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No Massive Companion to the Low-Frequency, Coherent Radio-Emitting M Dwarf GJ 1151

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ABSTRACT

The recent detection of circularly polarized, long-duration (> 8 hr) low-frequency radio emission from the M4.5 dwarf GJ 1151 has been interpreted as a Jupiter-like electron cyclotron maser instability arising from a star-planet interaction. The existence or parameters of the proposed planets have not been determined. In order to search for any planets or binary companions, we have obtained new HARPS-N observations

Using these data we do not detect a clear planetary signal, and we put 99^{th}-percentile upper limits on the mass of any companion to GJ 1151 at 5.1 $\mathrm{M}_{\oplus}$.

We infer interpolated, high-SNR, high-resolution spectra of GJ 1151.

1. INTRODUCTION

Exoplanet science has flourished over the last three decades. The number of known planets has doubled nearly every two years since 1995 (Mamajek 2016) and this accelerating rate of discovery is projected to continue for at least the next decade if current and upcoming space-based surveys deliver their expected results. However, despite extensive searches (e.g. Bastian et al. 2000; Lecavelier des Etangs et al. 2013; Lynch et al. 2018), neither exoplanets nor their host stars have been detected at

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radio frequencies, as the non-flaring emission of such systems has been too faint for current telescopes. The SKA-precursor LOFAR (the LOw-Frequency ARray: van Haarlem et al. 2013) has unparalleled sensitivity at 150 MHz where these interactions are expected to emit significant radiation via the electron cyclotron maser instability (Zarka 2007): with its orders-of-magnitude increase in sensitivity and survey speed, the detection of nearby stars and planets is a realistic prospect (Pope et al. 2019).

High stellar UV flux and flaring are thought to pose serious problems for habitability of planets around M dwarfs (Shields et al. 2016; Tilley et al. 2019), though this may be not sufficiently severe in comparison to the early Earth to prevent the emergence of life (O'Malley-James & Kaltenegger 2019). The stellar wind potentially poses a more severe problem. Theoretical studies have disagreed on the extent to which a planetary magnetosphere provides protection for its atmosphere from stripping by the radiation or wind of the host star (e.g. Zuluaga et al. 2013; Ribas et al. 2016; Garcia-Sage et al. 2017). Star-planet magnetic interactions (SPMI) analogous to the electrodynamic interaction of Jupiter and Io are theorized to occur when the interaction with the magnetized stellar wind of the host star is sub-Alfvénic, and the planet is magnetically connected to its star and their magnetospheres are not separated by shocks. This is thought to be the case for Proxima Centauri b (Garraffo et al. 2016) and the inner TRAPPIST-1 planets (Garraffo et al. 2017). With stellar wind flux orders of magnitude higher than that received by Earth, this may be a leading-order effect for stripping otherwise-habitable exoplanets of their atmospheres. The energy flux to the stellar surface from such an SPMI may give rise to optical Hα aurorae at the magnetic connection footprint on the star (Strugarek et al. 2019), or to radio signals. The search for the associated radio aurorae from M dwarf planets is therefore a key component of understanding their long term evolution and habitability (Burkhart & Loeb 2017; Turnpenney et al. 2018; Vidotto et al. 2019), but observational signatures of this have not so far been detected (e.g. Lynch et al. 2018; Lenc et al. 2018).

Rather than explicitly searching for radio emission from known exoplanet hosts, Callingham et al. (2019) cross-matched sources identified by the LOFAR Two-meter Sky Survey (LoTSS: Shimwell et al. 2019) with nearby stellar sources found by *Gaia*, finding the great majority of matches to be chance associations. But by restricting the survey to variable and circularly-polarized emission, the rate of chance associations with background radio galaxies is dramatically reduced. Based on this restricted cross-match, Vedantham et al. (submitted) have detected the quiescent M4.5 dwarf GJ 1151 at low radio frequencies with LOFAR that has properties that suggest the low-frequency radio emission is driven by a star-planet magnetic interaction. While M dwarfs are known to flare at low frequencies (e.g. Villadsen & Hallinan 2019), this emission lasts over 8 h and is $64 \pm 6\%$ circularly polarised. Such emission can be generated by the electron cyclotron maser instability (ECMI) through the interaction of the star with a short ($\sim 1 - 5$ day) period planet or a close stellar companion as seen in UV Ceti-like stars (Lynch et al. 2017).

