Application of transit light curve methods to direct imaging exoplanet detection

by Matthias Samland (MPIA)
Application of transit light curve methods to direct imaging exoplanet detection
What’s the problem?

- Contrast between companion and host star
  - Stellar Halo
  - Speckle noise
Angular Differential Imaging (ADI)

(Source: C. Thalmann)
Angular Differential Imaging (ADI)
The light curve approach
The light curve approach
The light curve approach
How does the light curve look?
How does the pixel light curve look?
How does the pixel light curve look?
How does the noise model look like?

- Take all other pixels not affected by planetary signal
- Decompose their temporal behavior into principle components (PCA) to form the basis vectors in which to represent the systematics
  - You can call them “eigen lightcurves” to sound fancy
How does the noise model look like?
How does the noise model look like?
How does the noise model look like?

Regressor matrix

Weights

Data

PCA systematic lightcurves (+constant offset)

Transit signal

Planet model coefficient = contrast
Result of our modeling.
It works actually really well!?
Result of our modeling.
It works actually really well!
Divide and conquer with negative signal injection

- First get rid of planet signal
- Then fit systematics
  - Optimize planet model parameters with MCMC
Divide and conquer with negative signal injection

Evolution of MCMC chain

planet @
R = 28.28 pix
Phi = 225 deg
5e-6 contrast

26 components
A real planet signal: 51 Eridani b

using 15 components
A real planet signal: 51 Eridani b
Extracted signal of 51 Eridani b
Extracted signal of 51 Eridani b

Extracted PSF of 51 Eri b

Residuals
Conclusion

- Problems in high-contrast imaging very similar to transit spectroscopy! Maybe we should talk more with each other.

- Non-local, co-temporal models open new opportunities when self-subtraction is a real problem
  - disks?
  - very close separations?
Thank you for your attention!
The light curve approach

- Change paradigm from a spatial to temporal perspective
- The planet is “transiting” over the detector!
  - Planet signal turns into a characteristic “positive” light curve shape
  - Switch to using a “non-local” noise model, the temporal behavior of the noise across the image has a common underlying cause (atmosphere, optics)
... but there is a problem.

- Every pixel is fitted independently with the respective light curve shape for that pixel
  - We get a different value for the contrast (weight) for the model for each pixel
  - But there is one underlying generative model
  - Only one weight should be fit to ALL pixels
  - How to do this…?
A possible alternative.
Divide and conquer with MCMC.

- Subtract the transit model for planet of certain position and brightness FIRST.
  - One consistent underlying (2D+time) model of planet
- Fit systematic model only
- Measure residuals
- Repeat at each MCMC step for different planet models
  - Get both the position and brightness distribution at the same time
Result of our modeling. It works actually really well!
Next steps, still a lot to do

- Direct comparison between this algorithm and current alternatives.
  - Works better at close separations? I hope so.
  - Self-subtraction not an issue
    - Co-temporal, but non-local noise model
- How to decide number of regressors to fit?
- ...
A possible alternative. Divide and conquer with MCMC.
A possible alternative. Divide and conquer with MCMC.
Define minimum displacement for subtraction:
Exclude frames with displacement due to field rotation of less than a certain angle

Source: Kandori
Self-subtraction vs correlation

- Training vs test set

Wavelength (SSDI)

\[ \lambda_{i-2} \quad \lambda_{i-1} \quad \lambda_{i} \quad \lambda_{i+1} \quad \lambda_{i+2} \]

Ref. Objects: \( O_1 \quad O_2 \quad O_3 \quad O_4 \quad O_5 \quad \ldots \)

(Source: Marois et al 2010)
Cumulative Explained Variance per component
Speckle correlation

Hinkley et al 2007
Principal Component Analysis
Small-number statistics....

- All things conspire to make small angles difficult...
Locally Optimized Combination of Images - LOCI

A very rough explanation of LOCI algorithm

Local area in a series of exposures

\[ \begin{align*}
\text{exp 1} & \quad \text{exp 2} & \quad \text{Target exposure} & \quad \text{exp 4} & \quad \text{exp 5} & \quad \text{exp 6} \\
\times_{\text{large}} C_1 & \quad \times_{\text{small}} C_2 & \quad & \quad \times_{\text{small}} C_4 & \quad \times_{\text{small}} C_5 & \quad \times_{\text{large}} C_6 \\
\end{align*} \]

Linear Combination

Target exposure

\[ \begin{align*}
\text{Local Reference PSF} & \quad \text{Result of Local Subtraction} \\
\end{align*} \]

Source: Kandori ‘s slides