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Letter to the Editor

The CARMENES search for exoplanets around M dwarfs

No evidence for a super-Earth in a 2-day orbit around GJ 1151★

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ABSTRACT

Context. The interaction between Earth-like exoplanets and the magnetic field of low-mass host stars are considered to produce weak emission signals at radio frequencies. A study using LOFAR data announced the detection of radio emission from the mid M-type dwarf GJ 1151 that could potentially arise from a close-in terrestrial planet. Recently, the presence of a 2.5-$M_\oplus$ planet orbiting GJ 1151 with a 2-day period has been claimed using 69 radial velocities (RVs) from the HARPS-N and HPF instruments.

Aims. We have obtained 70 new high-precision RV measurements in the framework of the CARMENES M-dwarf survey and use these data to confirm the presence of the claimed planet and to place limits on possible planetary companions in the GJ 1151 system.

Methods. We analysed the periodicities present in the combined RV data sets from all three instruments and calculated the detection limits for potential planets in short-period orbits.

Results. We cannot confirm the recently announced candidate planet and conclude that the 2-day signal in the HARPS-N and HPF data sets is most probably produced by a long-term RV variability, possibly arising from an outer planetary companion that has yet to be constrained. We calculate a 99.9% significance detection limit of 1.50 m s^{-1} in the RV semi-amplitude, which places upper limits of 0.7 $M_\oplus$ and 1.2 $M_\oplus$ on the minimum masses of potential exoplanets with orbital periods of 1 and 5 days, respectively.

Key words. techniques: spectroscopic – stars: late-type – planetary systems – stars: individual: GJ 1151

1. Introduction

Recently, Vedantham et al. (2020) reported the detection of circularly polarised radio emission in the LOw-Frequency ARray (LOFAR; van Haarlem et al. 2013) Two-Metre Sky Survey (LoTSS) data release I (Shimwell et al. 2019). It was detected over a relatively long duration (>8 h) and at a low frequency (∼150 MHz) at the position in the sky of the M4.5-type (Lépine et al. 2013) star GJ 1151, for which we calculated a mass of 0.170 ± 0.010 $M_\odot$ (Schweitzer et al. 2019). The star is a slow rotator with $v \sin i < 2$ km s^{-1} (Reiners et al. 2018), and with a photometric rotation period estimated at $P_{\rm rot} = 117.6$ d (Newton et al. 2016) and $P_{\rm rot} = 125 \pm 23$ d (Díez Alonso et al. 2019). All available evidence, including a measured pseudo-equivalent width of the Hα line pEW(Hα) = +0.342 ± 0.008 Å (following Schöfer et al. 2019), points at a very low magnetic activity in the star.

★ Table A.1 is only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/649/L12

Table 1. Statistics of the different RV data sets.

Instrument RV extraction code	Unit	HARPS-N TERRA	HARPS-N `wobble`	HPF SERVAL	CARMENES SERVAL	Combined ...	Combined residuals
$N_{\rm obs}$	...	20	19	25	70	115	115
rms	[m s^{-1}]	2.61	3.63	4.64	4.09	4.15	3.32
δRV	[m s^{-1}]	1.85	2.88	3.00	1.79	2.06	2.06
T	[d]	69	69	468	1793	1793	1793
Δt	[d]	3.6	3.8	19.5	26.0	15.7	15.7

Notes. $N_{\rm obs}$ is the number of observations, rms is the RV root mean square, δRV is the mean RV uncertainty, T is the time baseline of the observations, and Δt is the median time sampling between epochs.

