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No Massive Companion to the Coherent Radio-emitting M Dwarf GJ 1151

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Abstract

The recent detection of circularly polarized, long-duration (>8 hr), low-frequency (∼150 MHz) radio emission from the M4.5 dwarf GJ 1151 has been interpreted as arising from a star–planet interaction via the electron cyclotron maser instability. The existence or parameters of the proposed planets have not been determined. Using 20 new HARPS-N observations, we put 99th-percentile upper limits on the mass of any close companion to GJ 1151 at $M \sin i < 5.6\, M_{\oplus}$. With no stellar, brown dwarf, or giant planet companion likely in a close orbit, our data are consistent with detected radio emission emerging from a magnetic interaction between a short-period terrestrial-mass planet and GJ 1151 (https://github.com/benjaminpope/video).

Unified Astronomy Thesaurus concepts: Magnetic fields (994); Radial velocity (1332); Solar-planetary interactions (1472)

1. Introduction

Exoplanet science has flourished over the past 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; Murphy et al. 2015; Lynch et al. 2018) and the possible exception of a flare from ϵ Eri (Bastian et al. 2018), neither exoplanets nor their host stars have been detected at radio frequencies, as the non-flaring emission of such systems is likely too faint for most current low-frequency telescopes with the exception of the SKA-precursor the LOw-Frequency ARray (LOFAR; van Haarlem et al. 2013). LOFAR has unparalleled sensitivity at 150 MHz where these interactions are expected to emit significant radiation via the electron cyclotron maser instability (ECMI; Zarka 2007; Llama et al. 2018): 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 not be 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 (SPMIs) 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 (i.e., the Alfvén wave speed is greater than the wind velocity). Under these conditions there is no bow shock separating the magnetospheres of the star and planet, and particles from the stellar wind reach much deeper into the planetary magnetosphere (Cohen et al. 2014). 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 strong chromospheric lines at the magnetic connection footprint on the star (Cuntz et al. 2000; Shkolnik et al. 2008; Lanza 2013; Luger et al. 2017; Cauley et al. 2019; Strugarek et al. 2019), or to radio signals (Zarka 2007; Saur et al. 2013). Detections of radio emission from brown dwarfs (e.g., Kao et al. 2016; Gagné et al. 2017; Kao et al. 2018) have been interpreted as auroral, but have not so far been associated with exoplanet candidates. The search for the radio emission 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., Lenc et al. 2018; Lynch et al. 2018; Pineda & Hallinan 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 with radio-bright active galactic nuclei. But by restricting the cross-match to LoTSS sources to only those that display circularly polarized emission, the rate of chance associations with background radio galaxies is dramatically reduced. Based on this restricted cross-match, H. K. Vedantham et al. (2019, in preparation) report the detection of the quiescent M4.5 dwarf GJ 1151 at low radio frequencies with

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[7] NASA Sagan Fellow.

