POP: Inside the gap with NRM

Alexandra Greenbaum
Johns Hopkins University

Huelamo et al. 2011

Cieza et al. 2012

Andres et al., 2011

LkCa 15 disk

Hd 142527

Kraus & Ireland 2012

T Cha

Fl Cha

11 AU

(76 mas)

50 AU

850 μm

Appendix

Andrea et al., 2011

HD 142527

Biller et al. 2012

The observed morphology of LkCa 15′s candidate companion...
Inside the gap with NRM

NRM – **Non-Redundant mask interferometry**
Splits up the pupil into a set of unique baselines to measure interference fringes

- 0.5 \( \lambda/D \) resolution (\( \sim 30 \) mas in GPI H band)
- **Interferometric technique**, pushes a more aggressive inner working angle

- Probes contrasts down to \( 10^2 \) – \( 10^3 \) @ 5-15 AU scales
- Excellent tool for studying planet formation
Blended Source Confidence: a framework to compare high-spatial resolution techniques

High-resolution image of KOI-1546 obtained with AstraLux at Calar Alto Observatory (Almería, Spain).

Sensitivity curves for the candidate planetary system KOI-0082 obtained with different techniques.

High-resolution follow-up observations of planet candidates are crucial in the confirmation process. An exhaustive analysis of these images is necessary to quantify how they improve the quality of the candidate. The Blended Source Confidence (BSC) parameter provides this quantification and allows comparison between different techniques.
The BSC is an easily computable parameter given the sensitivity curve of a high-resolution image so that different methods can be compared. In Lillo-Box et al. (2014), we have obtained it for the 301 Kepler candidates observed with lucky imaging, improving the probability of being isolated in more than 50% for the 62% of the studied candidates. Comparison to other works show that our optical high-resolution survey combines a large number of observed sources with a high quality of the observations, reflected in the low BSC obtained for most of them.

\[ P_{BS,0} = \int_{0''}^{3''} 2\pi \alpha \rho(b, m_i, \Delta m_{max}) d\alpha = 9\pi \rho(b, m_i, \Delta m_{max}) \]

Density of stars with magnitudes between \( m \) and \( m + \Delta m \) at galactic latitude \( b \)

Now we remove the region where our high-resolution images have not detected any companion from the \( P_{BS,0} \).
Dark Speckle Statistics

See Labeyrie 1995 and Boccaletti et al 1998
The DS Method Requires a Photon Counting Detector

- **Detector:** Microwave Kinetic Inductance Detectors (MKIDS)
- **AO:** PALM-3000 at Palomar 200"
- **Coronagraph:** P1640 and SDC

Reciprocal of the Number of Zero Photon Events in 10,000 Images

- Low Background Counts
- Fast Exposures
- Small Pixels
DARKNESS: A MKID based IFS for high-contrast imaging at Palomar

MICROWAVE KINETIC INDUCTANCE DETECTORS

- Operating principle: photons break Cooper pairs in lithographed superconducting resonator. Broken Cooper pairs -> Inductance shift -> Resonance shift -> Phase shift in readout tone

- Measures individual photon arrival times to few μs and photon energy to ~10%

- Optimized for 0.7-1.4 μm photons for DARKNESS

MECHANICAL DESIGN

- LN2/LHe pre-cooled Adiabatic Demagnetization Refrigerator: Operating temperature = 100 mK

- Dewar fits PHARO envelope for easy integration with Palm-3000 AO system, Project 1640 coronagraph, and Stellar Double Coronagraph (SDC)
DARKNESS: A MKID based IFS for high-contrast imaging at Palomar

SIMULATED PERFORMANCE

- Project 1640 simulated with PROPER
- Includes residual WFE from P3K AO and P1640 optical aberrations
- Energy Resolution --> post processing with Spectral Differential Imaging (SDI)
- Photon Counting --> post processing with Dark Speckle Imaging (DS)

Angular Separation (arcseconds)
STORY OF A NEW METHOD ...

CONTEXT

- PhD
- From September 2009 to December 2012
- Two laboratories ONERA & IPAG

IDEA

- Spectral « deconvolution » [Sparks and Ford, 2002]
- + imaging model [Sauvage et al., 2010]

PEOPLE

A NEW METHOD IS BORN

- Evolutive method:
  - Diverse type of instruments
  - Diverse type of objects (planets, disks, brown dwarfs ...)
  - Detection and characterization
  - Combination of spectral and temporal information possible

- All-in-one method:
  - Joint estimation of aberrations and object of interest: paves the way for calibration by post-processing

- Joint design

A NEW METHOD IS BORN
THE STORY CONTINUES ...

