The HD 217107 Planetary System: Twenty Years of Radial Velocity Measurements

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The hot Jupiter HD 217107 b was one of the first exoplanets detected using the radial velocity (RV) method, originally reported in the literature in 1999. Today, precise RV measurements of this system span more than 20 years, and there is clear evidence for a longer-period companion, HD 217107 c. Interestingly, both the short-period planet \( P_b \sim 7.13 \) d and long-period planet \( P_c \sim 5059 \) d have significantly eccentric orbits \( e_b \sim 0.13 \) and \( e_c \sim 0.40 \). We present 42 additional RV measurements of this system obtained with the MINERVA telescope array and carry out a joint analysis with previously published RV measurements from four different facilities.

We confirm and refine the previously reported orbit of the long-period companion. HD 217107 b is one of a relatively small number of hot Jupiters with an eccentric orbit, opening up the possibility of detecting precession of the planetary orbit due to General Relativistic effects and perturbations from other planets in the system. In this case, the argument of periastron, \( \omega \), is predicted to change at the level of \( \sim 0.8^\circ \) century\(^{-1} \). Despite the long time baseline of our observations and the high quality of the RV measurements, we are only able to constrain the precession to be \( \dot{\omega} < 65.9^\circ \) century\(^{-1} \). We discuss the limitations of detecting the subtle effects of precession in exoplanet orbits using RV data.

KEYWORDS:
Planetary systems, planets and satellites: HD 217107
1 | INTRODUCTION

The announcement in 1995 of the first exoplanet detected using the Radial Velocity (RV) technique, 51 Peg b (Mayor & Queloz [1995]), marked the beginning of a period of rapid growth in our knowledge of planets orbiting stars other than our Sun. In the five years that followed the discovery of 51 Peg b, a handful of additional planets were found - most of which were more massive than Jupiter, but moved on surprisingly small orbits, with periods of just a few days to a few weeks. These unexpected short period planets soon became known as “hot Jupiters”. HD 217107 b was one of the first hot Jupiters discovered, initially reported in Fischer, Marcy, Butler, Vogt, & Apps (1999) as having a period of $P = 7.12 \pm 1$ d and a minimum mass of $m \sin i = 1.27 \, M_{\text{J}}$ based on 21 RV measurements with a typical precision of $6 \, \text{m s}^{-1}$, more than sufficient to reveal the star’s large RV semi-amplitude of $K \sim 140 \, \text{m s}^{-1}$. Later observations by Naef et al. (2001), Vogt et al. (2005), Vogt, Marcy, Butler, & Apps (2000), Wittenmyer, Endl, & Cochran (2007), Wright et al. (2009) revealed the presence of a long-term RV trend that emerged as the clear signal of an outer planet with a period of more than 10 years. Feng et al. (2015) presented a joint analysis of the existing RV data and determined a complete orbit for HD 217107 c with a period of $P = 5189 \pm 21$ d and $m \sin i = 4.153 \pm 0.017 \, M_{\text{J}}$.

Today, RV observations of some of the first exoplanets discovered span more than two decades. These long time baseline enable the search for not only outer companions with orbits similar to that of Jupiter in our solar system, but also subtle effects that may cause the orbits of the inner planets to change over time. For example, in General Relativity (GR), the orientation of the orbit of a planet will evolve in time as the orbital precession of the planet Mercury in our own solar system is well known and measured to be $56''$ year$^{-1}$, of which 43'' century$^{-1}$ is due to GR effects. As discussed by, among others, Miralda-Escudé (2002), Kane, Horner, & von Braun (2012), and Jordan & Bakos (2008), the gravitational quadrupole moment of the star and an outer-perturbing planet can also cause precession, but those effects are generally much smaller for the case of an exoplanet. Figure 1 depicts the phenomenon. These precession effects are difficult to measure in exoplanet systems, but may provide interesting tests of GR and models of stellar structure, as well as clues to the existence of undetected outer companions.