Vedantham et al. (2020) discuss that the Poynting flux required to produce the detected radio signal cannot be generated by a star with such characteristics and hence suggest that its origin is rather related to the interaction with a companion. The possibility for it to be a long-period substellar massive object was already ruled out by FastCam observations (Cortés-Contreras et al. 2017), at least for separations >1 au. Thus, the authors suggest the existence of a short-period ($P = 1-5$ d) Earth-like planet with an orbit interior to the habitable zone of the star. Then, they argue that the radio signal could originate from the sub-Alfvénic interaction of this planet with the plasma of the stellar magnetosphere inducing electron cyclotron maser instability (Melrose & Dulk 1982). Recent results of *XMM-Newton* X-ray data (Foster et al. 2020) seem to strengthen this assumption. Since this effect is expected to be very weak, the detection of an exoplanet at radio wavelengths is very intriguing.

The existence of such a planet was initially evaluated by Pope et al. (2020) using 19 epochs of High Accuracy Radial velocity Planet Searcher of the Northern hemisphere (HARPS-N; Cosentino et al. 2012) radial velocity (RV) data. The authors did not find any significant signal but they placed an upper limit of $M \sin i < 5.6\,M_\oplus$ on the minimum mass of any possible close-in planet, assuming a stellar mass of $0.167 \pm 0.025\,M_\odot$ (Newton et al. 2016), and conclusively ruled out close-in stellar or gas-giant companions. More recently, Mahadevan et al. (2021) analysed the same HARPS-N RVs together with 50 epochs from newly obtained Habitable-zone Planet Finder (HPF; Mahadevan et al. 2012) near-infrared RVs. The authors report a significant Doppler signal compatible with an $M \sin i = 2.5 \pm 0.5\,M_\oplus$ planet on a 2.02-day orbit, inducing an RV semi-amplitude of $K = 4.1 \pm 0.8$ m s^{-1}.

Here, we report on the combined analysis of the published HARPS-N and HPF RVs, together with an additional data set consisting of 70 epochs of Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Echelle Spectrographs (CARMENES; Quirrenbach et al. 2020) RVs of GJ 1151.

2. Radial velocity analysis

We used the 20 publicly available HARPS-N spectra of GJ 1151 and calculated RVs with the TERRA pipeline (Anglada-Escudé & Butler 2012). The measurements (see Table A.1) show significantly smaller variations and uncertainties than the 19 RVs (see Table 1) from both Pope et al. (2020) and Mahadevan et al. (2021), which were derived with the `wobble` code (Bedell et al. 2019). The observations were acquired from December 2018 to February 2019, with occasional dense sampling (top panel of Fig. 1). In addition,

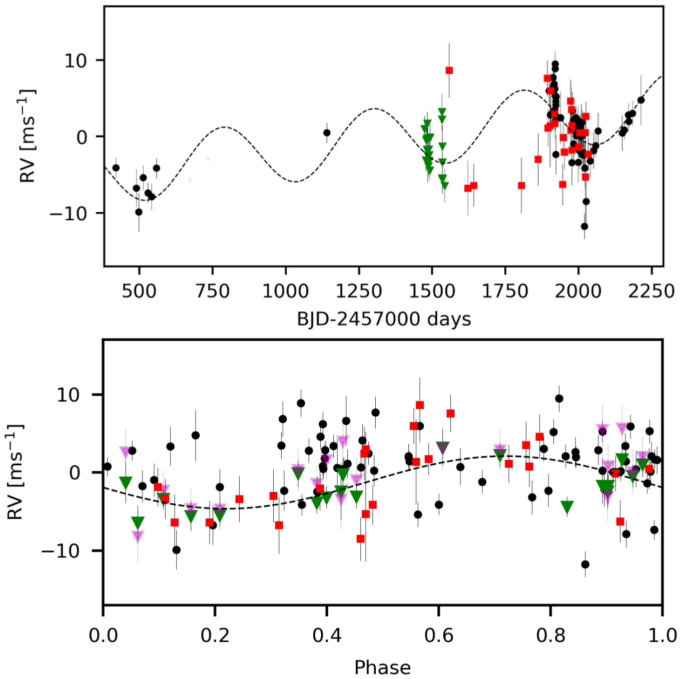

Fig. 1. RV data as observed from HARPS-N (green triangles), HPF (red squares), and CARMENES (black dots) in time series (*top panel*), and phase-folded (*bottom panel*) to the 2.02-day period of the planet candidate announced by Mahadevan et al. (2021). *Top panel*: we include the best-fitting linear trend of 1.73 m s^{-1} and the long-period signal of ~500 d represented by the black dashed line. *Bottom panel*: we also show the HARPS-N data as derived by the `wobble` code represented by magenta triangles.