Since the radio emission implies a potential planetary or sub-stellar companion, in this Letter we present and analyze HARPS-N (High Accuracy Radial velocity Planet Searcher: Cosentino et al. 2012) observations of GJ 1151 in order to search for radial velocity signals of the proposed companions. We do not detect any planets, but place strong upper limits of a few Earth masses on the $M \sin i$ of any possible companions, ruling out any short-period massive objects or close binary companion.

2. RV DATA

We obtained 20 epochs of observations of GJ 1151 with HARPS-N from 2018-12-20 to 2019-02-27, as a Director's Discretionary Time program (Program ID: A38DDT2; PI: Callingham). While RVs were extracted from these using the standard HARPS pipeline, its performance on this M4.5 dwarf was very poor, resulting in a spurious RV scatter of several km/s. We therefore reprocessed these data using *wobble* (Bedell et al. 2019), a data-driven package which simultaneously non-parametrically constructs a stellar spectral template and telluric spectral components and uses these, rather than model spectral masks, to extract radial velocities.

We found that the second epoch (2018-12-22) had a significantly higher extracted RV uncertainty than the others, and accordingly excluded this from the global *wobble* model. In order to assess template-dependent systematic errors, we conducted a 'leave-one-out' cross-validation, excluding one additional epoch at a time and rerunning *wobble* to search for consistency between the outputs. As seen in Figure 1, the different resulting time series are broadly consistent in their directions of deviation from the mean, with a scatter between them of order ∼ the quoted uncertainties. We therefore believe the uncertainties on the *wobble* RVs are realistic but that they are also model-dependent systematics, and therefore likely correlated.

3. KEPLERIAN INFERENCE

We use *the Joker* pipeline (Price-Whelan et al. 2017), which is optimized for small numbers of irregularly-spaced observations, to fit Keplerian signals and infer posterior planet parameters. We allow an additional astrophysical jitter (white noise) term to vary with a lognormal prior on jitter $\ln{(s/(\mathrm{m/s}))^2} \sim N(1, 2)$ for GJ 1151.

4. DISCUSSION

Hardegree-Ullman et al. (2019) using *Kepler* estimate that M3-M5 dwarfs host $1.19^{+0.70}_{0.49}$ planets per star with radii from $0.5 - 2.5 R_\oplus$ and periods from 0.5-10 d, the detection of a planet is actually less important than the exclusion of *non*-planetary models, such as emission from a stellar binary interaction. We can confidently say that there is no short-period stellar binary companion to GJ 1151, and that the posterior for the RV trend of 0.02 ± 0.03 m/s^{-1}d^{-1} is consistent with zero at $1\,\sigma$.

5. CONCLUSIONS

The results of this analysis conclusively rule out binary companions or planets on short orbits more massive than Neptune as the origin of the radio signal from GJ 1151.

