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Extrasolar Planetary Properties

Until the latter part of this past century humans had no evidence proving the existence of planets outside our solar system. As the scientific frontier progressed, so too did the capabilities of the instruments used in scientific discovery. When the detectors and telescope became precise enough to accurately measure fluctuations in stellar luminosities within our galaxy, certain patterns began to show up. Researchers noticed periodic, significant dips in the apparent brightness of a star. After further analysis these dips were determined to be the caused by orbiting bodies (planets).

This lab attempts to recreate the process in which these fluctuations are analyzed. The planet in question is WASP-4b. There are 6 total transits that are available for analysis, and students are tasked with analyzing them individually and combined for increased accuracy. Any other necessary data to calculate the radius of the planet (i.e. radius of star, mass of star, mass of planet) are all provided in the document with corresponding uncertainties.

The first section of the lab focuses entirely on simply displaying the data to begin analysis. After loading the data in from the data file provided online (*Figure 1)*, it becomes clear that the data collection is not continuous between the first and last transit. Strictly through visual analysis, it can be seen that there are 6 transits.

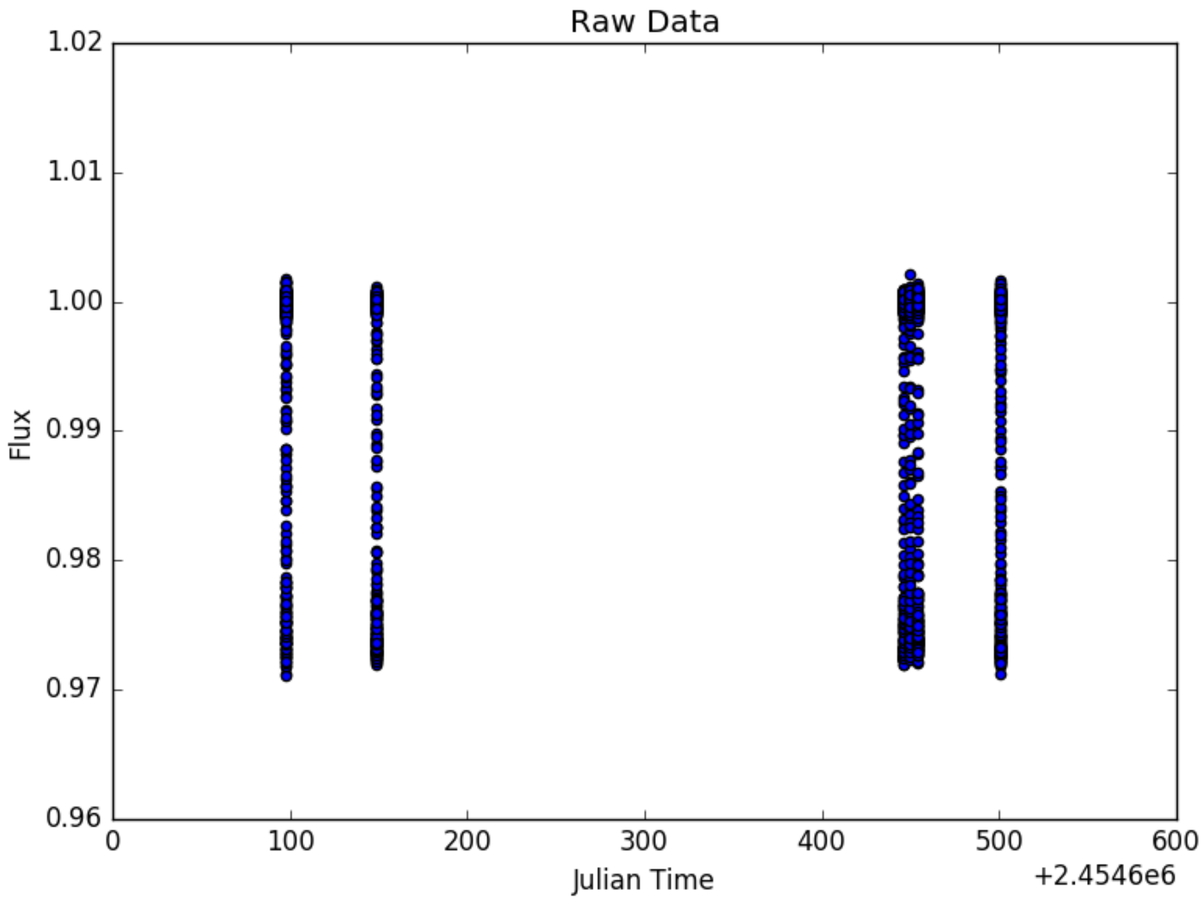

Figure 1: Scatter plot of raw transit data

As there are significant gaps of time between each transit, it's possible to break up the transits by writing an algorithm the separates data if the span of time is greater than 1.0 which proves to be sufficient if zoomed in enough on each transit. Once each transit is separated and their respective time intervals zeroed, they can then be plotted over each other for a more easily identifiable transit curve (*Figure 2*).

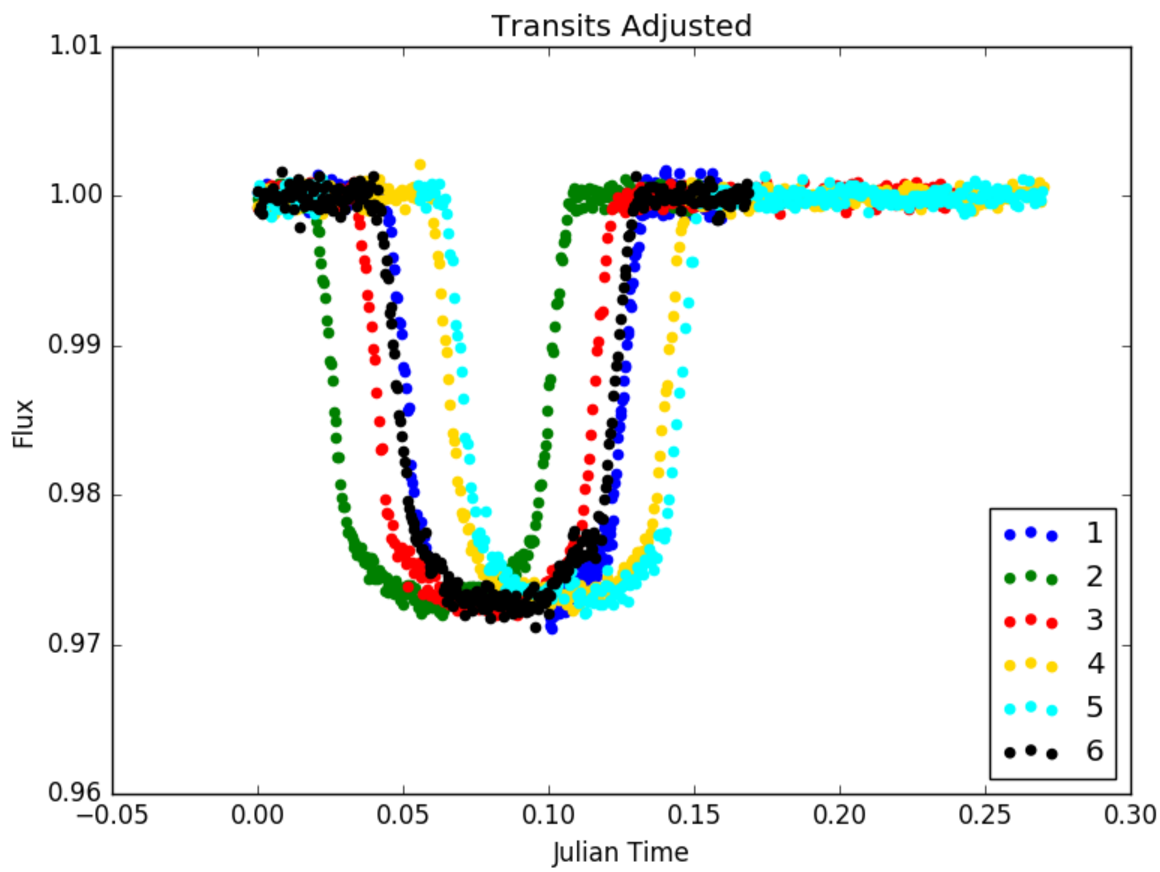

Figure 2: Scatter plot of raw transit data with adjusted times to easily see full transits

