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No Massive Companion to the M Dwarf Radio Source GJ 1151

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ABSTRACT

The recent detection of circularly polarized, variable low-frequency radio emission from the M4.5 dwarf GJ 1151 has been interpreted as a Jupiter-like electron cyclotron maser instability arising from 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$^{\text{th}}$-percentile upper limits on the mass of any companion to GJ 1151 at 5.1 $M_\oplus$.

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

1. INTRODUCTION

Exoplanet science has flourished over the last three decades to be one of the major topics in optical astronomy. 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 (Bastian et al. 2000; Lecavelier des Etangs et al. 2013; Lynch et al. 2018) neither exoplanets nor their host stars have been detected at radio frequencies, as the quiescent emission of such systems has been too faint for current telescopes. But as the Square Kilometre Array (SKA; Dewdney et al. 2009) and its precursors, in particular LOFAR

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(the LOw-Frequency ARray: van Haarlem et al. 2013) come online, the orders-of-magnitude increase in sensitivity and survey speed they provide makes the detection of nearby stars and planets 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. Star-planet interactions analogous to the magnetic interaction of Jupiter and Io are theorized to occur when a planet lies within the Alfvén surface of their host star, where 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 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 M4.5 dwarf GJ 1151 at low radio frequencies with LOFAR, finding a high degree of circular polarization and low X-ray luminosity consistent with a possible star-planet magnetic interaction. While M dwarfs are known to flare at low frequencies (e.g. Villadsen & Hallinan 2019), this emission shows a stead on/off duty cycle like that of electron cyclotron maser instability (ECMI) emission from Jupiter.

In this Letter we analyze new 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 planets. 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. While RVs were extracted from these using the standard HARPS pipeline, its performance on this M4.5 dwarf

