What Can the Phase Signatures of Kepler Multi-Planet Systems Teach Us?

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Phase Variations of Multi-Planet Systems

- The Kepler mission has revealed numerous cases of transiting planets in multi-planet systems
- The predicted phase variation for multi-planet systems can be complicated and depends upon the period, radius, and albedo distributions of planets in the system
- **Short-period and/or non-transiting planets in a system can add high-frequency correlated noise or low-frequency trends to the data stream**

Figure 1: Artist's rendition of an exoplanet moving through some of its phases as it orbits its parent star.

For different combinations of planets at superior conjunction, phase signatures of multi-planet systems teach us about the reflective and thermal properties of those planets.

Photometric Phase Variations

- Atmospheric models show a dependence of giant planet geometric albedo, A_g, on semi-major axis.
- **In eccentric orbits, all flux ratio components are time dependent**

Planet/Star Flux Ratio:

$$\varepsilon(\alpha,\lambda) \equiv \frac{f_p(\alpha,\lambda)}{f_*(\lambda)} = A_g(\lambda) g(\alpha,\lambda) \frac{R_p^2}{r^2}$$

Where for an eccentric orbit:

- R_p: Planet radius – dominant factor for phase variation amplitude
- r: Star-Planet Separation – time variable
- $A_g(\lambda)$: Geometric Albedo – time variable, based on r
- $g(\alpha,\lambda)$: Phase Function – time variable, based on Pioneer observations of Jupiter and Venus

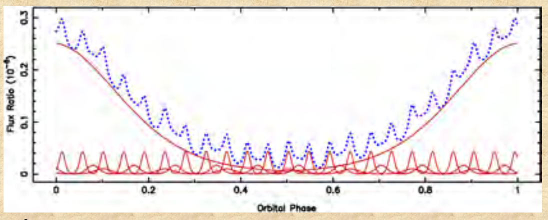

Figure 2: Model photometric flux variations due to planetary phases in a system consisting of three Earth-size planets interior to a Jupiter-size planet at 0.7 AU. The solid red lines show the phase variations due to the individual planets and the dotted blue line indicates the combined effect.

Combination Effects & Issues

- Short-period planets can cause confusion if their variation cycle is not observed with sufficient cadence
- Smaller short-period planets can appear as correlated noise in the data if a giant planet dominates the signatures
- Non-transiting planets may be unaccounted for if the model is solely based on known transiting planets

Fourier Decoupling

- The level of success achieved in using Fourier analysis to decouple the individual phase signatures depends on:
  1) Photometric precision, 2) Observational cadence, and
  3) Duration of the observations
- The Fourier method works well to disentangle phase signatures of multi-planet systems in most cases except for when the S/N of the observations is very low
- If one or more phase signatures dominate the combined signal, subtracting fitted signals and then reanalyzing the residuals in an iterative manner can reveal the remaining planets in the system

Our Solar System

- Jupiter and Venus dominate the phase variations, however, observations that reach the precision required to detect Jupiter may still cause the terrestrial planets to be seen as partially-correlated noise
- **Based on relative inclinations, the full compliment of Solar System planets would NOT be detected by Kepler:** at most only 2 planets (Mars and Neptune) would be seen from the same viewing angle!!

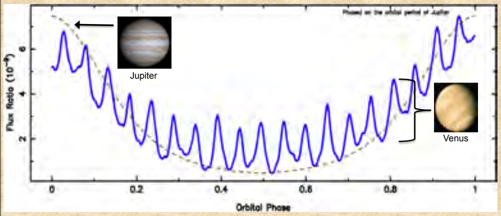

Figure 3: Total predicted photometric flux variation for our Solar System, phased on the orbit of Jupiter (solid blue line), for the Solar System as observed along the ecliptic. Jupiter (dashed red line) dominates the amplitude of the variation, with Venus' contribution being second highest at 43% of Jupiter's.

Kepler-20

- Consists of 5 known transiting planets: three super-earths and 2 earth-sized or smaller
- **Planets b and c provide the largest phase variation contributions due to their larger size and close proximity to the host star**
- Radial velocity (RV) data were used to look for signatures of non-transiting planets in the system
  - A Jupiter-mass planet in the system is ruled out to a period of ~1000 days, which would have produced a long-term trend in the photometry with an amplitude consistent with that of planet c

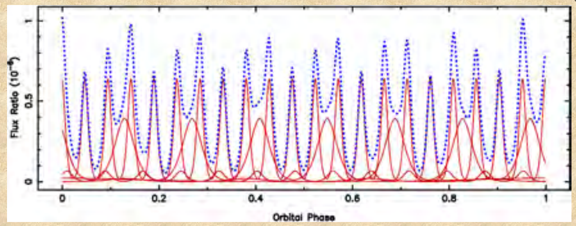

Figure 4: Modeled flux variations for the Kepler-20 system over one orbit of the outer planet (d) in the system. Contributions from the individual planets are shown by the solid red lines, and the result of combining the phase variations is shown by the dashed blue line.

Kepler-33

- Consists of 5 known transiting planets ranging from super-Earth to Neptune size with tight periods of 5 to 42 days, no RV data
- **The small range in size and orbital distance result in similar contributions from each planet to the system phase variations, which greatly improve the Fourier decoupling success**

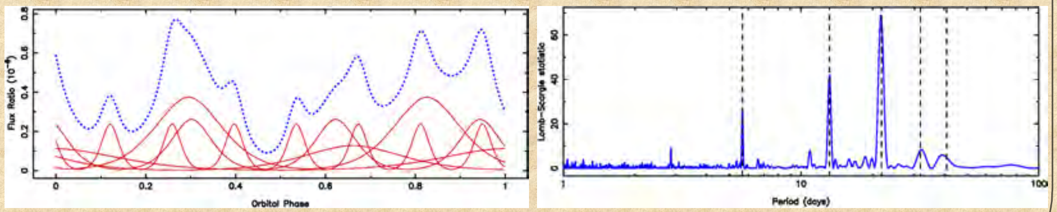

Figure 5 (Left): Modeled flux variations for the Kepler-33 system over one orbit of the outer planet (f) in the system. Contributions from the individual planets are shown by the solid red lines, and the result of combining the phase variations is shown by the dashed blue line. **(Right):** The resulting periodogram from a Fourier analysis of the flux variations. The vertical dashed lines show the published periods of the five planets.

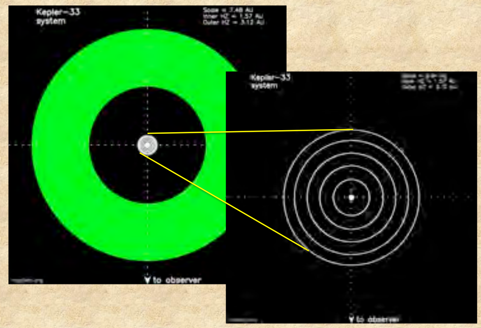

Figure 6: Top-down view of the **Kepler-33** system showing the tight orbits of its 5 planets. The green zone represents the calculated HZ for this system. For more images of exoplanet systems as well as more information on the Habitable Zone Gallery, visit: **www.hzgallery.org**

References:

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