Mahadevan (priv. comm.) kindly provided us with 25 RVs from the HPF near-infrared observations obtained between March 2019 and June 2020 which were computed with the SERVAL code (Zechmeister et al. 2018). These RVs correspond to nightly averages of the 50 individual measurements presented in their paper. The data points show significantly larger individual uncertainties than the RVs from the HARPS-N instrument.

GJ 1151 was observed on 70 occasions from 2016 to 2020 with CARMENES. The RVs of the visible channel were extracted with the SERVAL code (see Table A.1, for statistics see Table 1). The RVs of the near-infrared channel show average uncertainties of ~8 m s^{-1} for this star and they were not used in this study. The data are separated in two blocks, one consisting of seven measurements from February to June 2016 and one of 62 measurements, with more intensive monitoring periods from February to December 2020 (top panel of Fig. 1). There is also

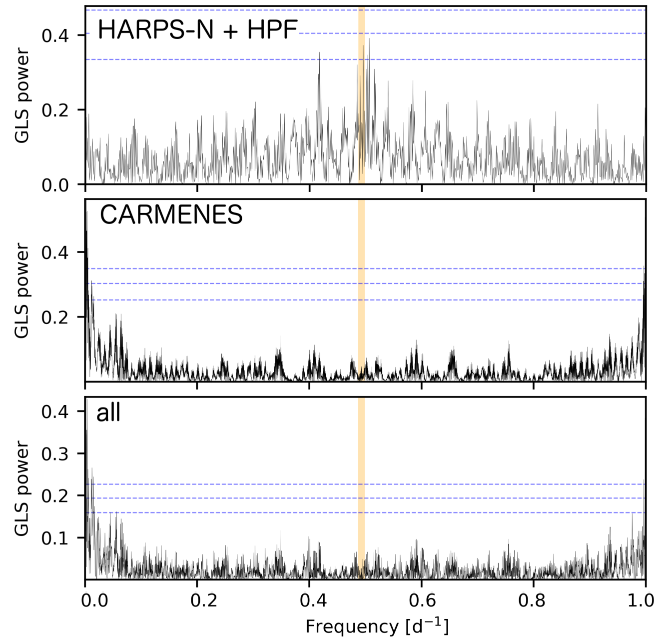

Fig. 2. Periodograms of the RVs as observed of the combined HARPS-N and HPF data sets (*top panel*), the individual CARMENES data set (*middle panel*), and the combined full RV data set (*bottom panel*). The orange vertical line highlights a period of 2.02 d, and the horizontal blue dashed lines indicate analytical false-alarm probabilities of 10, 1, and 0.1% (*from bottom to top*). The y axis is shown up to the largest GLS power or the 0.1% FAP level.