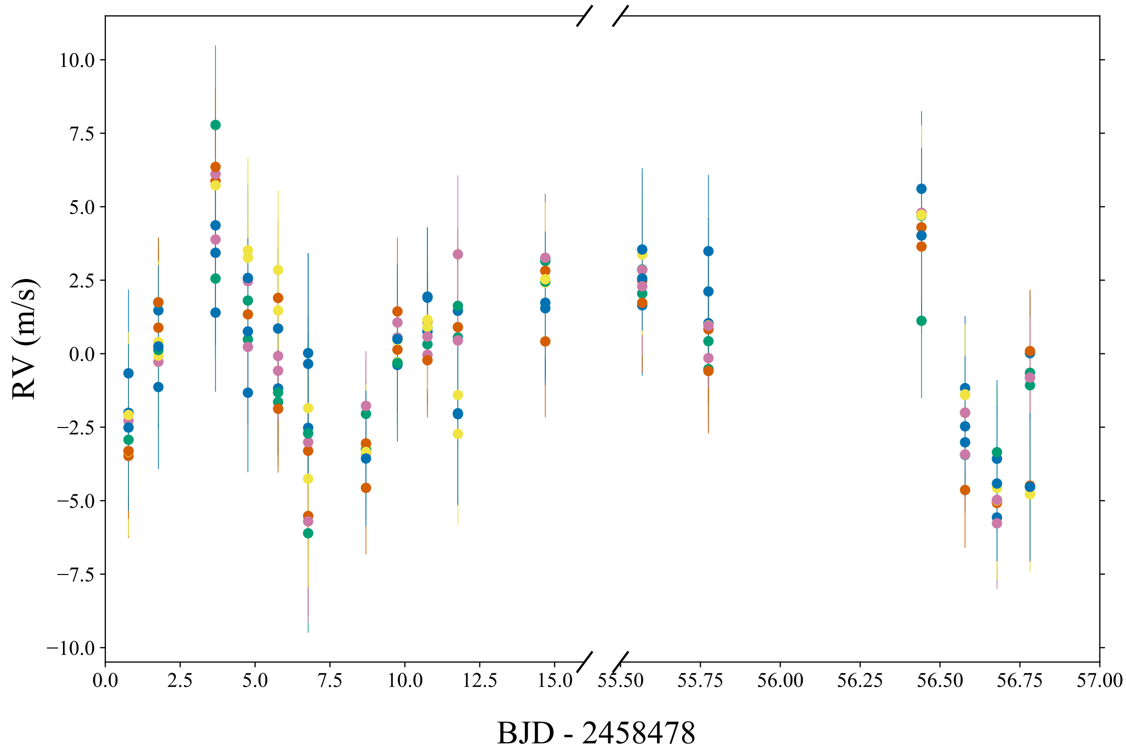

Figure 1. Leave-one-out cross-validation of *wobble* RVs. One epoch at a time is left out of the global model, and the results of processing the remaining epochs are shown in different colours. There is overall consistency between the different time series, with a diversity of order $\sim$ the quoted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

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 $\sim$ 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

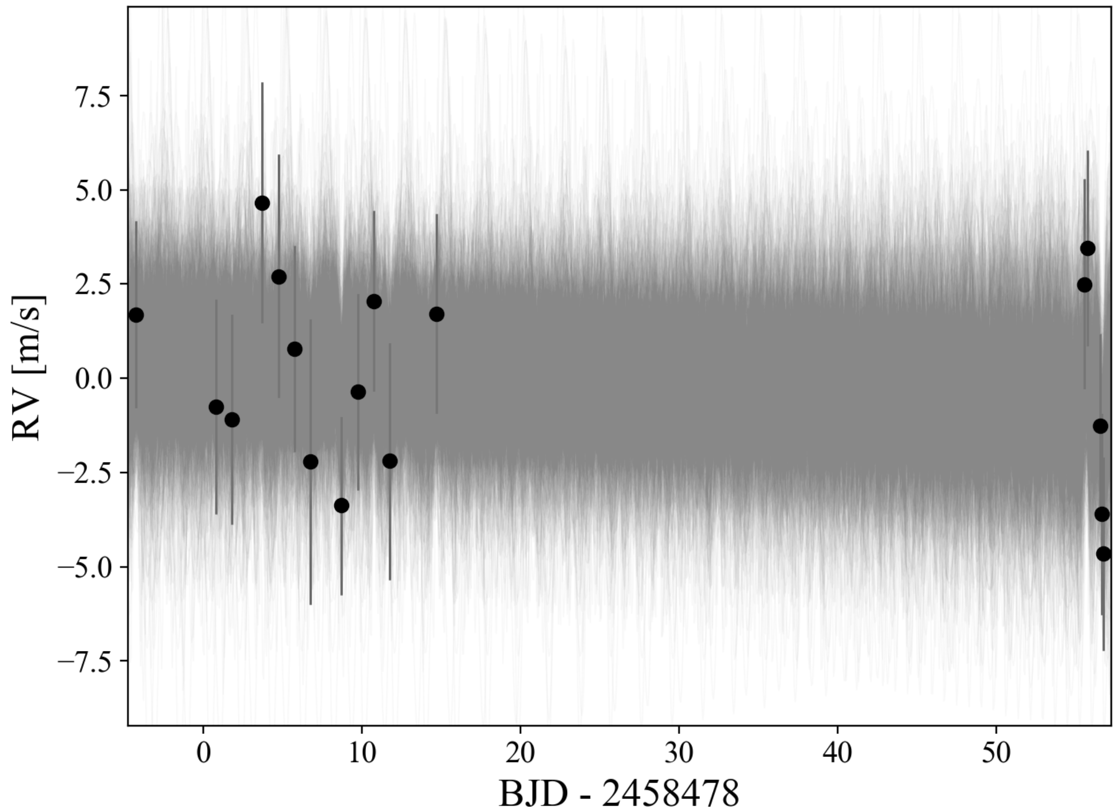

Figure 2. *The Joker* posterior samples for GJ 1151.

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. We nevertheless cannot rule out in either case planets less massive than a few Earth masses. Given that Vedantham et al. (submitted) find that even a planet with a mass around that of ∼Mercury could explain these signals, there is a very large region of parameter space for these planets that cannot be excluded and the star-planet interaction hypothesis remains reasonable.