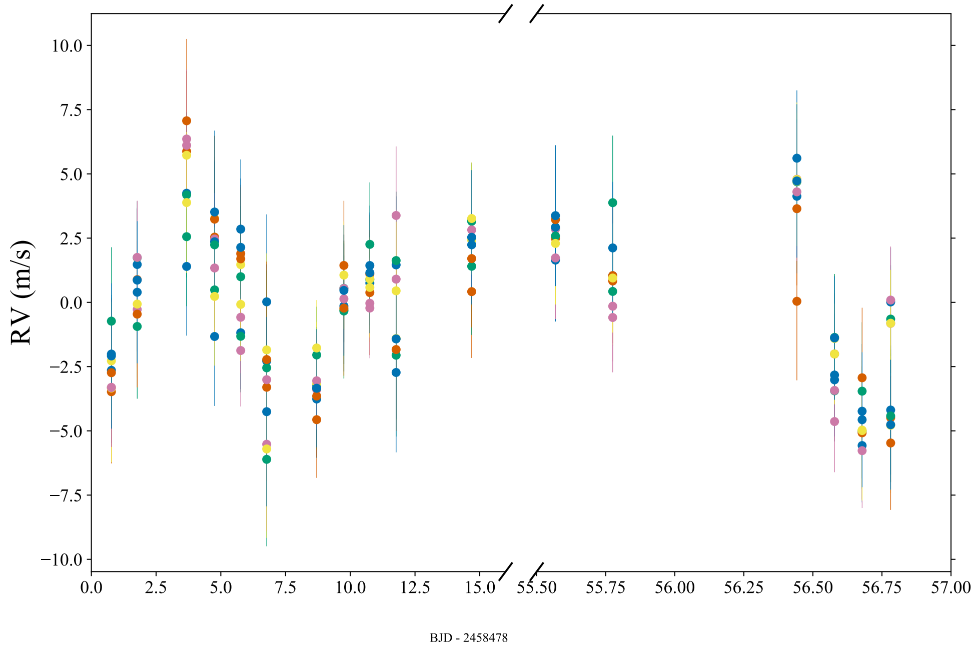

Figure 1. Leave-one-out cross-validation of *wobble* RVs. One epoch at a time is left out of the global model, and the results of processing the remaining epochs are shown in different colours. There is overall consistency between the different time series, with a diversity of order ∼ the quoted uncertainty between the individual realizations.

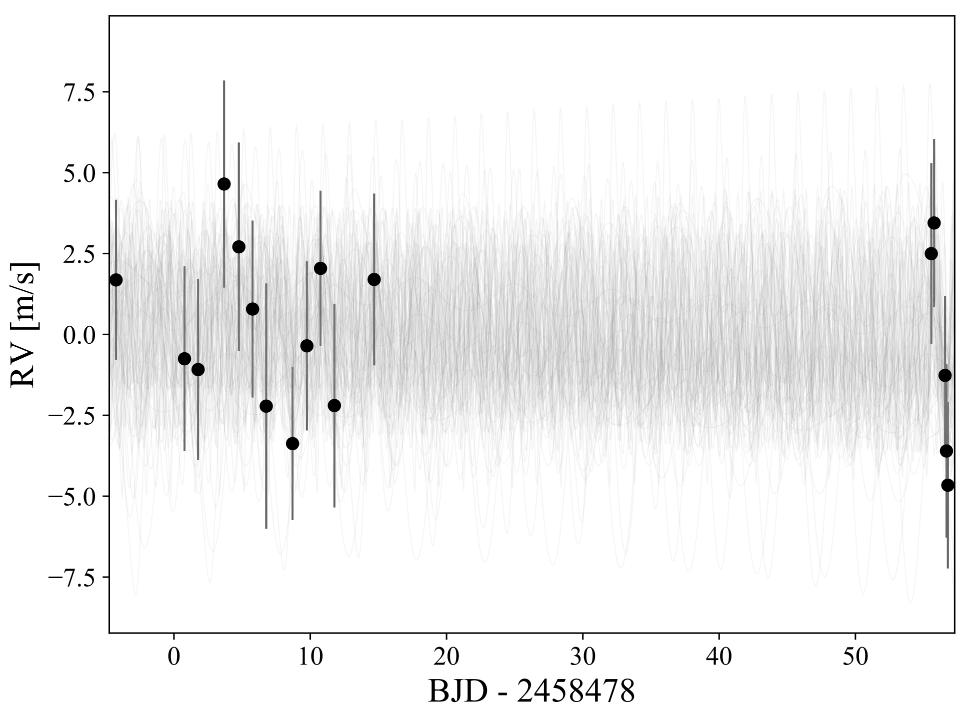

Figure 2. *The Joker* posterior samples for GJ 1151.

