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The HADES RV Programme with HARPS-N@TNG

GJ 3998: An early M-dwarf hosting a system of Super-Earths

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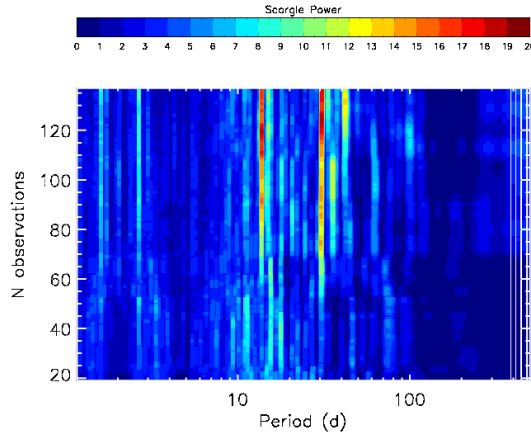
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We present here the detection of a system of two Super Earths orbiting at 0.029 AU and 0.089 AU from the central star, the early M dwarf GJ 3998. The analysis is based on high-precision, high-resolution spectroscopic Doppler time-series, spanning ≈ 2.4 years, gathered with the HARPS-N spectrograph on the Telescopio Nazionale Galileo as part of an RV survey for low-mass planets around a sample of northern-hemisphere early-M dwarfs. The HADES (HARPS-n red Dwarf Exoplanet Survey) observing programme is the result of a collaborative effort between the Italian Global Architecture of Planetary Systems (GAPS) Consortium, the Institut de Ciències de l'Espai de Catalunya (ICE), and the Instituto de Astrofísica de Canarias (IAC).

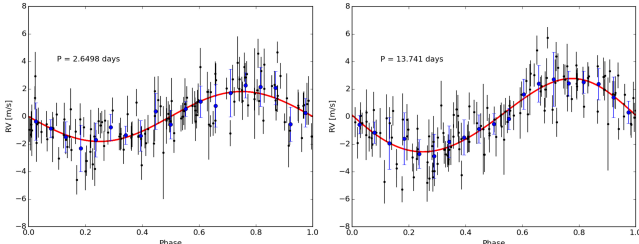
The homogeneous analysis of the 136 RV observations was carried out both with a frequentist approach and by comparing models with a varying number of Keplerian signals and different models of the stellar activity noise.

The analysis of the radial velocity time series unveiled the presence of at least four significant periodic signals, two of these are linked to the activity of the host star and two orbital periods:

$P = 30.7$ d, estimate of the rotational period of the star
 $P = 42.5$ d, modulation of the stellar variability, likely due to differential rotation
 $P = 2.6$ d, orbital period of GJ 3998b
 $P = 13.7$ d, orbital period of GJ 3998c



(Upper Panel) Periodogram power of the inspected periods as a function of the number of observations. The most significant periods (the reddest ones) at 30.7 d and 13.7 d are clearly visible with a high power for $N_{\text{obs}} > 60$, as well as the period at 2.65 d, which increases for $N_{\text{obs}} > 80$ and the period at 42.5 d whose power increases for $N_{\text{obs}} > 110$.



Parameter (planets)	Value	Prior
Planet b		
K [m s ⁻¹]	$1.82^{+0.14}_{-0.16}$	$\mathcal{U}(0, +\infty)$
P [days]	$2.64977^{+0.00081}_{-0.00077}$	$\mathcal{U}(1.5, 3.5)$
$T_{0,\text{conj.}}$ [BJD-2, 450, 000]	$6905.895^{+0.042}_{-0.040}$	$\mathcal{U}(6900, 6915)$
e	0 (fixed)	-
a [au]	0.029 ± 0.001	derived
$m_p \sin i$ [$M_{\oplus}$]	2.47 ± 0.27	derived
Planet c		
K [m s ⁻¹]	$2.67^{+0.28}_{-0.23}$	$\mathcal{U}(0, +\infty)$
P [days]	13.740 ± 0.016	$\mathcal{U}(12, 15.5)$
$T_{0,\text{conj.}}$ [BJD-2, 450, 000]	$6902.2^{+0.24}_{-0.29}$	$\mathcal{U}(6900, 6915)$
e	$0.049^{+0.052}_{-0.034}$	-
	$0.049^{+0.094}_{-0.045}$ (5% and 95% quantiles)	-
ω [rad]	unconstrained	-
$\sqrt{e} \cdot \sin \omega$	$0.079^{+0.17}_{-0.21}$	$\mathcal{U}(-1, 1)$
$\sqrt{e} \cdot \cos \omega$	$-0.003^{+0.161}_{-0.155}$	$\mathcal{U}(-1, 1)$
a [au]	0.089 ± 0.003	derived
$m_p \sin i$ [$M_{\oplus}$]	$6.26^{+0.79}_{-0.76}$	derived
RV_{offset} [m s ⁻¹]	$-0.27^{+0.49}_{-0.43}$	$\mathcal{U}(-5, +5)$

Table 1. Stellar parameters for the star GJ 3998 from the analysis of the HARPS-N spectra using the technique in Maldonado et al. (2015) (in the upper part). In the lower part of the table coordinates, V and K magnitudes, parallax, proper motions and space velocities are indicated.