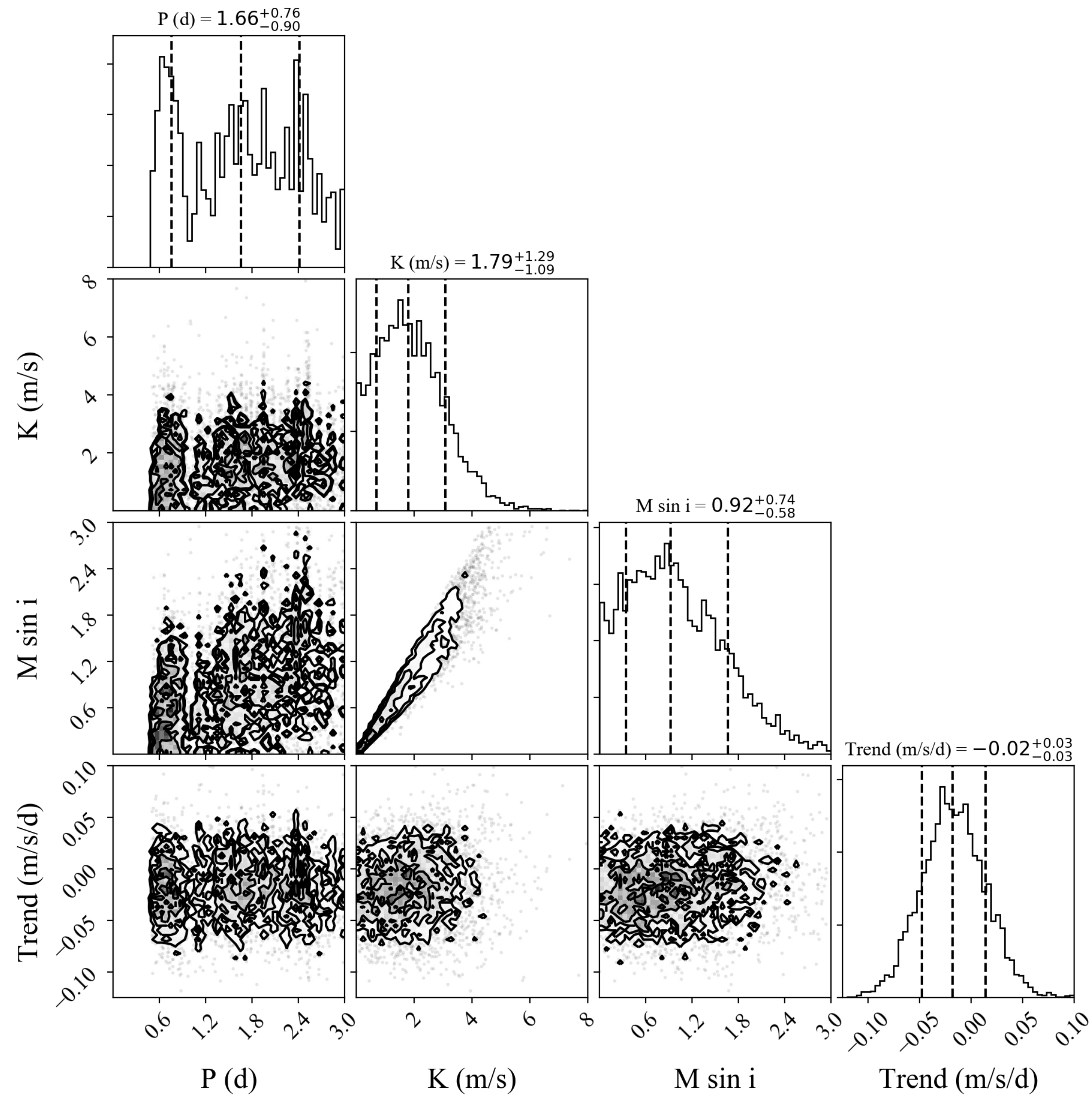

Figure 3. Cornerplot of posterior samples from *The Joker* for GJ 1151.

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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