RESULTS

NEW HORIZONS

• Post-doc - Marie Ygouf
  • From September 2014
  • STScI
  • AFTA project

• Second PhD - Faustine Cantalloube
  • From September 2013
  • Two laboratories ONERA & IPAG
  • See Faustine’s POP & Poster

FOR MORE INFORMATION ABOUT..

• The model used
• The criterion we minimize
• Strategies of minimization
• Perspectives
• References

SEE MY POSTER!
A retrieval approach to modeling giant planet spectra

Statia H. Luszcz-Cook¹, M. Ádámkovics², K. de Kleer²

Forward model: a flexible, python-based radiative transfer code

Retrieval: emcee.py — an affine invariant MCMC ensemble sampler by Dan Foreman-Mackey (NYU)

¹AMNH ²UC Berkeley

contact me: shcook@amnh.org
Example retrieval:

Advantages:

• Ability to explore a broad parameter space (e.g. of cloud properties, carbon/oxygen ratio, …)
• Flexibility

Current work: extension to exoplanets

• Greater range of temperatures, pressures, compositions
• Fewer constraints; fewer data points

contact me: shcook@amnh.org
The World’s First Diffraction-Limited Doppler Spectrometer

"Seeing" limited

All Previous Doppler Spectrometers

Diffraction-Limited

iLocater
Revolutionizing the Doppler RV method using Extreme AO

Eric Bechter
University of Notre Dame
MID-INFRARED HIGH-CONTRAST IMAGING OF HD 114174 B: AN APPARENT AGE DISCREPANCY IN A “SIRIUS-LIKE” BINARY SYSTEM

Christopher T. Matthews, Justin R. Crepp, Andrew Skemer, Philip M. Hinz, Alexandros Gianninas, Mukremin Kilic, Michael Skrutskie, Vanessa P. Bailey, Denis Defrere, Jarron Leisenring, Simone Esposito, Alfio Puglisi

HD 114174

LBTI AO, L-band May 24, 2013

<table>
<thead>
<tr>
<th>Object</th>
<th>Method</th>
<th>Age (Gyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 114174 A</td>
<td>Isochronology</td>
<td>4.7^{+2.3}_{-2.6}</td>
</tr>
<tr>
<td>HD 114174 A</td>
<td>Gyrochronology</td>
<td>4.0^{+0.06}_{-0.09}</td>
</tr>
<tr>
<td>HD 114174 B</td>
<td>Hydrogen model</td>
<td>7.77±0.24</td>
</tr>
<tr>
<td>HD 114174 B</td>
<td>Helium model</td>
<td>6.17±0.03</td>
</tr>
</tbody>
</table>

Deepest mid-infrared high-contrast image to date (including extrasolar planets):

Δλ' = 10.15 ± 0.15
ρ = 0.68''

A Diffraction Limited Doppler Spectrometer for the LBT

Andrew Bechter
University of Notre Dame
Sagan Workshop
HiCAT

High-contrast Imager for Complex Aperture Telescopes

HiCAT team:
Mamadou N'Diaye
Elodie Choquet
Sylvain Egron
Laurent Pueyo
Lucie Leboulleux
Olivier Levecq
Marshall D. Perrin
Erin Elliot
J. Kent Wallace
Emmanuel Hugot
Michel Marcos
Marc Ferrari
Chris A. Long
Rachel Anderson
Audrey DiFelice
Rémi Soummer

N’Diiaye et al. 2013, 2014

Status: 12nm rms WFE
HiCAT

High-contrast Imager for Complex Aperture Telescopes

Simulation of a segmented primary mirror

Wavefront sensing on coronagraphic images

Deformable mirrors for wavefront control

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Mamadou N'Diaye
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Rémi Soummer

N'Diaye et al. 2013, 2014

Status: 12nm rms WFE

Russell B. Makidon Optics lab

2014 Sagan Exoplanet Summer Workshop, Pasadena

Elodie Choquet (STScI)
ALICE
Archival Legacy Investigations of Circumstellar Environments

HD 141943, F110W
HD191089, F110W
HD 202917, F110W
HD 30447, F110W
HD 35841, F110W
GJ 3054, F160W

Consistent reprocessing of NICMOS archive:
~ 400 targets, 5600 images, mostly in J and H bands

Large PSF libraries for PCA reprocessing
New disks & companion candidates

Soummer et al. 2014
Choquet et al. 2014

**HST cycle 21:** PI L. Pueyo (WFC3), PI M. Perrin (STIS)
**HST cycle 22:** PI E. Choquet (STIS)

ALICE team:
Elodie Choquet
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John Debes
David Golimovski
Dean C. Hines
Mamadou N'Diaye
Glenn Schneider
Dimitri Mawet
Christian Marois
Rémi Soummer