We present a joint analysis of 377 RV observations of the HD 217107 system spanning 20.3 years. The 42 new measurements presented here, obtained with the MINERVA telescope array (Swift et al. 2015; Wilson et al. 2019), extend the total published observational time baseline by almost five years. We confirm the existence of the outer companion, HD 217107 c, and refine the orbital solutions for both components. We model the orbital precession of HD 217107 b and constrain it to be $\omega < 65.9 \, \text{century}^{-1}$ (95% confidence), an upper limit two orders of magnitude above the expected level of precession due to GR effects.

2 | STELLAR PARAMETERS

HD 217107 is a main-sequence star 20.3 pc away ($\pi = 49.817 \pm 0.057$ mas; Gaia Collaboration et al. 2018) and is similar in mass to our Sun. We used the SED fitting capabilities within EXOFASTV2 (Eastman 2017) to estimate the stellar properties of HD 217107 using the known distance and broad-band photometry. We estimated the stellar mass to be $1.09_{-0.065}^{+0.065} \, M_{\odot}$, the radius to be $1.140_{-0.036}^{+0.039} \, R_{\odot}$, the effective temperature to be $5670_{-100}^{+110}$ K, and the metallicity to be $[\text{Fe/H}] = 0.145_{-0.072}^{+0.067}$. The estimated surface gravity is $\log g = 4.362_{-0.048}^{+0.041}$, indicating that HD 217107 is a somewhat evolved yellow subgiant star (Stassun, Collins, & Gaudi 2017; Cubillos, Rojo, & Fortney 2011; Wittenmyer et al. 2007).

3 | DATA SETS

We analyzed published RV data sets from the HIRES, Hamilton, CORALIE, and Robert G. Tull Coudé spectrometers, in addition to the new MINERVA RVs presented here for the first

FIGURE 1 Argument of periastron, $\omega$, is defined as the angle between the line-of-sight plane as viewed from Earth and the planet’s point of periastron. In GR, planetary orbits are not necessarily closed and $\omega$ can change over time. Over some period of time, $\Delta t$, the orbit itself will rotate around the star by some angle $\Delta \omega$; this yields $\omega = \Delta \omega / \Delta t$. 

1 see http://exoplanets.org for chronology of discovery
time. We use 128 Keck-I RV measurements published in Feng et al. (2015) and break the full data set into two parts corresponding to before and after the HIRES CCD upgrade that took place in 2004 (denoted as HIRES and HIRES2, respectively, throughout this analysis). We use 121 measurements obtained with the Hamilton spectrometer at Lick Observatory as published in Wright et al. (2009), 23 RV measurements obtained with the Robert G. Tull Coudé at McDonald Observatory as published in Wittenmyer et al. (2007), and 63 RV measurements obtained with the CORALIE instrument at Observatoire de Haute-Provence as reported in Naef et al. (2001). The typical reported RV uncertainty on these measurements is between 2.5 and 7.5 m s$^{-1}$. In all cases we converted the reported times of observations, JD$_{UTC}$ or BJD$_{UTC}$, to BJD$_{TDB}$ following Eastman, Siverd, & Gaudi (2010) in order to facilitate direct comparisons over a time span of two decades.

The MINERVA array is a set of four 0.7 m telescopes at the Fred Lawrence Whipple Observatory in Arizona. MINERVA observed HD 217107 between May 2016 and November 2018 and the derived RV measurements are reported in Table 1. The MINERVA observatory, which is described in more detail in Swift et al. (2015) and Wilson et al. (2019), has been demonstrated to achieve an RV precision of $\sigma_{RV} \sim 2$ m s$^{-1}$ on bright RV standard stars. The four telescopes are fiber-coupled to a KiwiSpec echelle spectrometer with a resolution of $R \sim 84,000$ and a spectral coverage of approximately 500-600 nm. Four spectra, one from each telescope, are recorded simultaneously and the four derived RVs are combined. The spectrometer is stabilized in terms of temperature and pressure and uses an I$_2$ absorption cell for calibration of the wavelength solution and instrumental profile.

