The Planet Formation Imager (PFI) Project

2015 Annual CHARA Gathering

Dr. Gerard van Belle, PFI Kick-off Committee
Lowell Observatory
March 18th, 2015
Project Collaboration

- **Executive team:** John Monnier, Stefan Kraus, David Buscher, Mike Ireland
- **Kick-off committee:** Jean-Philippe Berger, Chris Haniff, Lucas Labadie, Sylvester Lacour, Romain Petrov, Jörg-Uwe Pott, Steve Ridgway, Jean Surdej, Theo ten Brummelaar, Peter Tuthill, Gerard van Belle
- **Science WG coordinators:** Jean-Charles Augereau, Gaspard Duchene, Catherine Espaillat, Sebastian Hönig, Attila Juhasz, Claudia Paladini, Joshua Pepper, Keivan Stassun, Neal Turner, Gautam Vasisht
- **Simulations:** Matthew Bate, Robin Dong, Tim Harries, Barbara Whitney, Zhaohuan Zhu
Exoplanetary systems show surprising diversity.
Exoplanetary systems

Architecture of planetary system determined by...

- Initial conditions of PMS disk
- Planetesimal formation/growth
- Planet-disk interaction (type I/II migration)
- Migration traps (deadzones, disk truncation, ...)
- Planet-planet scattering (resonances, planet ejection, ...)
- Disk evolution and environmental factors
- Scattering with planetesimal disk
- …other unexpected physics?

Dynamical interaction with gas-rich disk
Exoplanetary systems

Giant planet migration

Dynamical instabilities

PFI probes the age range that is most critical for understanding the dynamical evolution of planetary systems

Raymond et al. 2006
Science Case: Planet Formation

- Planet formation is one of the most exciting fields in astronomy, connecting star formation with exoplanets

- **Strong existing momentum** in the field, poised with many advances with ALMA, GPI/SPHERE, ELTs, ...

We expect complexity beyond what ALMA and single apertures can ever resolve

**Complexity requires imaging!**

A dedicated high-angular resolution facility would **fill a gap** in the instrumentation plan for the 2020/30’s (complementing ELTs, JWST, LSST, ...)
Planet Formation Imager (PFI) project

Goal of PFI:

Study the formation process and early dynamical evolution of exoplanetary systems on spatial scales of the Hill sphere of the forming planets

Strategy:

- Formulate the science requirements and identify the key technologies;
- Build support in the science & technology community;
- Prepare for upcoming funding opportunities (OPTICON, decadal review)

The project executives have been elected in February:

Project Director: John Monnier (University of Michigan)
Project Scientist: Stefan Kraus (University of Exeter)
Project Architect: David Buscher (University of Cambridge)

We have formed working groups:

- Science Working Group (SWG):
  Develops and prioritizes key achievable science cases

- Technical Working Group (TWG):
  Conducts concept studies that will allow us to identify the key technologies and to develop a technology roadmap
Radiation hydrodynamics simulations

2 µm
(K-band)

Radiation hydrodynamics simulation
M = 0.5 M☉
inclination = 30°
4 planets of 1 M₉up

NIR dominated by scattered light

Zhaohuan Zhu, Barbara Whitney, Robin Dong
Radiation hydrodynamics simulations

10 μm
(N-band)

Radiation hydrodynamics simulation

M = 0.5 M⊙
inclination = 30°
4 planets of 1 Mjup

MIR dominated by thermal emission of small grains

Zhaohuan Zhu,
Barbara Whitney,
Robin Dong
Radiation hydrodynamics simulations

24 \mu m
(Q-band)

Radiation hydrodynamics simulation
M = 0.5 \, M_\odot
inclination = 30°
4 planets of 1 \, M_{\text{Jup}}

MIR dominated by thermal emission of small grains

Zhaohuan Zhu, Barbara Whitney, Robin Dong
Radiation hydrodynamics simulations

100 $\mu$ m
(FIR, space)

Radiation hydrodynamics simulation

$M = 0.5 M_\odot$

inclination = 30°

4 planets of 1 $M_{\text{Jup}}$

FIR/ sub-mm traces primarily emission from large grains at gap edges

Zhaohuan Zhu, Barbara Whitney, Robin Dong

2015-03-18
Radiation hydrodynamics simulations

400 μm
(sub-mm, ALMA)

