Discovering **E**xoplanet **O**rbiting HD10442 from **R**adial **V**elocity **M**ethod

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Introduction:

The radial velocity technique is based on the fact that if a star hosts a planet then both the star and planet will rotate around a common center of mass (barycenter) due to mutual gravitational interaction. As the star rotates around the barycenter in its orbit, the stellar light will appear blue or red-shifted, due to the doppler effect, as the star moves toward and away, respectively, from the observer. This measured shift in stellar spectral line from spectroscopic observations can then be used to derive the corresponding velocity of the star, known as radial velocity. The magnitude of this radial velocity is determined by the planet's mass and the semi-major axis of the planet's orbit around the star. If the radial velocity of an exoplanet around a host star during different orbital phases are known, one can fit a model to determine the period (orbital) and eccentricity of the planets along with its minimum mass of the orbiting planet. The closeness of the calculated minimum mass to the true mass of the planet depends on the inclination of the star-planet system. If the planet is edge-on at the observer line of view, then it is possible to determine the true mass of the planet. Radial velocity as a function of time can be described as:

$$RV(t) = k*\sin(2\pi/P*t + t_0) + RV_0 \quad \ldots\ldots\ldots\ldots\ldots (1)$$

where t is the time, k is the absolute magnitude of the maximum radial velocity, P is the period of the orbit, t_0 is the phase, and RV_0 is the radial velocity of the system's center of mass. The analytical solution of the gravitational two-body problem describes the velocity of the star as:

$$RV(t) = k* (\cos(f(t) + \omega) + e \cos\omega) + RV_0 \quad \ldots\ldots\ldots\ldots\ldots (2)$$

where the time parameter in $f(t)$, called a true anomaly, is related to the period. Comparing with Eq.1, k is related to amplitude, ω is related to the phase, and e (the eccentricity of the orbit) is related to the offset. The true anomaly, $f(t)$ is related to time via two equations below:

$$E - e \sin E = n(t-\tau) \quad \ldots\ldots\ldots\ldots\ldots (3)$$

$$\tan\left(\frac{f}{2}\right) = \tan\left(\frac{E}{2}\right) * \sqrt{\left(\frac{1+e}{1-e}\right)} \quad \ldots\ldots\ldots\ldots (4)$$

where E is the eccentric anomaly, $n(t-\tau)$ is the mean anomaly, τ is the time of pericenter passage, and $n = 2\pi/P$ is the mean motion of the planet.

Data and method:

The radial velocity data of HD10442, one of the few metal-rich stars, was collected from Giguere et al. 2015. The dataset has a total of 43 radial velocity measurements (data point). The radial velocity measurements were considered as a gaussian distribution with standard deviation values (1-σ) as the error of the measurement (Fig. 1). The stellar properties of HD10442 are $\log_g$ = 3.50±0.06, T_{eff} = 5034±44 K, and [Fe/H] = 0.11±0.03 (Giguere et al. 2015). The median stellar mass (1.56 M_0), error/ standard deviation of the stellar mass (0.09), and the jitter value of 4.7 (Isaacson and Fischer, 2010) were used for this report. I used a python code[1] to fit the radial velocity data with a model described above. In the code, I calculated the periodogram of the data. The periodogram solves for finding the possible period of the star (prior for the model). The code finds the periodogram using `lombscargle` function of `scipy.signal` module. Then I plot the periodogram (Fig. 2). Having the time *t,* the code solves the Eq. 3 numerically to derive the value of the eccentric anomaly, *E*, using `fsolve` function of `scipy.optimize` module. Once *E* is calculated, the code finds the true anomaly, *f*, by plugging in the value of *E*.

