Lab 4: How Many Planets in the Gliese 581 System?

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Gliese 581 is a **planetary system** centered around an M3V **red dwarf,** about 20.5 light years from Earth. It is widely confirmed to host **at least four planets** (Gliese 581 b, c, d, e).

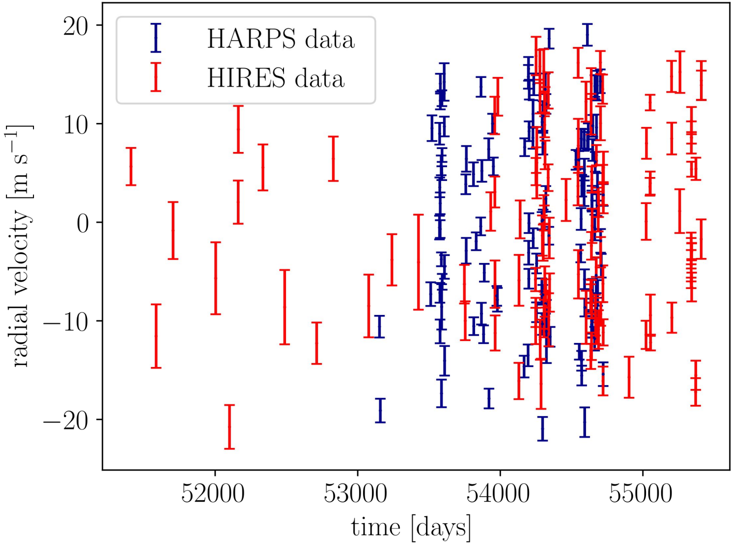
In 2010, Vogt et al. announced the supposed detection of **two more planets** in the system (Gliese 581 f, g), based on data from the ESO telescopes HARPS and HIRES. This was met with much excitement due to Gliese 581 g being within the habitable zone of the star.

This claim was soon **refuted** by follow-up analyses, particularly the introduction of **new HARPS data**. However, due to statistical errors made by Vogt's group (such as assuming perfect residuals and relying on p-value), **we investigate whether the 6-planet model is justified** using the **original data** used by Vogt's group.

We fit models for a 4-planet system, two 5-planet systems (only f and only g), and a 6-planet system, and then perform **model comparison** on **cross-validation** sets to select the best-performing of the four models.

Photo source: NASA Exoplanet Exploration, Dec. 2022

Initial Methodology



$$v_r = \sum_{i}^{n_{\text{planets}}} K_i \sin\left(\frac{2\pi t}{P_i} + q_i\right)$$

Data source: HIRES (Keck), HARPS (ESO)

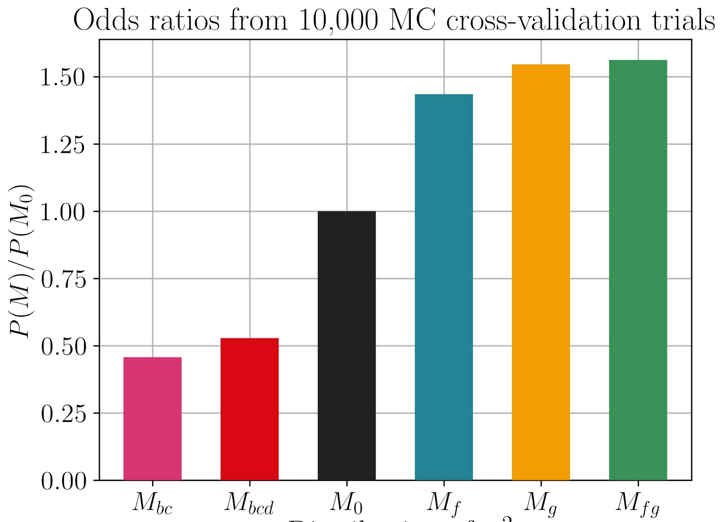
After importing the data (plotted on the left), we defined model-fitting functions for the 4 (null hypothesis), 5, and 6-planet cases according to the **equation for radial velocity** on the bottom left. Additionally, we include known incorrect 2 and 3 planet models to "sanity check" our calculations. To fit the model, we **first fit for the *q* (phase) terms** by fixing other parameters to the values reported by Vogt et al. Then, using the obtained phases as **initial guesses**, we obtained the best-fitting model parameters using the `curve_fit` routine from `scipy.optimize`.

To perform a preliminary evaluation of the different models, we fit all of the data (HIRES and HARPS) using the above method, calculated the residuals of the model on all of the data, and then calculated various model comparison metrics. These metrics show a **strong preference** for the **6 planet** model with a large advantage in all metrics with logarithmic scaling.

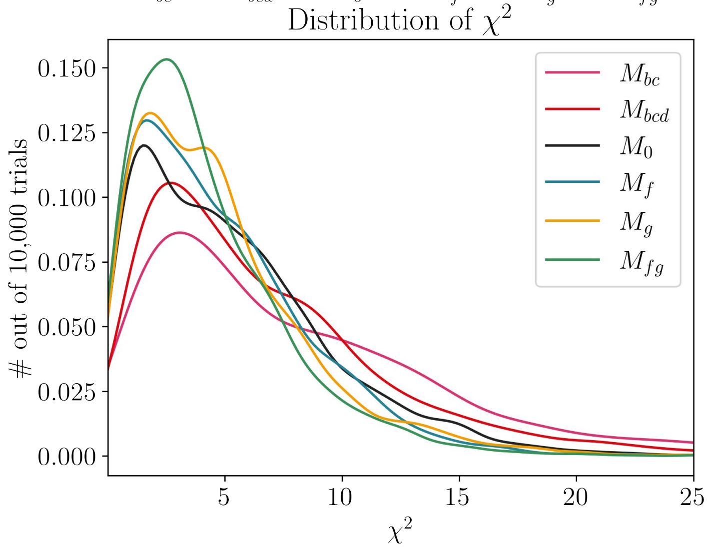
	χ^2	$\log \mathcal{L}$	χ^2_ν	BIC	AIC	mAIC
M_{bc}	588.54	-666.85	2.50	621.45	600.54	600.90
M_{bcd}	492.45	-618.81	2.12	541.82	510.45	511.23
M_0	390.53	-567.85	1.71	456.35	414.53	415.90
M_f	344.96	-545.06	1.53	427.23	374.96	377.09
M_g	341.94	-543.55	1.51	424.21	371.94	374.08
M_{fg}	297.54	-521.35	1.33	396.26	333.54	336.62

Testing & Results

To verify our preference for the 6-planet model, we conducted more thorough cross-validation tests. This involved using the “leave p out” method with p=3 with Monte Carlo selection of the three points to leave out for validation. For each combination of training and validation data (10000 total combinations), the six models were fit to the training data. The χ^2 for each model on the validation set was then computed, and if a model performed better than the four-planet model it had its score increased by one. The model scores are shown in the table below, giving an **odds ratio** for the **6-planet model** (compared to the 4-planet null hypothesis) of **1.56**, which suggests **very little confidence** in the detection of the additional planets.



The plots on the right show the χ^2-distribution for the six models from the cross-validation selections, as a simple histogram.. As seen in the plots (albeit less clearly), the leftmost peak is for the **6-planet model**, which **qualitatively suggests this model *is* the best overall fit** to the available data, but **not significantly**.



The reported result from Vogt et al. 2010 is *4.7 sigma* confidence in the detection of planets f and g. Our additional analysis finds that their reported confidence is **vastly overstated**, casting doubt on the “detection”.