Radiation hydrodynamics simulation

M = 0.5 M☉
inclination = 30°
4 planets of 1 M_Jup

FIR/ sub-mm traces primarily emission from large grains at gap edges

Zhaohuan Zhu, Barbara Whitney, Robin Dong
PFI:
Complementarity with ALMA
Objective: Trace small dust grains & detect spatial variations in dust mineralogy 
early stages of grain growth and gap opening, dust filtration

PFI + ALMA: Tracing complementary dust species

Oph IRS48

van der Marel et al. 2013
Objective: Determine distribution of water & ices
\link to habitability

Water on terrestrial planets:
• Planetesimal delivery (Morbidelli et al. 2000)
• Atmospheric capture in the inner disk (Ikoma et al. 2006)
PFI : Protoplanet detection
Objective: Detect young accreting protoplanets

Kraus et al. 2014, Forney et al. 2008

J
H
K
L'
M'

\( \frac{m_p}{m_*} \)

\( m_p = 4 \, M_j \)

Age [Myr]

Kraus & Ireland 2012

MIR likely sweet spot for tracing planets in the most relevant age range (0.1 … 100 Myr)
Resolving the circumplanetary accretion disk

Ayliffe & Bate 2009

Size circumplanetary disk (0.3 \( R_H \)) for Jupiter-mass planet

- at \( r=5.2 \) AU: 0.11 AU = 0.79 mas @ 140 pc
- at \( r=1 \) AU: 0.02 AU = 0.14 mas @ 140 pc
PFI: Architecture of planetary systems
Architecture of planetary systems

Objective: Measure system architecture for a statistically significant sample of systems at different evolutionary stages (e.g. 100 systems @ 0.5 / 5 / 50 Myr)

- Enables direct comparison of the exoplanet population during the PMS and main-sequence phase with population synthesis models
- Reveals the dynamical mechanisms that determine planetary system architecture
- Links the disk properties with the planet properties
PFI: Technology architectures under investigation
Top-Level Science Requirements (Preliminary!)

- Sensitivity to thermal emission for 300K grains \(\Rightarrow\) mid-IR (10 \(\mu m\))
- “Hill-sphere” size region of Jupiter at 1 AU (0.03 AU) in nearby star forming region (140 pc) \(\Rightarrow\) 0.2 milliarcseconds
- 0.2 mas at 10 \(\mu m\) \(\Rightarrow\) requires 10 km baselines
- Sensitivity to see a circumplanetary disk
  - T Tauri star \(N_{mag}=7.5\)
  - Best case circumplanetary disk: \(N_{mag}=11\)
- Also should image exoplanets themselves for <100 Myr clusters to probe dynamical relaxation of giant planet architectures
  - 10 Myr: 1 \(M_{Jup} = N_{mag} \approx 15.7\)
  - 100 Myr: 1 \(M_{Jup} N_{mag} \approx 18.5\)
- Very complex scenes... Like 400x400 pixel imaging
Architecture Overview

- NIR/MIR Conventional Direct Detection Interferometer
- MIR Heterodyne Interferometer
- MIR/FIR Space Interferometer
- ALMA ++
- Coronagraph, Occulter
**Architecture 1: Conventional ground-based interferometer design**

- Mid-infrared key science
- 7 km baselines (>0.4m vacuum pipes)
- 2m minimum telescope diameter for NIR fringe tracking
- Natural guide star AO is sufficient for YSO case
- 8m maximum telescope diameter to maintain at least 0.25” field of view
- N>20 telescopes due to complex imaging
Architecture 1: Sensitivity Considerations

- 4m telescopes with H/K band fringe tracking
- 10s coherent integrations can get to N~7.5
- Compatible with water vapor “seeing”
- 10 hours integration of bispectra can get down to N=15 in principle (detect individual giant planets)
- SWG/TWG will validate SNR model using realistic simulations
Architecture 2: Heterodyne Interferometry

- Charlie Townes’ Infrared Spatial Interferometer (ISI) is a mid-IR interferometer
- Limiting magnitude 500 Jy, Nmag = -2
- BUT… this is largely due to tiny ISI bandwidth ($\lambda/\Delta\lambda = 10,000$)
- Dispersing the light and mixing it with Laser Frequency Combs allows to create thousands of ISI bandwidths ($\Rightarrow$ SNR $\propto \sqrt{N}$) (see Ireland et al. 2014, SPIE)