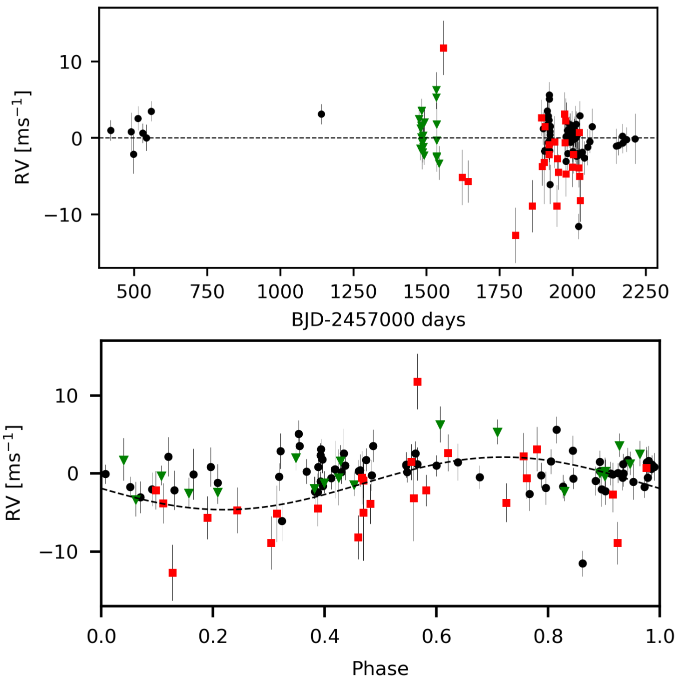

Fig. 3. Same as Fig. 1, but for the RV residuals that result after subtracting a linear trend and a long-period signal.

one single measurement in between the two blocks. An apparent global upward trend is clearly visible, and also some modulation with a period >300 d. The data do not overlap with the HARPS-N measurements, but they do with most of the HPF data. Both sets clearly show a quite steep downward trend around BJD = 2 458 900 d.

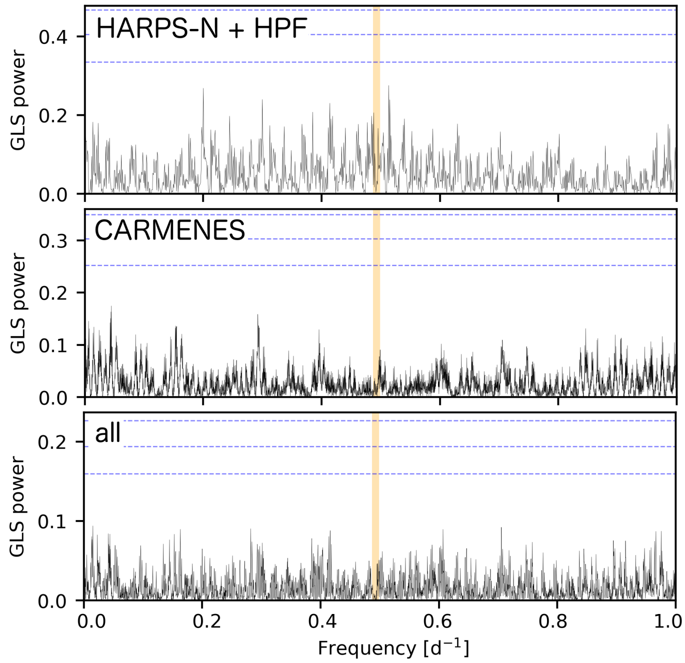

Fig. 4. Same as Fig. 2, but for the RV residuals that result after subtracting a linear trend and a long-period signal.

As an initial test, we phase-folded the full dataset to the 2.02-d period of the announced planet candidate by fitting individual offsets for each instrument and using the best-fit semi-amplitude for the RVs of the present work. This is graphically shown in the bottom panel of Fig. 1. While the HPF data seem to favour such a fit, therefore reproducing the results of Mahadevan et al. (2021), the HARPS-N data show phases with poor coverage, which then make the data compatible with the Keplerian signal found by the HPF data. In clear contrast, the CARMENES data do not confirm the modulation nor do they show any sign of periodic variability at 2.02 d. This can also be seen in the periodograms of Fig. 2 for the combined HARPS-N and HPF sets (top panel), the individual CARMENES RVs (middle panel), and the full data set (bottom panel).