## 4 ORBITAL ANALYSIS

We carried out an analysis of the combined RV data set using RadVel: The Radial Velocity Fitting Toolkit (Fulton, Petigura, Blunt, & Sinukoff 2018). We fit for five Keplerian orbital parameters for each planet: Period ($P$), eccentricity ($e$), argument of periastron ($\omega$), time of inferior conjunction ($T_{\text{con}}$), and RV semi-amplitude ($K$). At the same time, we fit for an RV offset ($\gamma$) between each facility (one offset for each of the two parts of the HIRES data set), along with an additional RV “jitter” term ($\sigma$) for each facility, and a long-term RV trend ($\dot{\gamma}$). We use the RadVel fitting basis that corresponds to fitting the Keplerian orbital parameters directly.

RadVel is a Python package that fits for the Keplerian orbital parameters through maximum a posteriori optimization and a Markov Chain Monte Carlo (MCMC) approach to sampling the posterior distributions of the parameters and estimating confidence intervals. We place uniform priors, corresponding to physical bounds, or wide regions around previously published parameters, on all parameters except eccentricity (see Table 2). We do not specifically exclude scenarios where the periastron distance of planet b is comparable to the radius of

### TABLE 1 MINERVA RV Measurements

| Time (BJD$_{TDB}$) | RV (m s$^{-1}$) | $\sigma_{RV}$ (m s$^{-1}$) |
|--------------------|----------------|--------------------------|
| 2457531.95052      | 148.95         | 5.67                     |
| 2457532.94528      | 18.36          | 5.31                     |
| 2457533.94540      | -64.68         | 5.39                     |
| 2457534.94600      | -74.95         | 5.32                     |
| 2457746.67498      | 44.62          | 5.75                     |
| 2457749.65332      | -6.48          | 5.60                     |
| 2458013.79434      | -2.62          | 6.39                     |
| 2458014.79785      | 111.80         | 5.32                     |
| 2458014.82302      | 117.47         | 5.34                     |
| 2458018.66054      | -86.83         | 6.06                     |
| 2458018.89143      | -86.63         | 7.34                     |
| 2458019.73547      | -81.30         | 6.42                     |
| 2458020.88991      | -30.12         | 7.87                     |
| 2458023.71030      | 142.42         | 6.69                     |
| 2458024.73673      | -4.62          | 7.20                     |
| 2458025.73526      | -79.90         | 7.06                     |
| 2458026.74815      | -97.34         | 6.10                     |
| 2458030.85046      | 127.45         | 6.49                     |
| 2458033.67697      | -91.08         | 5.95                     |
| 2458037.67320      | 173.83         | 6.14                     |
| 2458040.72114      | -91.73         | 6.15                     |
| 2458040.85717      | -91.52         | 6.06                     |
| 2458043.67616      | 139.18         | 6.42                     |
| 2458045.72767      | 58.24          | 5.65                     |
| 2458046.74262      | -55.11         | 10.88                    |
| 2458050.68397      | 132.03         | 6.41                     |
| 2458052.70612      | 68.54          | 6.27                     |
| 2458053.72147      | -39.66         | 5.78                     |
| 2458055.66905      | -62.48         | 5.98                     |
| 2458056.69235      | 15.60          | 5.81                     |
| 2458060.67300      | -41.74         | 8.16                     |
| 2458063.66764      | -5.03          | 5.95                     |
| 2458081.62238      | 28.64          | 5.67                     |
| 2458083.62211      | -84.46         | 5.76                     |
| 2458429.62483      | 162.07         | 5.55                     |
| 2458430.62032      | 40.33          | 5.44                     |
| 2458431.62414      | -68.00         | 5.36                     |
| 2458432.62643      | -110.29        | 5.43                     |
| 2458433.62326      | -70.04         | 5.47                     |
| 2458434.61911      | 12.17          | 6.02                     |
| 2458435.59711      | 128.74         | 5.77                     |
| 2458439.62649      | -103.08        | 5.50                     |
TABLE 2 Prior distributions used as input to Radvel MCMC analysis. A prior of $[p_1, p_2]$ denotes a uniform bound between $p_1$ and $p_2$. A prior of $N[\mu, \sigma]$ denotes a Gaussian prior centered at $\mu$ with standard deviation $\sigma$.