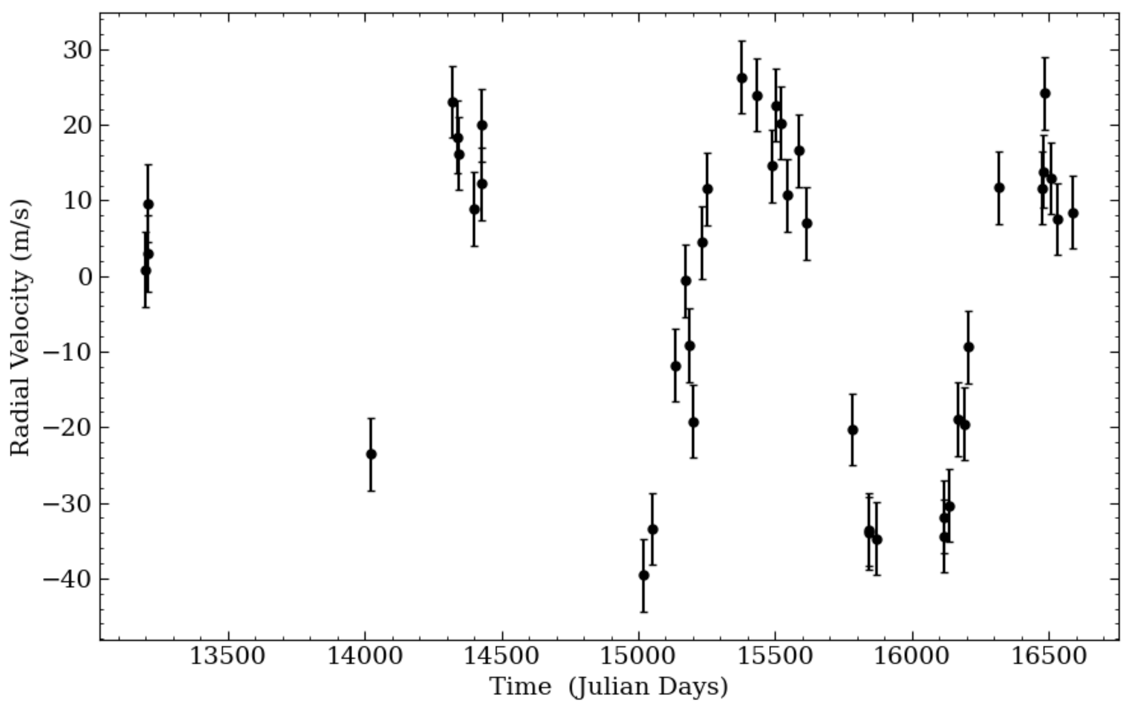

Fig. 1: Radial velocity (m/s) plots a total of 43 radial velocity measurement points for HD10442.

[1] The basic idea of the RV code was derived from GitHub and then I created my own code to use for this project. [GitHub: https://adamdempsey90.github.io/python/radial_velocities/radial_velocities.html]