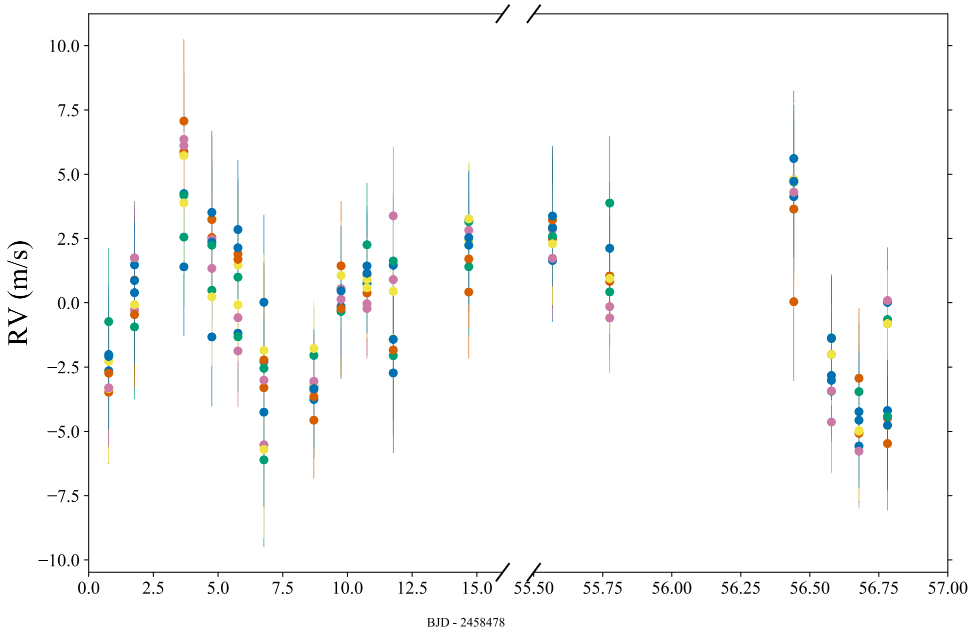

Figure 1. Leave-one-out cross-validation of *wobble* RVs. One epoch at a time is left out of the global model, and the results of processing the remaining epochs are shown in different colors. There is overall consistency between the different time series, with a diversity of the order of approximately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

LOFAR, with properties that suggest the low-frequency radio emission is driven by an SPMI. While M dwarfs are known to flare at low frequencies (e.g., Villadsen & Hallinan 2019), this emission lasts over 8 hr and is 64% ± 6% circularly polarized. Such emission can be generated by the ECMI through the interaction of the star with a short (∼1–5 day) period planet or a close stellar companion as seen in interacting binaries such as UV Ceti or RS CVn systems (Lynch et al. 2017).

Since the radio emission implies a potential planetary or substellar companion, but no such companion is previously known, in this Letter we present and analyze High Accuracy Radial velocity Planet Searcher (HARPS-N; 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 a close binary companion.

2. RV Data and Analysis

We obtained 20 epochs of observations of GJ 1151 with HARPS-N from 2018 December 20 to 2019 February 27, as a Director's Discretionary Time program (Program ID: A38DDT2; PI: Callingham). While radial velocities (RVs) were extracted from these using the standard HARPS pipeline, its performance on this M4.5 dwarf was poor, resulting in a spurious RV scatter of several km s^{-1}.

We therefore reprocessed these data using *wobble* (Bedell et al. 2019), a data-driven package that 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 used only the 30 reddest echelle orders, as the signal to noise in the blue orders was much too low to resolve spectral features in this extremely red star. We expect *wobble* to perform favorably in this regime compared to the standard HARPS cross-correlation-based approach. This is because *wobble* can extract RV information from telluric-contaminated spectral regions, which are increasingly prevalent in the red, and it needs no a priori knowledge of the underlying stellar spectrum, for which templates may be unreliable for such a late spectral type.

We found that the second epoch (2018 December 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 approximately 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, though in subsequent analysis we will treat them as independent and Gaussian.

We use *The Joker* Bayesian RV analysis pipeline (Price-Whelan et al. 2017) with its default prior choices implemented in the new version 1.0 of the package (A. M. Price-Whelan et al. 2019, in preparation). This pipeline is optimized for small numbers of irregularly spaced observations, using importance sampling to fit Keplerian orbits to RV data and infer posterior planet parameters. We draw 10^7 samples from a separable prior, such that all orbital elements are assumed to be independent. The prior over log-period is uniform over the range $\log P \in$ [0.5 day, 8 day], the prior over eccentricity is given by Kipping (2013), the priors over velocity semi-amplitude K and systemic velocity are assumed to be very broad and Gaussian (such that they are effectively uniform over the region that the likelihood has support), and all other priors are assumed to be uniform. We allow an additional astrophysical jitter (white noise) term to vary with a lognormal prior on jitter $\ln (s/(\mathrm{m\ s^{-1}})^2 \sim N(1, 2)$. We also include a term for a linear trend, which allows for very long period companions.