| Parameter       | Prior                      | Units |
|-----------------|----------------------------|-------|
| $P_b$           | $[7.126746, 7.126946]$     | days  |
| $T_{\text{conj}}$ | $[2452889.51658, 2452896.64342]$ | days  |
| $e_b$           | $N[0, 0.3]\cup[0, 0.99]$   |       |
| $\omega_b$      | $[-\pi, \pi]$             | rad   |
| $K_b$           | $[130.30, 150.30]$         | m s$^{-1}$ |
| $P_c$           | $[4650, 5450]$             | d     |
| $T_{\text{conj}}$ | $[2452411.38, 2457461.38]$ | days  |
| $e_c$           | $N[0, 0.3]\cup[0, 0.99]$   |       |
| $\omega_c$      | $[-\pi, \pi]$             | rad   |
| $K_c$           | $[0, 500]$                 | m s$^{-1}$ |
| $\sigma_\text{HIRES}$ | $[0, 25]$           | m s$^{-1}$ |
| $\sigma_\text{HIRES2}$ | $[0, 25]$        | m s$^{-1}$ |
| $\sigma_\text{CORALIE}$ | $[0, 25]$        | m s$^{-1}$ |
| $\sigma_\text{Hamilton}$ | $[0, 25]$           | m s$^{-1}$ |
| $\sigma_\text{CES}$ | $[0, 25]$              | m s$^{-1}$ |
| $\sigma_\text{MINERVA}$ | $[0, 25]$           | m s$^{-1}$ |

The results of the RadVel fits are given in Table 3, and the best-fit orbital solution and residuals are shown in Figure 2. In Figure 3 we show a subset of the posterior distributions from the MCMC analysis, demonstrating that the orbital parameters are well-measured. The orbital parameters are consistent with the most recent literature values from Feng et al. (2015), though our analysis prefers a slightly shorter period for the outer planet, $P_c = 5059 \pm 51$ d, approximately 131 d less than the period reported in Feng et al. (2015). All other orbital parameters are consistent with Feng et al. (2015) within the reported uncertainties. We note that an overall RV trend, $\hat{\gamma} \sim 0.0025$ m s$^{-1}$, is detected at the $2.5\sigma$ level. This may be evidence for an additional companion with a period longer than 20 years. However, we note that there is strong covariance between $P_c$, $K_c$, and $\hat{\gamma}$, meaning that the long-term RV trend may be an artefact of the relatively sparse time coverage of the long HD 217107 c orbit and the RV offsets between facilities (HIRES2 to MINERVA - see Figures 2 and 3). We considered a three-planet model and found a solution with a third companion with low significance at $P_d = 12283 \pm 440$ d, $K_d = 13 \pm 13$ m s$^{-1}$ and $e_d = 0.21 \pm 0.17$. We note that this period is longer than the duration of our RV data set, so any estimate of the orbital parameters of this potential planet d are highly degenerate with the RV offset, $\gamma_{\text{MINERVA}}$, for the MINERVA measurements relative to the HIRES, CORALIE, and CES measurements.
5 | ORBITAL PRECESSION

In GR, the orbit of a planet is not necessarily closed as it is, in the absence of other perturbers, in Newtonian gravity. This results in a slow evolution of the argument of periastron of an orbit. Famously, this effect was measured in the orbit of Mercury in our own solar system as one of the first direct tests of GR. The size of the GR effect is given as

$$\dot{\omega}_{\text{GR}} = \frac{7.78}{(1 - e^2)} \frac{M_P}{M_0} \left( \frac{a}{0.05 \text{AU day}} \right)^{-1} \text{[°/century]} \quad (1)$$

In Table 4 we report the known exoplanets expected to exhibit GR precession at the level of 10° century\(^{-1}\) or more.