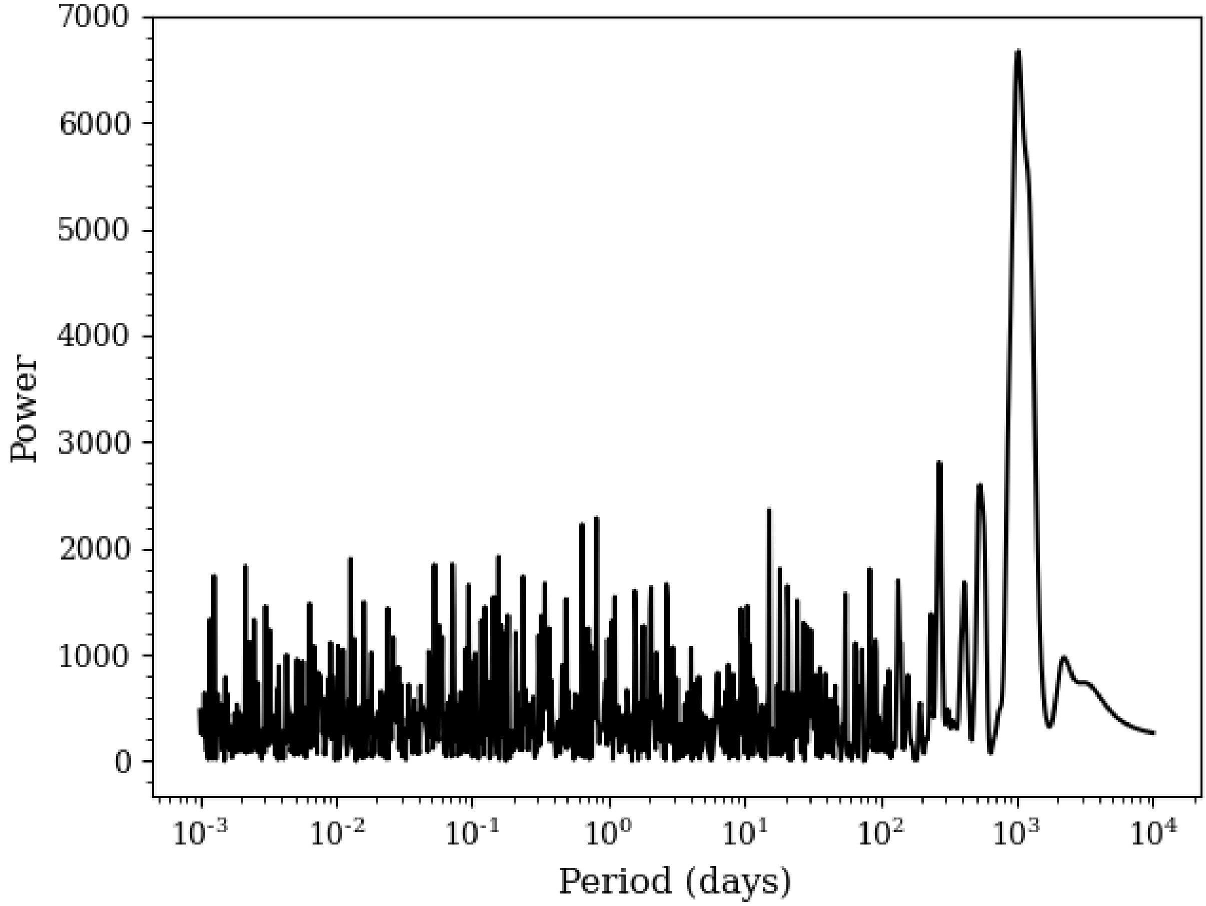

Fig. 2: Periodogram (the power vs period [in days]) of radial velocity measurements for HD10442.

The data were fitted with the model (Eq. 2) using the `curve_fit` function of `scipy.optimize` module. The `curve_fit` function uses non-linear least squares to fit a function to the model. The model fits five parameters *(k, e, ω, τ, n)* to the radial velocity data. The error of the model parameters was calculated from the covariance matrix found from the `curve_fit` output. The method employs a *Gauss-Newton (GN)* and *Levenberg-Marquardt (LM)* algorithm to find the minimum *chi-square* value of the model fitting. Once the model fits and has the model parameters on hand, the other parameters of the exoplanet e.g., mass (M_p), period (P), and semi-major axis (a), were then derived from the *Kepler* and others supplementary equations. The uncertainties of these parameters were calculated using the error propagation rules considering a Gaussian probability and 1- σ error.

Results:

Using the code, the result of the model fitting renders expected values of the parameters along with the 1-σ uncertainty of the parameters. I found the mass of the planet $M_p > 2.523 \pm 0.1529$ M*j,* eccentricity $e = 0.280 \pm 0.0400$, orbital period $P = 1012.526 \pm 5.0588$ days, and semi-major axis of the planet orbit $a = 2.327 \pm 0.0454$ AU. The best fit model, parameter values, and residual (data value - model value) of the fitting were given in Fig.3. For the HD10442, the study of Giguere et al. 2015 found mass of the planet $M_{sin\ i}$ (M_J) = *2.10* ± *0.15*, orbital period *P(days)* = *1043* ± *9*, eccentricity e = *0.11* ± *0.06*, and semi-major axis of the planet orbits a = *2.335* ± *0.014.* The slight discrepancy between the result of Giguere et al. 2015 and this project is because I have used a very simple fitting model considering a single planet system whereas Giguere et al. 2015 have used a more sophisticated fitting routine. Moreover, there might be a multi-planet possibility in the system (as evident from the residual plot in Fig. 3) that needs to be accounted for in the future study.