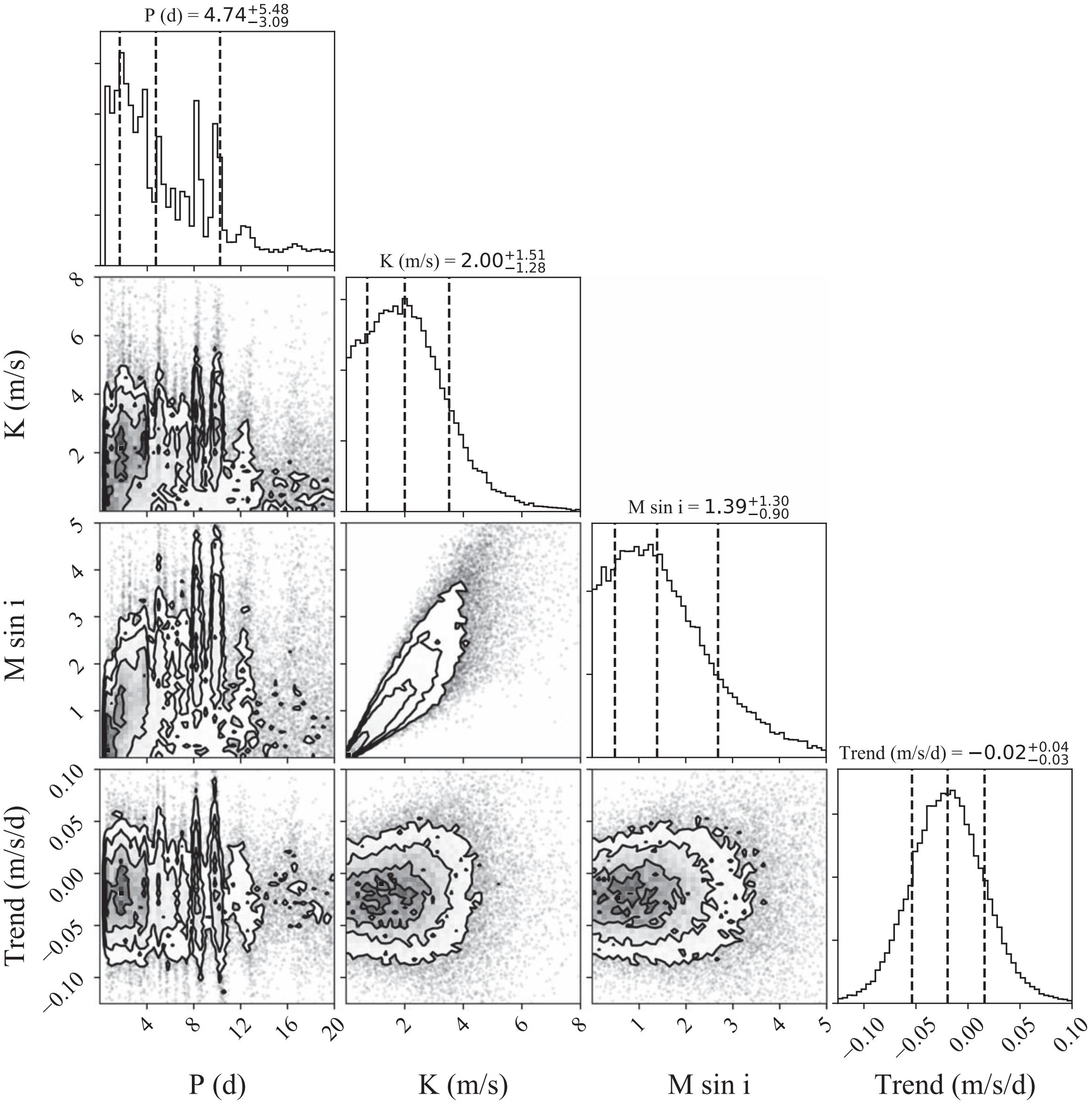

Figure 2. Cornerplot of posterior samples from *The Joker* for GJ 1151, made using `corner.py` (Foreman-Mackey 2016). The RV trend, the RV semi-amplitude K, and $M \sin i$ of any companion are all consistent with zero. The spread in the relation between $M \sin i$ and K is due to the estimated uncertainties in the stellar mass.