Other effects can also lead to orbital precession, including the quadrupole moment of the star and the influence of massive, outer companions. Attempts at measuring the precession of an exoplanet orbit have been made (see, for example, Figueira et al. [2016], Iorio [2011], Watanabe, Narita, & Johnson [2020]). Figueira et al. [2016] used high-precision RV data in an attempt to detect a predicted precession in HD 80606 b of $\dot{\omega} \sim 0.06^\circ$ century\(^{-1}\), but doing so with only RV measurements proved difficult. Figueira et al. [2016] were only able to place an upper limit of $\dot{\omega} < 2.7 \pm 3.1^\circ$ century\(^{-1}\). Transit observations, with their sharp features that can be precisely timed, may provide a better opportunity for measuring orbital precession in exoplanet systems. For example, Blanchet, Haldbrand, & Larroude [2019] proposed that, given future transit data from the James Webb Space Telescope (JWST), $\dot{\omega}$ for HD 80606 b could be easily measured.

Given the long time baseline and high RV precision of our observations, we attempted to measure $\dot{\omega}$ for the HD 210107 b orbit. We developed a code to directly incorporate $\dot{\omega}$ into the two-planet Keplerian orbit fits by including a time-dependent term of the form $\omega(t) = \omega_0 + \dot{\omega} \cdot t$. Starting from the best-fit orbital parameters determined with RadVel, we refit the RV data with the $\dot{\omega}$ term using maximum a posteriori optimization and an MCMC approach to explore the posterior distributions of the parameters. In this case, we used the differential evolution MCMC code within EXOFASTV2 [Eastman 2017] to carry out the MCMC analysis. With our data, we find that we are only able to rule out very large values of $\dot{\omega}$ and with 95% confidence constrain $\dot{\omega} < 65.9^\circ$ century\(^{-1}\). This is a factor of $\sim 80$ greater than the predicted precession for the orbit of HD 217107 b, which is $0.81^\circ$ century\(^{-1}\).

### Table 3: HD 217107 System Best-fit Orbital and Derived Parameters

| Parameter | Maximum Likelihood | Units |
|-----------|---------------------|-------|
| $P_b$     | $7.126853 \pm 1.2e - 05$ | days |
| $T_{\text{con}}$ | $2452893.0794^{+0.0067}_{-0.0066}$ | days |
| $e_b$     | $0.1272 \pm 0.0028$     |       |
| $\omega_b$ | $0.419 \pm 0.023$     | rad   |
| $K_b$     | $140.02 \pm 0.42$      | m s\(^{-1}\) |
| $a_b$     | $0.0746^{+0.0015}_{-0.0016}$ | AU |
| $m_b \sin i_b$ | $1.394^{+0.057}_{-0.099}$ | M\(_J\) |
| $P_c$     | $5059.34^{+72.78}_{-49.02}$ | days |
| $T_{\text{con}}$ | $24549507^{+24}_{-25}$ | days |
| $e_c$     | $0.3991 \pm 0.0103$     |       |
| $\omega_c$ | $3.572 \pm 0.031$     | rad   |
| $K_c$     | $49.85^{+1.49}_{-1.39}$ | m s\(^{-1}\) |
| $a_c$     | $5.94 \pm 0.13$        | AU    |
| $m_c \sin i_c$ | $4.09^{+0.23}_{-0.224}$ | M\(_J\) |
| $\dot{\gamma}$ | $-0.00245^{+0.00099}_{-0.00095}$ | m s\(^{-1}\) day\(^{-1}\) |