After this manipulation is done, further manipulation is needed in order to directly compare each of the transits. This means that an alignment of each of the 6 transits needs to be done. This is done through cross-correlating each transit with the second transit. The second transit is used as the reference because it seems to have the most continuous set of data out of the 6 transits. There were two methods by which the cross-correlation is done: physical space and spectral space. The physical space method consists of interpolating each of the transits to fit the second transit more closely and then multiplying corresponding flux values and summing the new array of products. The transit is then shifted over one δt and repeat the process. This process repeats until the whole transit has been shifted back to its original position. The shift at which the maximum sum is achieved corresponds to the most ideal shift for alignment. The spectral space method consists of using the correlation theorem between the reference and interpolated fluxes which uses Fourier Transforms to perform the cross-correlation. The time shifts that correspond to the largest cross-correlation (implying most ideal time shift) is presented in *Table 1*.

	Transit 1	Transit 2	Transit 3	Transit 4	Transit 5 (greatest shift)	Transit 6
Time Shift	0.02517498	0.0	0.01519999	0.03989997	0.04464997	0.02232498

Table 1: Table of time shifts (in Julian time) needed to align each transit to the second transit.

After applying these shifts to the transit's data, they are plotted on top of each other in order to see that the alignment worked properly (*Figure 3*).

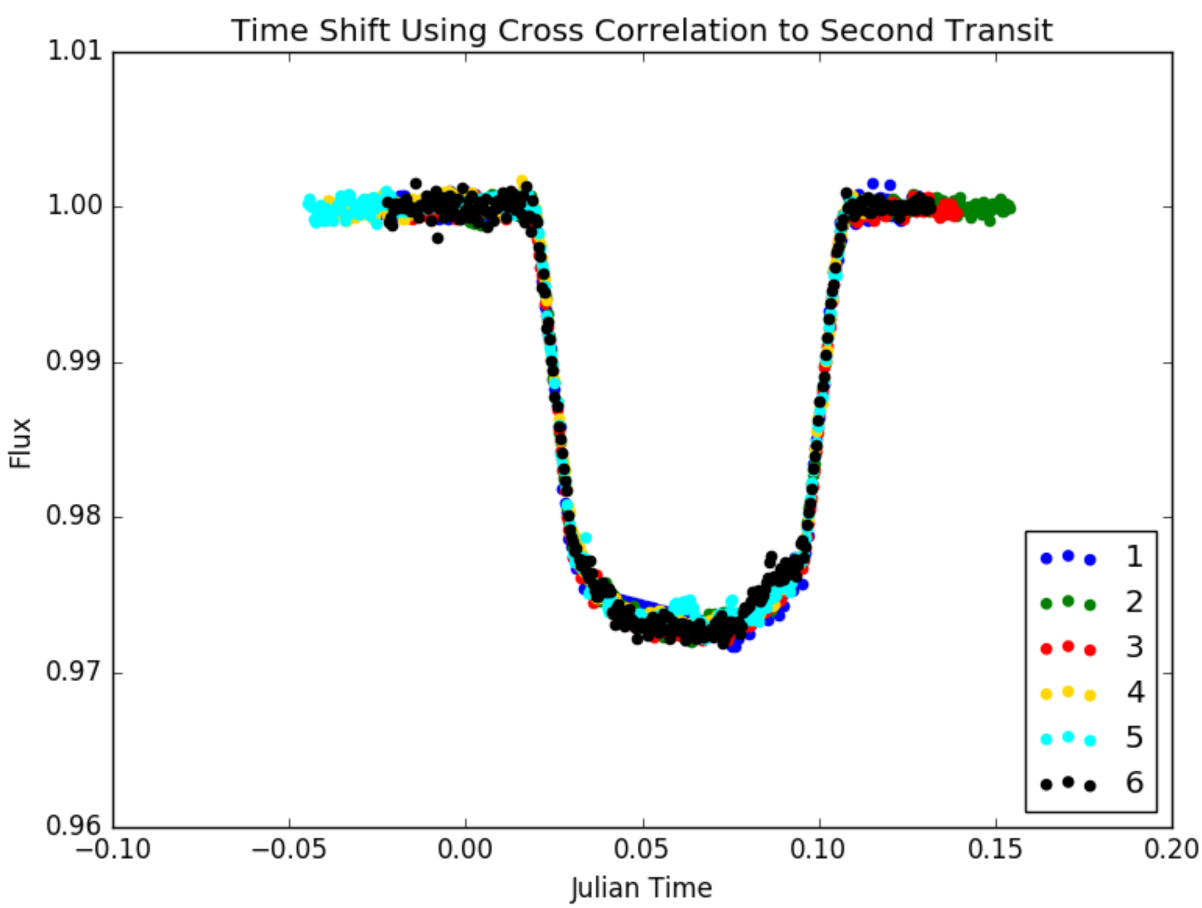

Figure 3: Scatter plot of interpolated transit data with adjusted times achieved through cross-correlation