After rejection sampling, we obtain 32,768 posterior samples, displayed in Figure 2. In Figure 3 we show posterior model draws overlaid on the data: it is clear that no good fit is found. We place 99th-percentile upper limits on the RV semi-amplitude $K < 7.7\,\mathrm{m\,s^{-1}}$, which translates to $M \sin i < 5.6\,M_\oplus$, using a stellar mass of $0.167 \pm 0.025\,M_\odot$ (as determined by Newton et al. 2016, and estimated Gaussian uncertainties). The posterior for the RV trend of $-0.02^{+0.04}_{-0.03}$ $\mathrm{m/s\,day^{-1}}$ is consistent with zero, providing no evidence for a long-period massive companion. The source code and data for our calculations are available online at github.com/benjaminpope/video.

3. Discussion and Outlook

As part of the CARMENES project (Quirrenbach et al. 2010), high angular resolution observations of of GJ 1151 have been obtained by the lucky imaging instrument FastCam (Cortés-Contreras et al. 2017), ruling out a stellar companion at separations greater than ~1 au. These new RV data fill in this gap to short periods, indicating no massive companion except if it is in a face-on orbit, which is unlikely a priori.

Planets are common around M stars such as GJ 1151: using *Kepler*, Hardegree-Ullman et al. (2019) 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 to 10 days. The results of this analysis indicate no 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, or highly inclined short-period orbits. The non-detection of a planet is therefore less important than the exclusion of *non*-planetary models, such as emission from a stellar binary interaction.

Vedantham et al. (submitted) derive an approximate mass and period estimate for their planet candidate based on the energetics of the SPMI. In their benchmark model, an Earth-like planet in a ~1–5 day orbit can generate the observed emission within a reasonable range of interaction and emission efficiencies. A planet with a larger radius r has a larger cross-

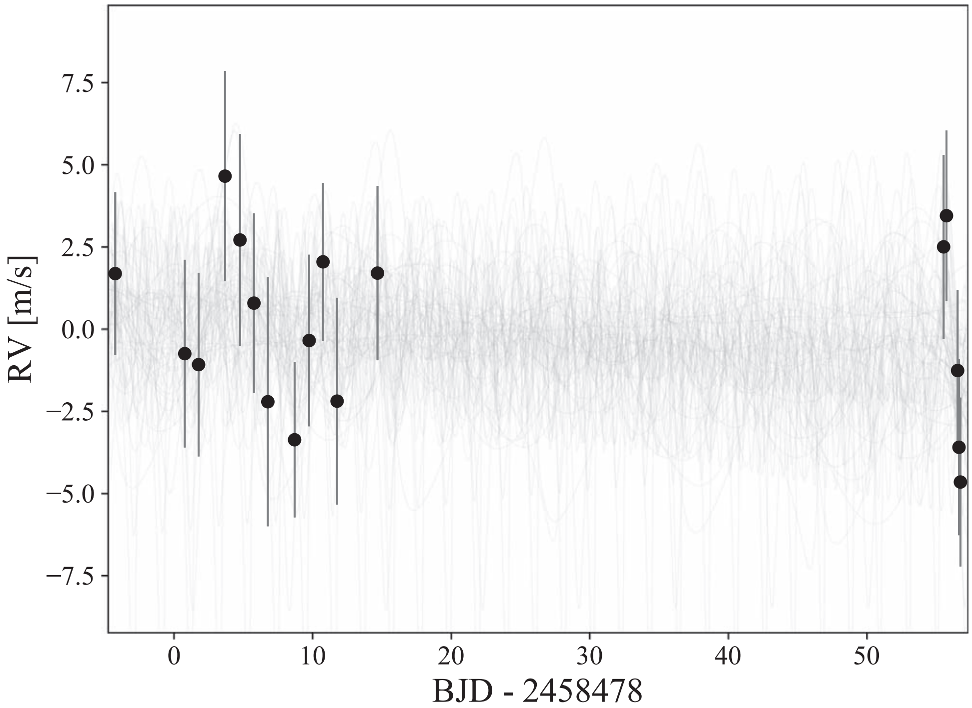

Figure 3. RV time series generated from *The Joker* posterior samples overlaid on the HARPS-N data for GJ 1151. We see no clear Keplerian fit.

section for wind interaction $\propto r^2$, while the stellar Poynting flux at the location of the planet drops with semimajor axis[8] a as $\approx a^{-2}$, so that the radio flux provides a lower limit on r/d. Given a planetary mass scaling $\propto r^3$ and orbital period $\propto a^{\frac{2}{3}}$, the radio detection provides a lower limit on m/p^2. Hence, at sufficiently high efficiencies, even a sub-Earth-mass planet is plausible.