Parameter ⁽¹⁾	GJ 3998
Spectral Type	M1
T_{eff} [K]	3722 ± 68
[Fe/H] [dex]	-0.16 ± 0.09
Mass [$M_{\odot}$]	0.50 ± 0.05
Radius [$R_{\odot}$]	0.49 ± 0.05
$\log g$ [cgs]	4.77 ± 0.04
Luminosity [$L_{\odot}/L_{\odot}$]	0.041 ± 0.008
$v \sin i$ [km s ⁻¹]	0.93 ± 0.55
α (J2000)	$17^{\text{h}}16^{\text{m}}00.7^{\text{s}}$
δ (J2000)	$+11^{\circ}03'30''$
$V_{\text{mag}}^{(1)}$	10.83
$K_{\text{mag}}^{(2)}$	6.82
π [mas] ⁽³⁾	56.20 ± 2.26
μ_{α} [mas/yr] ⁽³⁾	-136.21 ± 2.30
μ_{δ} [mas/yr] ⁽³⁾	-347.84 ± 1.93
U_{LSR} [km s ⁻¹] ⁽⁴⁾	-26.7 ± 1.1
V_{LSR} [km s ⁻¹] ⁽⁴⁾	-52.8 ± 1.3
W_{LSR} [km s ⁻¹] ⁽⁴⁾	-28.8 ± 0.6
S [km s ⁻¹] ⁽⁴⁾	65.8 ± 1.2

References. ⁽¹⁾ Koen et al. (2010); ⁽²⁾ Cutri et al. (2003); ⁽³⁾ Van Leeuwen (2007); ⁽⁴⁾ This work (see text).

(Right Panels) GLS periodograms of the radial velocities of GJ 3998, of the original data (upper panel) and after removing – from top to bottom – the 30.7 d (marked with the red dot), the 42.5 d (magenta dot), the 13.7 d (blue dot) and finally the 2.65 d (cyan dot) signals. The dashed lines indicate 0.1%, 1% and 10% level of false alarm probability.

(Left Panels) RV data folded at the best-fit orbital period of inner (left panel) and outer planet (right panel). For each folding the signal of the other planet, the RV offset and the best-fit solution for the stellar activity noise have been subtracted. Blue dots are the mean values in bins of amplitude 0.05. The red solid line is the best-fit orbital solution.

The conclusions on activity-related periods are confirmed by the analyses of the **Ca II H&K activity indicators** and of the **photometric light curves** of two independent sets of observations. The time series of S-index and H α show periodic variations around the 30.7 d and 42.5 d signals. The photometric results from both programs confirm the presence of variations in the period range 30 d -- 32 d, highlighting the strong connection of the long RV periods to chromospheric activity and to its rotational modulation.

We run an **MCMC simulation** and use **Bayesian model selection** to determine the number of planets in the system and estimate their orbital parameters and minimum masses. We test several different models, varying the number of planets, eccentricity and treatment of stellar activity noise. We select a model involving **two Keplerian signals**, with a circular orbit for the inner planet and the eccentricity of the outer planet treated as a free parameter.

The two planets appear to have minimum masses compatible with those of **super-Earths**, the inner planet has a minimum mass of $2.47 \pm 0.27 M_{\oplus}$, at a distance of **0.029 AU** from the host star, the outer has a minimum mass of $6.26 \pm 0.79 M_{\oplus}$ and a semi-major axis of **0.089 AU**.

These close distances strongly call for a search of **potential transits** in the next months, in particular for the inner planet, through a proposal for observing time on the **Spitzer Space Telescope**. A potential transit could provide a constraining point in the mass-radius diagram of known planets, enabling also the determination of the mean density and a better characterization of the system architecture with future follow-up observations. The eventuality of a transit, given the small distance from the host and the brightness of GJ 3998 ($V = 10.83$), would make this star a **natural target** for follow-up observations with the **ESA CHEOPS** space telescope and also one of the most interesting M-dwarf targets for a detailed **atmospheric characterization**.