The third and final part of the project was the section in which analysis of the data itself is to be done. The first step is to determine the ratio of the transit flux to the non-transit flux. In order to do this, there needs to be specified time frames for each transit that differentiate between what is considered "non-transit" and "transit" flux values. This is done by determining a mean of a small portion of the pre-transit flux values, the post-transit flux values, and a small portion centered around the center of the transit. After this mean is determined, a variance is calculated, and the timeframes used for transit/non-transit flux values include all points within one sigma of the means. This ensures that the steep flux "walls" as seen on *Figure 3* are ignored as these would decrease accuracy on the ratio. Transit 1 is ignored due to the missing data during transit. Once the ratio is calculated, the uncertainty in the ratio was propagated (*Table 2*).

	Transit 2	**Transit 3**	**Transit 4**	**Transit 5** (greatest shift)	**Transit 6**	**Combined Transits**
Ratio	0.9731±0.017	0.9726±0.024	0.9734±0.018	0.9737±0.015	0.9730±0.015	0.9730±0.005

Table 2: Table of the ratio of transit flux to non-transit flux with respective error.

Finally, after determining these ratios and attaining values for the intensities of the transit and non-transit data, the radius and density of the planet can be determined using the data given in the document (*Table 3*). From the calculated densities, WASP-4b is likely a gaseous planet.

	Radius [m]	**Density [kg/m³]**
Transit 2	$9.98 \times 10^{7} \pm 3.15 \times 10^{7}$	774 ± 77
Transit 3	$10.08 \times 10^{7} \pm 4.41 \times 10^{7}$	752 ± 75
Transit 4	$9.92 \times 10^{7} \pm 3.38 \times 10^{7}$	788 ± 78
Transit 5	$9.89 \times 10^{7} \pm 2.78 \times 10^{7}$	797 ± 79
Transit 6	$10.01 \times 10^{7} \pm 2.74 \times 10^{7}$	767 ± 76
Combined Transits	$10.01 \times 10^{7} \pm 1.02 \times 10^{7}$	768 ± 76

Table 3: Table of the radius and density of WASP-4b

Thought Questions

1. The second transit was chosen because it has the most continuous set of data out of all the sets. Aligning all with all in a single algorithm wouldn't have necessarily created a better reference as some of the transits (most notably Transit 1) have large gaps in their data that would've skewed the results greatly.
2. The difficulty in taking averages of all the transits in order to make a single transit as opposed to the interpolation methods used in part B, is that not all the transits are "continuous." This meaning that some of them have large gaps in the data collection that could cause inaccurate averages at corresponding locations. It would indeed provide an average transit, but some areas of the data may be slightly biased towards higher or lower fluxes due to some outliers in the individual transits. To overcome this, one would need to locate these gaps and outliers and ensure that they are ignore when calculating averages so that their affect on the outcome is minimal.
3. Treating it as random error assumed that all of the uncertainty in the data is due to fluctuations in the observed object or noise in the instruments. When it's random error, we can essentially take an average around a given point to find what the value should be because the points are just slightly off of what was expected. When it is systematic error, the data is centered around a point that is not what was expected and this is usually due to a miscalculation or a problem with the calibration of the equipment. To account for this, one could take the known distance from the planet and the star and calculate how long it takes from the beginning of the transit (where it first dips) to the point at which the transit begins to steady (where the steep part ends). The period can then be used to calculate an orbital

velocity of the planet. Coupling this with the time it took for the dip in the transit to settle at the bottom of the well can give a rough estimate of the planet's radius without having to worry about inaccurate intensity readings from the equipment.

4. The calculated densities were about 700-800 [kg/m^3]. This is rather low for something that is a rocky planet based on knowledge I've attained from my past astronomy classes, so I'm confident in that respect. Another notable feature is that rocky planets are often too small to make significant dips in the star's luminosity, so it would require a significantly larger planet. Based on the features of our own solar system, it's safe to assume that a significantly large planet is most likely gaseous.