While the data presented in this Letter conclusively rule out stellar and gas-giant companions, there is a substantial region of parameter space for terrestrial planetary companions that cannot be excluded and the star–planet interaction hypothesis remains reasonable. Furthermore, from the radio observations of Vedantham et al. (submitted) alone, it is possible that the emission from the GJ 1151 system could originate directly from an exoplanet's magnetosphere. However, such an emission site would imply an unreasonably strong magnetic field for a terrestrial-sized planet, with only hot Jupiter magnetic fields considered to be on the order of tens of Gauss (Cauley et al. 2019). For comparison, M dwarfs are known to possess magnetic fields on the order of tens of Gauss and greater (Morin et al. 2008). Therefore, the present work disfavors radio emission directly from an exoplanet magnetosphere unless a terrestrial planet can generate a much stronger magnetic field than has previously been considered. We propose it is likely that the emission is from a star–planet interaction.

Because GJ 1151 is so red, to achieve significantly higher precision than attained by HARPS would require moving to the infrared, using an IR-precision RV instrument such as the Habitable-zone Planet Finder (HPF: Mahadevan et al. 2012), SPIRou (Artigau et al. 2014), or CARMENES (Quirrenbach et al. 2010), by which GJ 1151 is already subject to monitoring (Alonso-Floriano et al. 2015).

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Software: wobble (Bedell et al. 2019); *The Joker* (Price-Whelan et al. 2017); `corner.py` (Foreman-Mackey 2016); IPython (Pérez & Granger 2007); SciPy (Jones et al. 2001); and Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2013).

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[8] Assuming a Parker-spiral configuration for the stellar magnetic field.

