SCIENTIFIC GOALS FOR DIRECT IMAGING AND SPECTROSCOPY OF GIANT PLANETS

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Directly Imaged Planetary (or Nearly Planetary) Companions

Lagrange et al. 2008, 2010
Kraus and Ireland 2012
Marois et al. 2008, 2010
Bailey et al. 2013
Chauvin et al. 2017
Macintosh et al. 2015
Rameau et al. 2013
Characterization – Where are we now?

- Spectroscopy / Spectrophotometry
- Rotation / Variability
- Orbital Monitoring / Mass constraints
- Ensemble Properties / Tests of Formation Mechanisms
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Spectroscopy/Spectrophotometry

- Only a handful of directly imaged exoplanets with spectroscopy
- Spectroscopy exists for a larger cohort of free-floating planetary mass objects

Bonnefoy et al. 2016

Wavelength (1-5 μm)
HIP 65426b: a warm, dusty giant planet

Chauvin et al. 2017
51 Eri b: a young Jupiter analogue

GPI/H-band

GPI/J-band

NIRC2/L′-band

\[ \Delta F_1 (10^{-16} \text{W.m}^2) \]

\[ H_2O \quad \text{CH}_4 \quad \text{CH}_4 \quad H_2O \]

2M 1207 b (VLG M8.5-L4)
J162414.37+0029 (field T6.0)

Macintosh et al. 2015

Wavelength (\(\mu\)m)
Colors = Atmospheric Information

Red Colors = Dusty Clouds?

Barman et al. 2011
Explanations of Red Colors

- **Thick silicate clouds** persisting to lower effective temperatures (e.g. Madhusudhan et al. 2011)

- **Non-equilibrium chemistry / vertical mixing** (e.g. Barman et al. 2011, 2015, Zahnle and Marley 2014)

- **Thermochemical instabilities** driving vertical mixing (e.g. Tremblin et al. 2015, 2016, 2017)
In these cloud-free models, thermochemical instabilities produce the observed red colors.
Spectral Retrieval for HR 8799b
Wagner et al. 2016

L Dwarfs
Silicate clouds visible

600-900 K

~1600 K

1100-1300 K
WISE 0855 – an example of a very cool ~250 K atmosphere

Skemer et al. 2016
As this audience certainly knows, we have a small but growing cohort of directly imaged exoplanets. To date, these are young, widely separated super-Jupiter planets, generally with masses > 3 $M_{\text{Jup}}$ and >100 au from their stars. Currently, we can only image them in the IR via their own thermal emission. Longer wavelength observations distinguish better between models.
Direct Access to Silicate Features in the Mid-IR may settle the clouds / no clouds debate

Cushing et al. 2006
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$\beta$ Pic b – a rapid rotator

![Graph showing cross correlation signal, velocity (km/s), and log(planet mass).](image)

Snellen et al. 2014

Beth Biller  April 23, 2018
Young planetary mass objects with measured periods are fast rotators.

Allers et al. 2016
PSO J318.5-22: $8.5\pm0.5 \ M_{\text{Jup}}$

member of the $\sim23 \ \text{Myr} \ \beta \ \text{Pic MG}$ (Liu et al. 2013, Allers et al. 2016)
How to explain this? – different clouds at different heights?

Wavelength (micron)

Pressure Level (bar)

- best fit ExoREM model
- best fit M11 model
- white light
- j
- H
- water
- methane
- Spitzer Ch2

Biller et al. 2018
JWST will enable high-fidelity searches for variability for exoplanet companions
Future prospects for Doppler Imaging

- Limited currently to 1-2 bright brown dwarfs (with 8m class telescopes + high-resolution spectrographs)

- ELT-METIS may enable mapping for a handful of bright exoplanet companions (specifically β Pic b) and also free-floating planetary mass objects like PSO 318.
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Measuring Orbital Motion for Directly Imaged Young Planets

β Pic b
Lagrange et al. 2008, 2010

HR 8799 bcde
Marois et al. 2008, 2010
Figure 1: The marginalized distributions of the orbital parameters of orbital N58 with 16, 50, and 84 percentiles (solid, dashed, and dotted line, respectively).
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Gravitational Instability vs. Core Accretion

Vigan, Bonavita, Biller et al. 2017
This allows us to strongly constrain the fraction of stars that host GI planetary systems.

Wide directly imaged planets likely formed via GI, but GI still only occurs relatively rarely.

Vigan et al. 2017
Predicted contrasts for next-generation imagers, from http://asd.gsfc.nasa.gov/luvoir, adapted from Lawson et al. (2012); Mawet et al. (2012).
JWST and ELTs: sensitivity to warm Saturns and warm Neptunes

WFIRST-AFTA/HabEx/LUVOIR: pushing past the thermal emission / reflected light divide
Next Steps: Towards cooler, closer-in planets:

- **Characterization at longer wavelengths**
  (3-5 μm from the ground, >5 μm with JWST)

- **Characterization at higher resolution**
  probing planet rotation and composition

- **Characterization of a larger cohort of planets**
Direct Imaging of Extrasolar Earths around Nearby M Stars

Crossfield 2013, Guyon et al. 2013
We will learn much more about these worlds in the next few years!

Kraus and Ireland 2012

Lagrange et al. 2008, 2010

Delorme et al. 2013

Ireland et al. 2011

Bowler et al. 2011

Chauvin et al. 2005

Rameau et al. 2013

Carson et al. 2013

Marois et al. 2008, 2010v

Chauvin et al. 2004, 2005

Kalas et al. 2008

Bailey et al. 2013

Todorov et al. 2010