2014 Sagan Exoplanet Summer Workshop, Pasadena
Image processing for exoplanet detection and characterization

**Method:** Bayesian inverse problem solving

**ANDROMEDA**

**Ingredients:**
- Coronagraphic / saturated images
- Pupil tracking mode
- 1 PSF (unsaturated exposure)

1- ADI based algorithm:

\[ \text{Annulus}(t1) - \gamma \times \text{Annulus}(t2) = \text{Pseudo-annulus} \]

2- Model for the pseudo-image:

\[ \text{Flux} + \text{noise} \]

(unknown)

3- Maximum likelihood:

\[ \text{Likelihood map} \rightarrow \text{Detection + position} \]

\[ \text{Flux map} \rightarrow \text{Flux} \]

4- Comparison to other algorithms

**Beta-Pictoris b**

- **ANDROMEDA**
- **LOCI**
- **PCA**

**Main interest:**
- Thresholding for detection
- Direct flux retrieval
- Speed and accuracy

**See my poster for more nice results!**
Image processing for exoplanet detection and characterization

Method: Bayesian inverse problem solving

Multispectral data

What we know...
- Spectrum star ≠ planet
- Planet's position is still
- Spreading of the speckles

What we want to distinguish...
- Planets: position and spectrum
- Speckle distribution: Aberrations

How I will do that...

→ Joint estimation of object and aberrations
  Start from Marie Ygouf PhD results

→ Preparation for real data application:
  - Refined model of coronagraphic image
  - Introduce field rotation
  - Introduce prior knowledge on planets

→ Application to real data (SPHERE):
  - Improvements, optimization ...
  - Performances assessment
  - Comparison to other algorithms

See Marie Ygouf's poster for more info about the inner method
Stability of Spectral Extractions Utilizing Project 1640 Data and the S4 Pipeline

AAron Veicht
American Museum of Natural History
Columbia University
High-Contrast Imaging and Planet Detection with Project 1640

RAW IMAGE
2040x2040
37,146 spectra

PCXP
90 s/cube

EXTRACTED CUBES (x, y, λ) with size 250 × 250 × 32 (3.8'' × 3.8'', 995-1769 nm)

S4d
~10 hrs

CACS
60 s/cube

DISPERSION CORRECTION Sub-pixel determination of stellar position from grid spots.

Grid-spot tracking

Fitting of centroid path

SPECKLE SUPPRESSION Modeling of speckles using Principal Component Analysis (PCA).
DETECTION MAP
Residuals cross correlated with PSF model

LOCAL S/N MAP
Automated search for significant peaks and extraction of raw spectrum.

SPECTRUM OF PLANET CANDIDATE
PCA modeling and extraction of calibrated spectrum, including noise and stability analysis (see POP by Veicht).

References
Nilsson et al. (in prep.)
Fergus et al. (2014, submitted)
Pueyo et al. (2014, submitted)
Oppenheimer et al. (2014, 2013, 2012)
Zimmerman et al. (2011)
KLIP speckle suppression and spectrum extraction at Project 1640

Jonathan Aguilar (Johns Hopkins University)
Laurent Pueyo (Space Telescope Science Institute)

KLIP: Karhunen-Loeve Image Projection
1) Scale and align slices (1/\( \lambda \))
2) Partition the image into search zones
3) Remove adjacent wavelengths from PSF lib
4) Compute the K-L transform of each zone
5) Reconstruct the zones based on top \( n \) modes
6) Subtract reconstructed zones from the true image to remove speckles
Direct Imaging of HD 19467
with Justin Crepp (Notre Dame) and Emily Rice (CUNY) and the P1640 team
Crepp et al., 2013

Brown dwarf in a high mass-ratio system with both RV trend and NIR colors (Keck)

<table>
<thead>
<tr>
<th>Proj.sep. [AU]</th>
<th>51.1 +/- 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_J$</td>
<td>15.16 +/- 0.12</td>
</tr>
<tr>
<td>$T_{\text{eff}}$ [K]</td>
<td>1050 +/- 40</td>
</tr>
<tr>
<td>Dynamical mass [$M_J$]</td>
<td>$&gt;$51.9 +3.6/-4.6</td>
</tr>
<tr>
<td>Model mass [$M_J$]</td>
<td>56.7 +4.6/-7.2</td>
</tr>
</tbody>
</table>

Project 1640 imaged HD 19467 B with 32 wavelengths

Fitting atmospheric models to the P1640 spectrum

- NIR spec of prob. a T6 dwarf
- If it's 10 Gy old, evolutionary models give $m \sim 52 \ M_J$, right at the dynamical mass limit
- If it's younger... the models are way off

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