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References

Alonso-Floriano, F. J., Morales, J. C., Caballero, J. A., et al. 2015, A&A, 577, A128
Artigau, É., Kouach, D., Donati, J.-F., et al. 2014, Proc. SPIE, 9147, 914715
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Bastian, T. S., Dulk, G. A., & Leblanc, Y. 2000, ApJ, 545, 1058
Bastian, T. S., Villadsen, J., Maps, A., Hallinan, G., & Beasley, A. J. 2018, ApJ, 857, 133
Bedell, M., Hogg, D. W., Foreman-Mackey, D., Montet, B. T., & Luger, R. 2019, AJ, 158, 164
Burkhart, B., & Loeb, A. 2017, ApJL, 849, L10
Callingham, J. R., Vedantham, H. K., Pope, B. J. S., & Shimwell, T. W. 2019, RNAAS, 3, 37
Cauley, P. W., Shkolnik, E. L., Llama, J., & Lanza, A. F. 2019, NatAs, 3, 1128
Cohen, O., Drake, J. J., Glocer, A., et al. 2014, ApJ, 790, 57
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, Proc. SPIE, 8446, 84461V
Cuntz, M., Saar, S. H., & Musielak, Z. E. 2000, ApJL, 533, L151
Foreman-Mackey, D. 2016, JOSS, 1, 24
Gagné, J., Faherty, J. K., Burgasser, A. J., et al. 2017, ApJL, 841, L1
Garcia-Sage, K., Glocer, A., Drake, J. J., Gronoff, G., & Cohen, O. 2017, ApJL, 844, L13
Garraffo, C., Drake, J. J., & Cohen, O. 2016, ApJL, 833, L4
Garraffo, C., Drake, J. J., Cohen, O., Alvarado-Gómez, J. D., & Moschou, S. P. 2017, ApJL, 843, L33
Hardegree-Ullman, K. K., Cushing, M. C., Muirhead, P. S., & Christiansen, J. L. 2019, AJ, 158, 75
Jones, E., Oliphant, T., & Peterson, P. 2001, SciPy: Open source scientific tools for Python, http://www.scipy.org/
Kao, M. M., Hallinan, G., Pineda, J. S., et al. 2016, ApJ, 818, 24
Kao, M. M., Hallinan, G., Pineda, J. S., Stevenson, D., & Burgasser, A. 2018, ApJS, 237, 25
Kipping, D. M. 2013, MNRAS, 435, 2152
Lanza, A. F. 2013, A&A, 557, A31
Lecavelier des Etangs, A., Sirothia, S. K., Gopal-Krishna, & Zarka, P. 2013, A&A, 552, A65
Lenc, E., Murphy, T., Lynch, C. R., Kaplan, D. L., & Zhang, S. N. 2018, MNRAS, 478, 2835
Llama, J., Jardine, M. M., Wood, K., Hallinan, G., & Morin, J. 2018, ApJ, 854, 7
Luger, R., Lustig-Yaeger, J., Fleming, D. P., et al. 2017, ApJ, 837, 63
Lynch, C. R., Lenc, E., Kaplan, D. L., Murphy, T., & Anderson, G. E. 2017, ApJL, 836, L30
Lynch, C. R., Murphy, T., Lenc, E., & Kaplan, D. L. 2018, MNRAS, 478, 1763
Mahadevan, S., Ramsey, L., Bender, C., et al. 2012, Proc. SPIE, 8446, 84461S
Mamajek, E. 2016, Figshare dataset, doi: 10.6084/m9.figshare.4057704.v1,
Morin, J., Donati, J.-F., Petit, P., et al. 2008, MNRAS, 390, 567
Murphy, T., Bell, M. E., Kaplan, D. L., et al. 2015, MNRAS, 446, 2560
Newton, E. R., Irwin, J., Charbonneau, D., et al. 2016, ApJ, 821, 93
O'Malley-James, J. T., & Kaltenegger, L. 2019, MNRAS, 485, 5598
Pérez, F., & Granger, B. E. 2007, CSE, 9, 21
Pineda, J. S., & Hallinan, G. 2018, ApJ, 866, 155
Pope, B. J. S., Withers, P., Callingham, J. R., & Vogt, M. F. 2019, MNRAS, 484, 648
Price-Whelan, A. M., Hogg, D. W., Foreman-Mackey, D., & Rix, H.-W. 2017, ApJ, 837, 20
Quirrenbach, A., Amado, P. J., Mandel, H., et al. 2010, Proc. SPIE, 7735, 773513
Ribas, I., Bolmont, E., Selsis, F., et al. 2016, A&A, 596, A111
Saur, J., Grambusch, T., Duling, S., Neubauer, F. M., & Simon, S. 2013, A&A, 552, A119
Shields, A. L., Ballard, S., & Johnson, J. A. 2016, PhR, 663, 1
Shimwell, T. W., Tasse, C., Hardcastle, M. J., et al. 2019, A&A, 622, A1
Shkolnik, E., Bohlender, D. A., Walker, G. A. H., & Collier Cameron, A. 2008, ApJ, 676, 628
Strugarek, A., Brun, A. S., Donati, J. F., Moutou, C., & Réville, V. 2019, arXiv:1907.01020
Tilley, M. A., Segura, A., Meadows, V., Hawley, S., & Davenport, J. 2019, AsBio, 19, 64
Turnpenney, S., Nichols, J. D., Wynn, G. A., & Burleigh, M. R. 2018, ApJ, 854, 72
van Haarlem, M. P., Wise, M. W., Gunst, A. W., et al. 2013, A&A, 556, A2
Vidotto, A. A., Feeney, N., & Groh, J. H. 2019, arXiv:1906.07089
Villadsen, J., & Hallinan, G. 2019, ApJ, 871, 214
Zarka, P. 2007, P&SS, 55, 598
Zuluaga, J. I., Bustamante, S., Cuartas, P. A., & Hoyos, J. H. 2013, ApJ, 770, 23