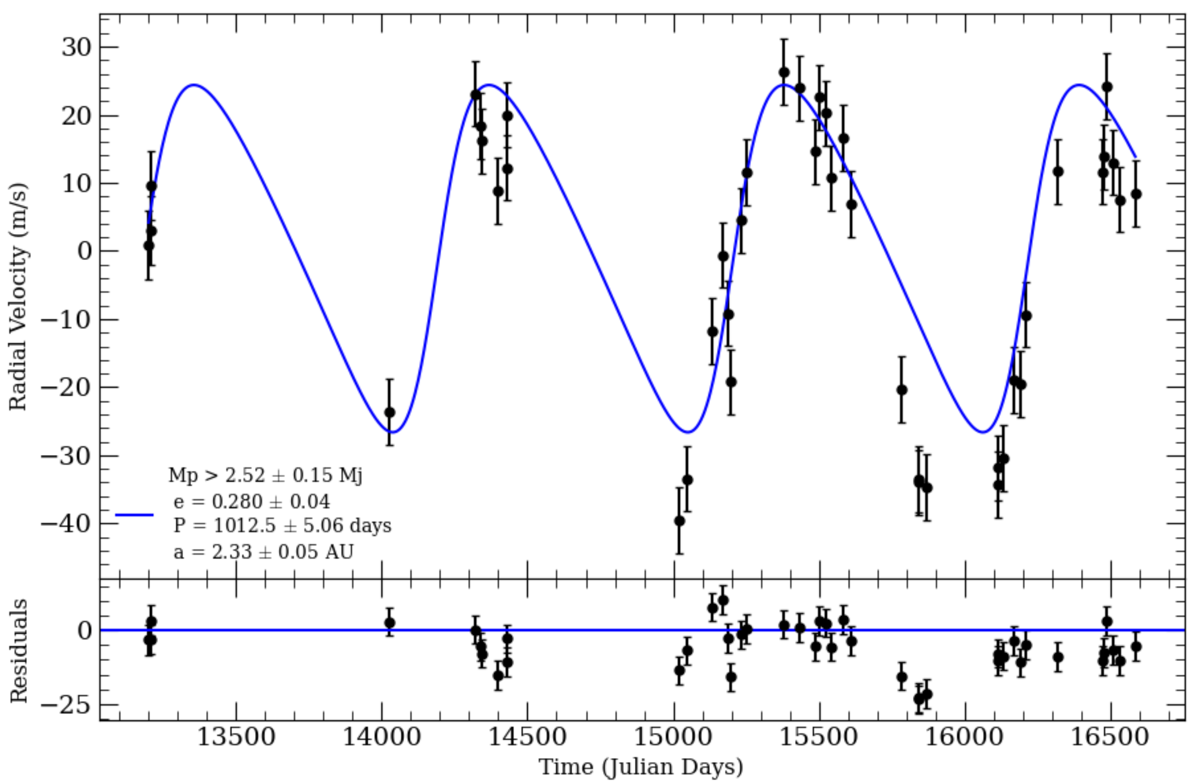

Fig. 3: Best fit model, parameters, and residual of radial velocity measurements of HD10442.

References: [1] Giguere, M.J., Fischer, D.A., Payne, M.J., et al. 2015, ApJ, 799, 89. [2] Isaacson, H., Fischer, D. 2010, ApJ, 725, 875–885. [3] Mayor, M., Queloz, D. 1995, Natur, 378, 355–359. [4] Seager, S. (Ed.). 2011. Exoplanets (1st ed. University of Arizona Press, Tucson: Houston).