| Parameter | Credible Interval | Units |
|-----------|-------------------|-------|
| $\sigma_{\text{HRES}}$ | $0.0$ | m s\(^{-1}\) |
| $\sigma_{\text{HRES2}}$ | $0.3$ | m s\(^{-1}\) |
| $\sigma_{\text{CORALIE}}$ | $0.0$ | m s\(^{-1}\) |
| $\sigma_{\text{Hamilton}}$ | $13.0$ | m s\(^{-1}\) |
| $\sigma_{\text{CES}}$ | $4.6$ | m s\(^{-1}\) |
| $\sigma_{\text{MINERVA}}$ | $8.6$ | m s\(^{-1}\) |
To test the reliability of our code, and explore the quantity and quality of RV data that would be required to measure orbital precession in HD 217107 b, we generated synthetic observations at the actual times of the observations of our RV data set and differing levels of Gaussian noise. We included in these synthetic data sets \( \dot{\omega} = 0.81^\circ \text{ century}^{-1} \) and attempted to recover the known \( \dot{\omega} \) to high accuracy given the 377 simulated measurements over 20 years. However, for realistic measurement precision, these simulations indicated that detecting precession effects in exoplanet orbits with RV data alone is going to be very challenging. For example, we found that \( \sigma_{\text{RV}} = 0.15 \text{ m s}^{-1} \) would be required to detect precession of \( 0.81^\circ \text{ century}^{-1} \) at 95\% confidence in a data set identical in total duration and cadence to our actual observations. At the level of precision readily achievable with modern instruments, 2 m s\(^{-1} \), our simulations indicate that more than 50 years of once-per-week observations would be required to detect the \( 0.81^\circ \text{ century}^{-1} \) precession.

In addition to GR effects, the influence of an outer companion may cause orbital precession of HD 217107 b. In our own solar system, it is the effect of the other planets that are responsible for the vast majority of Mercury’s precession. \( \text{Jordan & Bakos (2008)} \) give an approximation for the effect of perturbing bodies, \( \dot{\omega}_{\text{pert}} \), to first order in eccentricity and lowest order in the ratio of the semi-major axes of the two planets as follows.

\[
\dot{\omega}_{\text{pert}} \approx 29.6 \left( \frac{P}{\text{day}} \right)^{-1} \left( \frac{a_{b}}{a_{c}} \right)^{3} \left( \frac{M_{c} M_{\odot}}{M_{b} M_{\odot}} \right) \left[ \sigma / \text{century} \right]
\]

Given that the ratio of the semi-major axes of the two HD 217107 planets is so small \( (a_{b}/a_{c}) \sim 2 \times 10^{-6} \), the perturbing effect is expected to be substantially smaller than the GR effect in the orbit of HD 217107 b. Planet c is expected to induce a precession of \( 0.01^\circ \text{ century}^{-1} \), roughly 1\% of the GR component of \( \dot{\omega} \). Finally, effects related to star-planet tides and the quadrupole moment of the star are also discussed in \( \text{Jordan & Bakos (2008)} \) and are expected to be very small for HD 217107 b. We note that precession effects, as well as other dynamical effects related to the interaction of planets b and c, may be more readily detectable through Transit Timing Variations (see, for example, \( \text{Horner et al. (2020)} \) \( \text{Kane et al. (2012)} \)). However, we are not aware of the detection of any transits of the host star by planet b, and HD 217107 has not been observed by the Transiting Exoplanet Survey Satellite (TESS). HD 217107 was observed as part of the extended Kepler mission K2. Observations spanning approximately two weeks seemingly show no signs of a transit signal at the period of HD 217107 b. Though the expected amplitude of the transit is large, \( \sim 1\% \), the K2 light curve exhibits significant systematic effects. If future photometry can confirm that there is no transit signal, we could constrain the inclination of HD 217107 b to be \( i < 86^\circ \), but we are currently unable to rule out the possibility that the system’s planets transit.

We investigated the long-term dynamical stability of the HD 217107 system within the angular momentum deficit framework \( \text{(AMD; Laskar & Petit (2017), Petit, Laskar, & Boué (2017), Petit, Laskar, & Boué (2018), Glaser, McMillan, Geller, Thornton, & Giovinazzi (2020), which considers orbital overlap, mean motion resonances (MMR), and Hill instabilities. By exploring the inclination parameter space of a co-planar two-planet system, we found that the system is dynamically stable on a timescale equivalent to the lifespan of HD 217107 for inclinations \( i > 23.7^\circ \) with an AMD coefficient \( \beta_{\text{AMD}} < 1 \).

