severely truncated and eccentric disc, thus leaving more flexibility for the growth of the planets. However, we note that the WJ's orbit is rather close to the instability limit (see Extended Data Fig. 4), meaning that, for this scenario to work, the BD would have to arbitrarily stop its inward migration, so as not to disrupt the WJ. Thus, although possible, this explanation may be more fortuitous. A more distant BD, if it formed inclined with respect to the disc, would also require more time to allow for disc-BD realignment.

In any case, the WJ most likely formed in an initially dense, relatively circular disc (Panel C, I), with initially $e_{WJ}\cos(\Delta\omega) \sim e_{WJ}\sin(\Delta\omega) \sim 0$, where $\Delta\omega = \omega_{BD} - \omega_{WJ}$ is the relevant secular angle (see Methods section 'Orbital state and stability analysis'). Looking at Extended Data Fig. 4, this configuration means that $e_{WJ,free} \sim e_{WJ,forced}$, but the WJ is initially decoupled from the BD. Then, as the WJ became massive enough to open a gap[29] (Fig. 3, Panel C, II), or as the disc became less dense and thus eccentric (or both), the eccentricity of the WJ could have been pumped[30–33]. The WJ started secularly evolving with the BD around $e_{WJ,forced}$, and reached its currently observed state (Panel C, III) with $e_{WJ,free} > e_{WJ,forced}$ due to e-pumping.

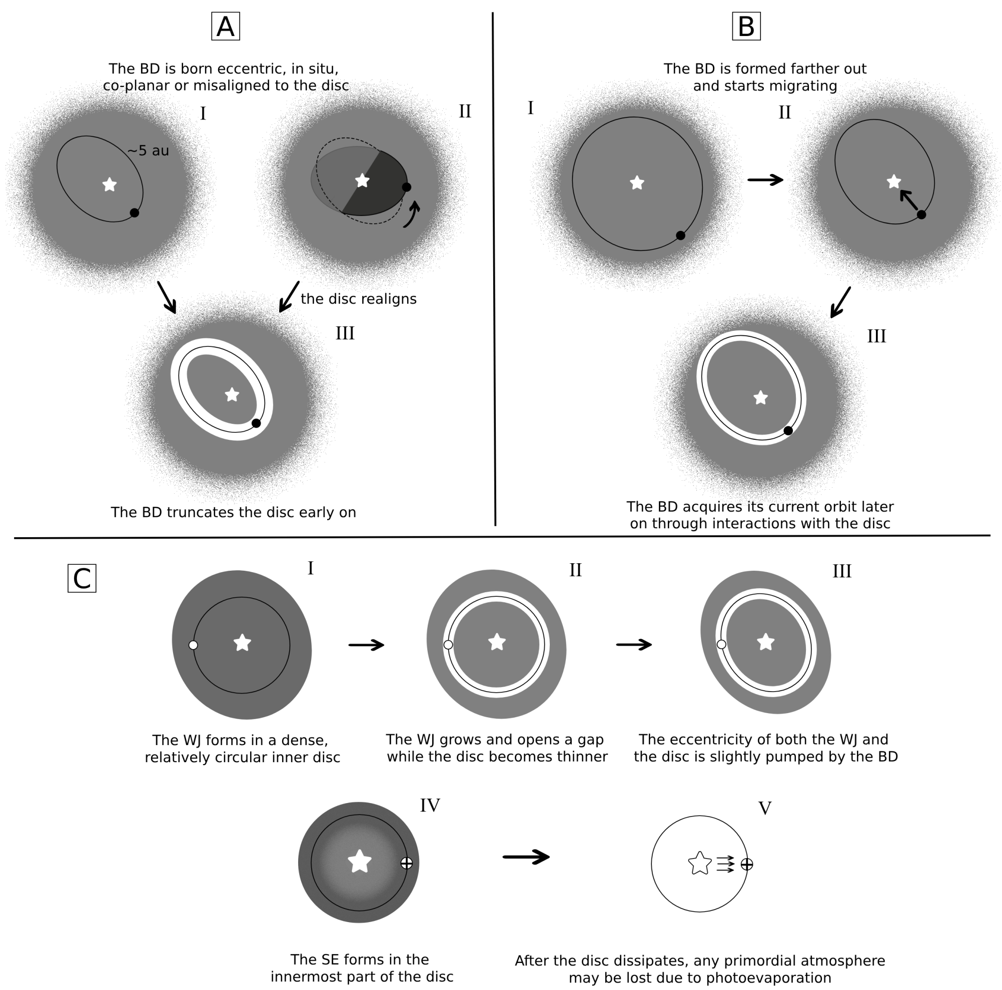

Figure 3. Diagram of the possible formation scenarios discussed in the main text. Panel C focuses on the inner region where TOI-201 b and TOI-201 c form, with the enlarged star symbol denoting a smaller spatial scale.

The inner SE also most likely formed in the disc (Panel C, IV), as gas-free formation[34] is unlikely because of the low isolation mass at these locations. Moreover, the forced eccentricity near the current location of the SE is ~ 0.1; left-over planetary cores and planetesimals would experience inefficient growth due to high-velocity dispersion, with limited gravitational focusing and collisions leading to fragmentation/erosion rather than growth.

For the bulk of the SE population, the dichotomy[35] between single- and multi-transiting systems can be explained by the assembly of multiple SEs within the same system and invoking post-disc instabilities[36–38], even when outer giants are present[39]. In TOI-201, however, this scenario is disfavoured because the SE would have likely acquired some inclination with respect to the outer bodies, as well as a larger eccentricity after the instability compared to its current eccentricity, which is instead close to the forced eccentricity driven by the outer bodies. Unless additional yet-undetected planets are orbiting the star on inclined orbits, this suggests that the SE may have formed alone in the innermost region of the disc. There, it could have acquired a primordial atmosphere which, given its current radius ($\sim 1.4 R_{\oplus}$), may have been removed (Panel C, V). Given the relatively young age of the system ($\sim$ 1 Gyr), photoevaporation[40] appears to be a more viable atmospheric escape mechanism than core-powered mass loss[41].

The TOI-201 system represents an exceptional and unique multi-planet system, offering a rare window into the processes of planet formation and dynamical evolution. Its rare configuration provides invaluable insights into the formation and evolution pathways, suggesting a dynamically mild, coplanar and almost in-situ formation of a WJ, a highly eccentric BD, and a lone inner SE, within a common protoplanetary disk. Future studies, such as high-cadence spectroscopic follow-up to measure the mass of the SE and the spin-orbit alignment of the WJ, will provide further information about the current architecture and the past evolution of this system.

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