The combined RV time series of the three instruments suggests the presence of a linear trend and a long-term modulation. Thus, we considered these two effects and optimised (maximum likelihood) their parameters together with the RV offsets amongst the different data sets. As a result, we find a linear trend of 1.73 m s^{-1} yr^{-1} and a highly significant signal with a period of ~500 d and a semi-amplitude of K = 4.2 m s^{-1} in the combined data. Because of seasonal gaps, this long-period signal was not fully sampled in phase. The combined fit of the trend and the long-term signal is shown in the top panel of Fig. 1. The residuals from subtracting this fit from the data are shown as a time series in the top panel of Fig. 3, and they are folded to the 2.02-day period of the candidate planet in the bottom panel of Fig. 3. It is readily seen that the individual data sets, including HARPS-N and HPF, no longer support the existence of a significant periodicity. This is also observed in the periodograms of the residuals in Fig. 4 of the combined HARPS-N and HPF data sets (top panel), the individual CARMENES data set (middle panel), and the combined full RV data set (bottom panel). No prominent periodic signals are visible, including a lack of significant periodicity at 2.02 d. The signal identified in the HPF data was removed by the fit of the linear trend and the long-period signal. We therefore conclude that it was most likely a spurious signal

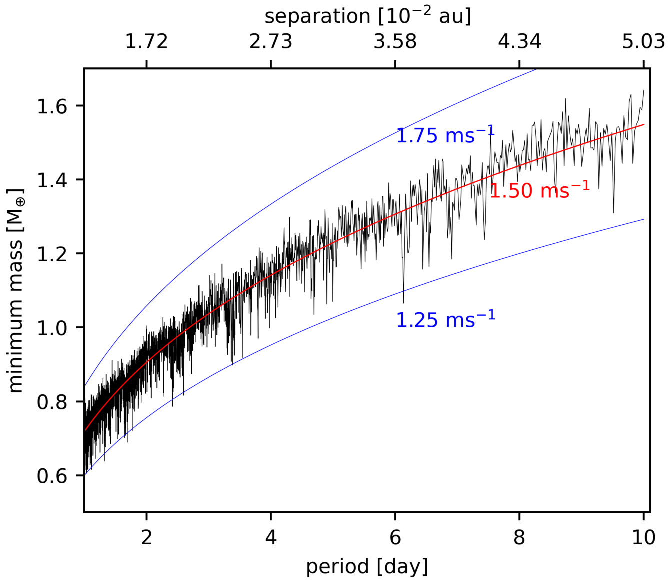

Fig. 5. Detection limits of the RV residuals (after correcting for a trend and long-term modulation) of the combined RVs of GJ 1151 of 20 HARPS-N, 25 HPF, and 70 CARMENES observations. We show the minimum planetary mass for which we detect (bootstrap false-alarm probability <0.1%) an injected planetary companion for each period (black line). Coloured lines show constant semi-amplitudes of 1.25, 1.75 m s^{-1} (blue lines), and the average detection limit of 1.50 m s^{-1} (red line).

caused by the dominant downward trend of the HPF data during the densely sampled epoch.

We followed the procedure described in Bonfils et al. (2013) to calculate the detection limits for the RV dataset and the limit for the minimum masses of planets with 1- to 5-d orbital periods. We employed a significance threshold at a false-alarm probability of 0.1%. We firstly considered the RV time series as observed, that is, without subtracting the trend and long-term modulation, and we obtained a flat detection limit of $K = 2.21 \pm 0.15$ m s^{-1} for the RV semi-amplitude of circular orbits with periods between 1 and 5 d. When we ran the same calculations on the residuals after performing the correction, we derived a mean limiting RV semi-amplitude of $K = 1.50 \pm 0.07$ m s^{-1}, which translates into minimum planet masses of 0.72, 0.91, and 1.23 $M_\oplus$ for orbital periods of 1, 2.02, and 5 days, respectively. A graphical representation of the experiment is shown in Fig. 5. Since the scatter of the RV residuals (Table 1) is of the order of 3.3 m s^{-1}, the simulations show that we would be able to detect planets with semi-amplitudes some 2.2 times smaller than such velocity scatter.

