A Spectral Approach to TTVs

Aviv Ofir
Weizmann Institute of Science

ApJ submitted
Collaborators: Oded Aharonson (WIS), Jiwei Xie, Chao-Feng Jiang (Nanjing), Re'em Sari (HUJI).

2017 PLATO conference, Warwick, UK – 6/9/2017
“Classical” approach

• Fit planetary parameters and all $T_{\text{mid},i}=1..N$ simultaneously.
  – Recent major work: Kepler TTVs catalog by Holczer+2016

• Limitations of classical TTVs searches:
  – Strong Biases:
    Deep transits (All KOIs: 428 ppm, $H_{16}$: 1075 ppm)
    Long periods (All KOIs: $P=9.5\,d$, $H_{16}$: $P=29.8\,d$)
  – Blind to short-transit planets or low-SNR objects
  – Large number of DOFs: $\sim O(N_{\text{transits}})$
Spectral approach to TTVs

Lessons learned:

• Linear ephemeris means: $T_{\text{mid},i} = T_0 + iP$

• TTV information approx. sinusoidal

A new way to look for TTVs:

• $T_{\text{mid},i} = T_0 + iP + A_{\text{TTV}} \cdot \sin[2\pi f_{\text{TTV}} t - \varphi_{\text{TTV}}$

• Check: did it improve $\chi^2$ relative to $\chi^2_{\text{linear}}$?

• Scan over $A_{\text{TTV}}, f_{\text{TTV}}, \varphi_{\text{TTV}}$

• WORKS! But.... Problematic search space.
Perturbative Approximation (PA)

- Large-amplitude TTVs probably already found

- Add two perturbation: $f=$ sine & $g=$ cosine:
  
  \[ m(z_i) \approx m(x_i) + Af_i m'_i + B g_i m'_i \]

- Would fit both $\varphi_{TTV}$ and $A_{TTV}$ analytically
- Sensitive, nearly unbiased, fast
Kepler Results - statistics

• Required Bootstrap confidence ≥0.999
• 131 new TTVs in (+2/3 over H16*)
• Depth:
  – All KOIs: 428ppm
  PA: 458ppm
• Period:
  – All KOIs: 9.5d
  PA: 10.8d
Results - Examples

- KOI-209 (Kepler-117): text-book example
Results - Examples

- **KOI-935 (Kepler-31)**
  - .01-.02: main .01 peak
  - .01-.03: new secondary
  - .02-.03: wide .02 peak

1:2:4 resonant chain w/masses?
TDVs: Transit Duration Variations

- Origin of TDVs is:
  - Change in tangential orbital velocity.
  - Change in apparent transit chord length
  - Both simultaneously
- Noisier measurement than TTVs.
- TbVs are only caused by change in apparent transit chord length.
- PA: linearly perturb $b$
KOI 13.01 TDV/TbV

- Mazeh+13 catalog (Q1-Q12 data): fractional TDV of $0.00316 \pm 0.00012 \text{ yr}^{-1}$.
- Circular orbit $\Rightarrow$ TbV $= \frac{(1 - b^2)}{-b} \text{(Frac. TDV)} = -0.00142 \pm 6e-5 \text{ yr}^{-1}$
- PA gives TbV $= -0.00130 \pm 5.9e-5 \text{ yr}^{-1}$ (Preliminary analysis)
Conclusions

• Spectral Approach is a new TTV detection technique, allowed many new detections.
• Its PA generalizable to other transit variations.
• Unbiased, sensitive, general, very fast.
• May contribute to M-R relation of small planets
• First-line detector of TTVs/TbVs/…: very suitable to short-baseline datasets like: TESS, PLATO, ...

Thank you.