Advantages
- Higher throughput to detection
- Ideal beam combining which is crucial for complex imaging
- Must still phase up MIR using NIR fringe tracking
- However, it is sufficient to phase up 4-5 nearest neighbors
- Also need 2-4m class telescopes
Architecture 3: Space-Interferometry

- Advantages of space
  - 26 million times less background
    - Cooled 1mm telescope in space has same SNR as 8m on ground…
  - Access to wide range of interesting wavelengths, dust temperatures
- Will require formation flying over >10 km
  - With >10 elements?
- Quite different than DARWIN/TPF-I
  - Incredibly broad science – extragalactic, star formation
  - Great JWST follow-up mission
- Connects with far-IR interferometry groups
  - But they interested in shorter baselines, fewer elements: FISICA, Hyper-FIRI
  - Some shared technology requirements
Architecture 4: ALMA with longer baselines

- Advantage of extending an existing successful facility

- Disadvantages:
  - sensitivity only to large dust grains, cool grains
  - no access to complementary new line tracers

- LLAMA: Long Latin American Millimeter Array
Non-interferometry architectures

- Ground-based Coronagraph
  - Visible 30m extreme AO – 4 milliarcseconds
  - Insufficient resolution for core science…
    but complementary and very exciting!

- Space occulter

  \[ \text{Resolution} \propto \sqrt{\frac{\lambda}{d}} \]

  ➔ Distance between spacecraft and shade: 30AU
  (and 10km shade – use asteroid?)
The PFI Science Working Group (SWG)

Develops and prioritizes key achievable science cases
Lead by PFI Project Scientist: Stefan Kraus

About 100 scientist investigate the following topics:

1. Protoplanetary Disk Structure & Disk Physics (lead by Neal Turner)
2. Planet Formation Signatures in PMS Disks (lead by Attila Juhasz)
3. Protoplanet Detection & Characterisation (lead by Catherine Espaillat)
4. Late Stage of Planetary System Formation (lead by Jean-Charles Augereau)
5. Architecture of Planetary Systems (lead by Joshua Pepper)
6. Planet formation in Multiple Systems (lead by Gaspard Duchene)
7. Star Forming Regions / Target Selection (lead by Keivan Stassun)
8. Secondary Science Cases: Exoplanet-related Science (lead by Gautam Vasisht)
9. Secondary Science Cases: Stellar Astrophysics (lead by Claudia Paladini)
10. Secondary Science Cases: Extragalactic Science (lead by Sebastian Hönig)

Interested scientists are welcome to join \[ \text{www.planetformationimager.org} \]
The PFI Technical Working Group (TWG)

Identifies the key technologies and develops a technology roadmap
Lead by PFI Project Architect: David Buscher

Concept architectures:
1. Visible and NIR interferometry (lead by Romain Petrov)
2. Mid-IR interferometry – direct detection (lead by David Buscher)
3. Mid-IR interferometry – heterodyne (lead by Michael Ireland)
4. Far-IR interferometry (lead by Stephen Rhinehard)
5. mm-wave interferometry (lead by Andrea Isella)
6. Non-interferometric techniques: Occulters, ELTs, Hypertelescopes, …

Technology Roadmap Team:
1. Space-based systems (lead by Gautam Vasisht and Fabien Malbet)
2. Heterodyne systems (lead by Ed Wishnow)
3. Adaptive optics and laser guide stars (lead by Theo ten Brummelaar)
4. Fringe tracking (lead by Antoine Merand)
5. Polarimetry (lead by Karine Perraut and Jean-Baptiste LeBouquin)
6. Telescopes and enclosures (lead by John Monnier and Jörg-Uwe Pott)
7. Beam relay (lead by David Mozurkewich)
8. Delay lines (lead by David Buscher)
9. Beam combination optics (lead by Stefano Minardi)
10. Detectors
11. Nonlinear optics for mid-IR frequency combs
12. Image Reconstruction
Planet Formation Imager (PFI) Concept Studies

Learn more and join us at: [www.planetformationimager.org](http://www.planetformationimager.org)
(Series of SPIE papers can be found in “Resources” section)