3. Conclusions

We analysed published HARPS-N and HPF RVs of the low-mass star GJ 1151 together with 70 new CARMENES RVs, following up on the recent announcement of a possible planet being responsible for low-frequency radio emission detected by LOFAR. The full combined data set shows a linear trend of 1.73 m s^{-1} yr^{-1} and contains a long-period signal >300 d. We are not yet able to unambiguously derive the parameters and to assess the nature of the suggestive, potentially planetary, long-period signal, but observations are still ongoing and will be investigated in an upcoming article.

If we subtract a trend and a long-period signal from the observations, effectively applying a high-pass frequency filter, the resulting residual RVs show no signs of the 2.5 $M_\oplus$ planet in a 2.02-day orbit proposed by Mahadevan et al. (2021), which would induce a periodic RV signal with a semi-amplitude of 4.1 m s^{-1}. We find that the reported periodic signal may rather be produced by the long-period signal that is not accounted for and the free offset used when combining both HPF and HARPS-N datasets.

In our study of the full RV data, we place an new upper limit on the semi-amplitude of a possible exoplanet orbiting GJ 1151 at 1.50 m s^{-1}. A putative planetary companion with an orbit below 5 days, as put forward to explain the LOFAR data, would need to have a minimum mass lower than 1.2 $M_\oplus$ to remain compatible with the available RV dataset.

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References

Anglada-Escudé, G., & Butler, R. P. 2012, ApJS, 200, 15
Bedell, M., Hogg, D. W., Foreman-Mackey, D., Montet, B. T., & Luger, R. 2019, AJ, 158, 164
Bonfils, X., Delfosse, X., Udry, S., et al. 2013, A&A, 549, A109
Cortés-Contreras, M., Béjar, V. J. S., Caballero, J. A., et al. 2017, A&A, 597, A47
Cosentino, R., Lovis, C., Pepe, F., et al. 2012, SPIE Conf. Ser., 8446, 84461V
Díez Alonso, E., Caballero, J. A., Montes, D., et al. 2019, A&A, 621, A126
Foster, G., Poppenhaeger, K., Alvarado-Gómez, J. D., & Schmitt, J. H. M. M. 2020, MNRAS, 497, 1015
Lépine, S., Hilton, E. J., Mann, A. W., et al. 2013, AJ, 145, 102
Mahadevan, S., Ramsey, L., Bender, C., et al. 2012, in Ground-based and Airborne Instrumentation for Astronomy IV, eds. I. S. McLean, S. K. Ramsay, & H. Takami, SPIE Conf. Ser., 8446, 84461S
Mahadevan, S., Stefánsson, G., Robertson, P., et al. 2021, ApJL, submitted [arXiv:2102.02233]
Melrose, D. B., & Dulk, G. A. 1982, ApJ, 259, 844
Newton, E. R., Irwin, J., Charbonneau, D., et al. 2016, ApJ, 821, 93
Pope, B. J. S., Bedell, M., Callingham, J. R., et al. 2020, ApJ, 890, L19
Quirrenbach, A., CARMENES Consortium, Amado, P. J., et al. 2020, SPIE Conf. Ser., 11447, 114473C
Reiners, A., Zechmeister, M., Caballero, J. A., et al. 2018, A&A, 612, A49
Schöfer, P., Jeffers, S. V., Reiners, A., et al. 2019, A&A, 623, A44
Schweitzer, A., Passegger, V. M., Cifuentes, C., et al. 2019, A&A, 625, A68
Shimwell, T. W., Tasse, C., Hardcastle, M. J., et al. 2019, A&A, 622, A1
van Haarlem, M. P., Wise, M. W., Gunst, A. W., et al. 2013, A&A, 556, A2
Vedantham, H. K., Callingham, J. R., Shimwell, T. W., et al. 2020, Nat. Astron., 4, 577
Zechmeister, M., Reiners, A., Amado, P. J., et al. 2018, A&A, 609, A12