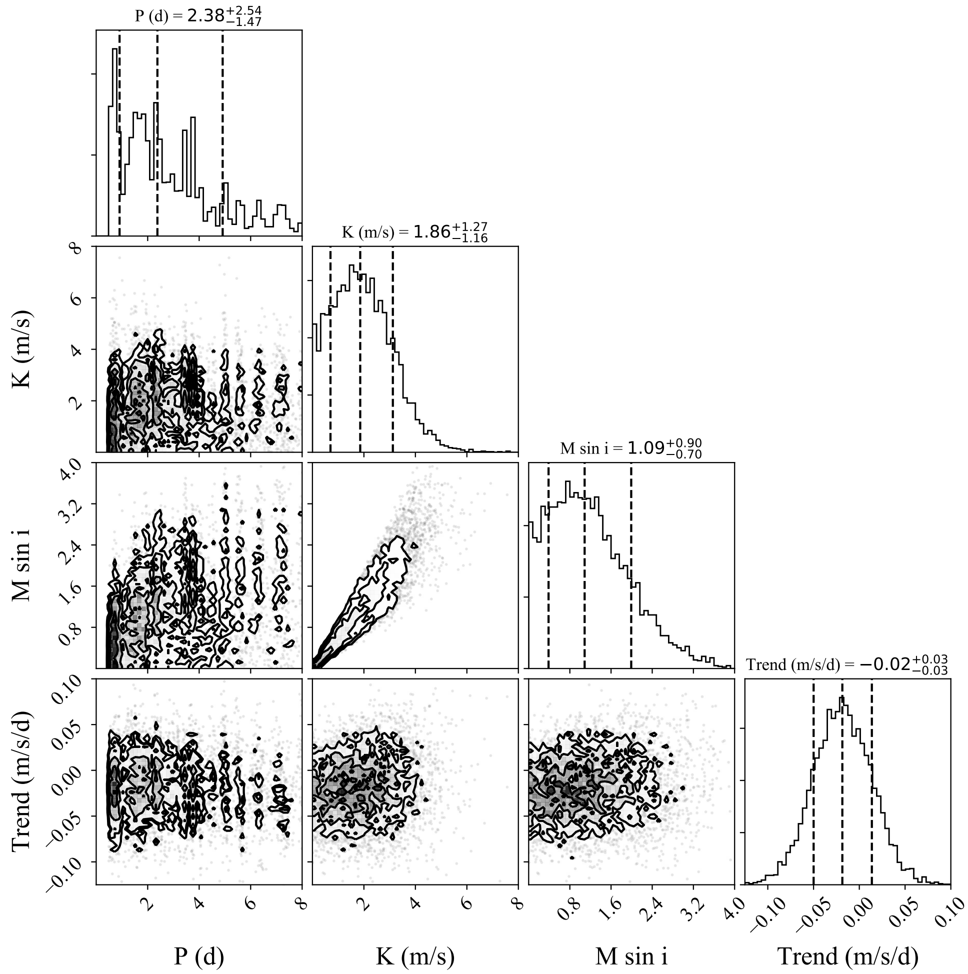

Figure 3. Cornerplot of posterior samples from *The Joker* for GJ 1151.

We nevertheless cannot rule out in either case planets less massive than a few Earth masses.

Vedantham et al. (submitted) derive an approximate mass and period estimate for their planet candidate based on the scaling relations of the SPMI. A planet with a larger radius r has a larger cross-section for wind interaction $\propto r^2$, while the B-field drops with semi-major axis a as $\approx a^{-2}$, so that the radio flux only provides a lower limit on r/d. Given the mass scaling $\propto r^3$ and orbital period $\propto a^{\frac{2}{3}}$, the radio detection provides a lower limit on m/p^2. An Earth-mass planet in a $1-5$ d orbit is consistent with the observed radio flux, and at a sufficiently short period even a planet with a mass around that of ~Mercury would be sufficient. While the data presented in this Letter conclusively rule out any more massive companion, there is a substantial region of parameter space for these planets that cannot be excluded and the star-planet interaction hypothesis remains reasonable.

Because our target is so red, to achieve significantly higher precision than attained by HARPS would require moving to the infrared, using one of the IR precision RV instruments currently being commissioned, such as the Habitable-zone Planet Finder

(HPF: Mahadevan et al. 2012) or CARMENES (Quirrenbach et al. 2010), by which GJ 1151 is already subject to monitoring (Alonso-Floriano et al. 2015).

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