6 | CONCLUSIONS

We present a joint analysis of RV measurements of the HD 217107 planetary system spanning 20.3 years. In addition to measurements previously reported in the literature, we include 42 new measurements obtained with the MINERVA telescope array for a total of 377 RV measurements. We confirm the existence of a massive, long-period companion on an eccentric orbit (HD 217107 c) and refine its orbital parameters. Given that HD 217107 b has a short-period orbit with a significant eccentricity, we consider the possibility of measuring the precession of the argument of periastron, \( \dot{\omega} \), due to GR and other effects. We find that with our current data we are only able to constrain \( \dot{\omega} \) to \( < 65.9^\circ \text{ century}^{-1} \), a level approximately 80 times larger than the expected precession due to GR effects alone. We find that our mean RV precision would need to improve by approximately a factor of 40 to \( \sigma_{\text{RV}} < 0.2 \text{ m s}^{-1} \) in order to expect to detect GR precession in the orbit of HD 217107 b at high significance. We note that there are nine known exoplanet systems for which the inner planet’s GR precession is expected to be greater than \( 10^\circ \text{ century}^{-1} \) (see Table 4). While our simulations indicate that a data set similar to our HD 217107 data set in terms of precision and extent is not quite sufficient to detect GR precession, modest improvements in overall RV precision could make this possible for the systems in Table 4.
TABLE 4 Known exoplanets expected to have $\dot{\omega} > 10^{6}$ century$^{-1}$. These are planets that have been discovered via Doppler spectroscopy or the transit method. Orbital period and magnitude, in V or Kepler bands, are given, along with the estimated $\dot{\omega}$. Even though the predicted precessions are large, some of these targets are faint enough that obtaining precise RV measurements will be challenging.

| Planet     | Magnitude | Period [d] | $\dot{\omega}$ [°/century] |
|------------|-----------|------------|-----------------------------|
| KOI 13 b   | 9.96      | 1.77       | 10.42                       |
| HATS 70 b  | 12.57 V   | 1.89       | 10.43                       |
| WASP 114 b | 12.74 V   | 1.55       | 11.36                       |
| GJ 3138 b  | 10.98 V   | 1.22       | 11.42                       |
| HATS 67 b  | 13.65 V   | 1.61       | 11.52                       |
| Kepler 17 b| 14.14 Kepler | 1.49     | 11.72                       |
| HATS 52 b  | 13.67 V   | 1.37       | 13.46                       |
| KELT 1 b   | 10.70 V   | 1.22       | 17.10                       |
| WASP 19 b  | 12.59 V   | 0.79       | 27.16                       |

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Author Contributions

Giovinazzi carried out the RadVel analyses. Blake carried out the analyses and simulations related to constraining $\dot{\omega}$. Eastman is the MINERVA lead and is responsible for the operation of the MINERVA array. Sliski assisted with MINERVA operations. Wright provided input on orbit fitting, mechanisms of orbital evolution, and feedback on the manuscript. McCrady is responsible for the optimization of MINERVA observing schedules. Wittenmyer, Wright, J. A. Johnson, and McCrady are founding PIs of the MINERVA project. Wilson assisted in maintaining the MINERVA array as well as developing its operational code and Doppler pipeline. Houghton assisted with remote operations of the MINERVA array. S. A. Johnson assisted in developing MINERVA operational code and maintaining the array. Plavchan, Kane, and Horner provided feedback on the manuscript. García-Mejía assisted with the MINERVA spectrograph installation and has provided observatory operational support on site. Glaser carried out the AMD calculations and subsequent simulations to constrain the orbital configuration of HD 217107 b, c, and the theoretical third companion, HD 217107 d.

6.1 Financial Disclosure

None reported.

6.2 Conflict of Interest

The authors declare no potential conflict of interests.

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