Protoplanetary Disk Structure and Planet Formation Signatures resolved with Interferometry

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Part 1: Planet-formation signatures revealed with infrared interferometry

Part 2: The Planet Formation Imager (PFI) project

**PFI project collaborators:**

**Executive team:** John Monnier, David Buscher

**Kick-off committee:** Jean-Philippe Berger, Chris Haniff, Mike Ireland, Lucas Labadie, Sylvestre 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

**Science and Technical WG members**

**Simulations:** Matthew Bate, Robin Dong, Tim Harries, Barbara Whitney, Zhaohuan Zhu
Part 1:
Planet formation signatures revealed with infrared interferometry
Protoplanetary disk structure

- Dust rim
- Planet-forming region

0.1 AU 0.001"
1 AU 0.01"
10 AU 0.1"
100 AU 1" (@100pc)

- 1500 K
- 300 K
- 10 K

- Star
- "Full" disk
Gap-opening mechanisms under discussion:

- photoevaporation
- grain growth
- stellar companions
- planet-disk interaction

Calvet et al. 2002; Espaillat al. 2014
Spatially unresolved techniques face severe limitations:

- Parameter degeneracies
- Planet-disk interaction results in complex / asymmetric structures → **Direct imaging essential**
- Dynamical processes accompanied by changes in dust mineralogy (e.g. dust filtration or dust traps) → **Need to probe multiple grain sizes (=multiple wavelengths)**
Disk structure in transitional disks

(Sub-)millimeter interferometry reveals central density depressions

Casassus et al. 2013

Andersens et al. 2011
IR interferometric studies on transitional disks

V1247 Ori
- Gap 0.2 – 46 AU, partially depleted
- Gap contains optically thin carbonaceous dust

HD100546
- Gap 0.3 – 29 AU, fully depleted
- Companion candidate (Quanz et al. 2013)

T Cha
- Gap 0.1 – 25 AU, fully depleted
- Companion candidate (Huelamo et al. 2011)

TW Hya
- Depleted region <2.5 AU with very large settled grains

Kraus et al. 2013
Benisty et al. 2010
Tatulli et al. 2011
Panic et al. 2012
Mulders et al. 2013
Olofsson et al. 2011, 2013
Eisner et al. 2006
Ratzka et al. 2007
Akeson et al. 2011
Arnold et al. 2012
Menu et al. 2014
V1247 Ori exhibits MIR flux deficit compared to typical protoplanetary disks

→ Indirect evidence for a gapped disk structure

Kraus et al. 2013

Spectral type F0V

$T_{\text{eff}} = 7250 \pm 100$ K

d = 385$ \pm 15$ pc

M = 1.86 $M_{\odot}$

Age = 7.4$ \pm 0.4$ Myr
Gemini/TReCS speckle interferometry yields MIR 2-D power spectra

**Inclination:** $31 \pm 7^\circ$

**PA:** $104 \pm 15^\circ$
V1247 Orionis

Keck/NIRC2
Keck/V2-SPR
VLTI/AMBER
VLTI/MIDI
Gemini/TReCS

Squared Visibility

Spatial Frequency [10^{-6} \lambda]
Scenario 1: Gapped disk

- Model under-predicts MIR size by order of magnitude
Scenario 2: Gapped disk + disk wall

Realistic temperature range for wall @ 22 AU:
90K for grey dust
160K for 0.1μm grains

→ Requires unphysically high wall temperature of 400 K @ 22 AU
Scenario 3: Gapped disk + optically thin gap material

→ Gap filled with optically thin dust
\[ \Sigma_{\text{gap}} = 9 \times 10^{-6} \text{ g/cm}^2 \]

→ Gap material dominates MIR emission

V1247 Orionis
AU-scale asymmetries: Disk inhomogeneities

Keck/NIRC2 aperture masking reveals asymmetries

→ Not consistent with companion scenario

→ Complex density structures in the gap region, possibly due to dynamical interaction with gap-opening planets

Kraus et al. 2013
SAO206462, Garufi et al. 2013
MWC758, Grady et al. 2013
Part 2:
The Planet Formation Imager (PFI) Project

simulations by Dong, Whitney, Zhu, Ayliffe & Bate
Exoplanetary systems show surprising diversity.
Architecture of planetary systems

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

Raymond et al. 2006
The 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 (considering ground & space as well as non-interferometric techniques)
- Build support in the science community & interferometry community
- Start lobbying with decision makers (e.g. NSF, ASTRONET, ESO,...)
- Prepare for upcoming funding opportunities (US decadal review, OPTICON)

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

1-planet simulation (Tim Harries, Matthew Bate)

4-planet simulation (Robin Dong, Barbara Whitney, Zhaohuan Zhu)
Radiation hydrodynamics simulations

2µm (K-band)

Radiation hydrodynamics simulation

$M_\star = 0.5 \, M_\odot$

inclination = 30°

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

**NIR dominated by scattered light**

Zhaohuan Zhu, Barbara Whitney, Robin Dong
Radiation hydrodynamics

10µm
(N-band)

Radiation hydrodynamics simulation

M_★=0.5 M_☉
inclination=30°
4 planets of 1 M_{Jup}

MIR dominated by thermal emission of small grains

Zhaohuan Zhu,
Barbara Whitney,
Robin Dong
Radiation hydrodynamics simulations

24µm (Q-band)

Radiation hydrodynamics simulation
$M_\ast = 0.5 \, M_\odot$
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

100µm (FIR, space)

Radiation hydrodynamics simulation

$M_\star = 0.5 \, M_\odot$

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
Radiation hydrodynamics simulations

400µm (sub-mm, ALMA)

Radiation hydrodynamics simulation
$M_\star = 0.5 \, M_\odot$
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
Resolving planet-induced disk structures

Objective: Image the complex & highly dynamical processes in the innermost AU and study their temporal evolution

Various disks exhibit **quasi-periodic variability on time scales of months**, indicating structural changes in the inner disk

**Spectroscopic variability**
(HD100546)

**Structural variability**
(HD100546)

Panić et al. 2014; Brittain et al. 2013
also: Mosoni et al. 2013
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

van der Marel et al. 2013

PFI+ALMA: Tracing complementary dust species

Oph IRS48
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 &
Planetary system architecture
Detect accreting young protoplanets

Objective: Detect young accreting protoplanets

$m_p = 4 \, M_j$

Forney et al. 2008

$K \text{band}$

LkCa 15

$11 \, AU$

(76 mas)

→ MIR likely sweet spot for tracing planets in the most relevant age range (0.1 ... 100 Myr)

Kraus & Ireland 2012
Resolving the circumplanetary accretion disk

Size circumplanetary disk ($\approx 0.3 R_H$) 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
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

Mordasini et al. 2014
The PFI Science Working Group (SWG)

Develops and prioritizes key achievable science cases

We currently set up working group on 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 ➔ www.planetformationimager.org
PFI: Technology architectures under investigation

Slides from SPIE talk by John Monnier
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 (140pc) \(\rightarrow\) 0.2 milliarcseconds

- 0.2 mas at 10 \(\mu\)m \(\rightarrow\) requires 10 km baselines

- Sensitivity to see a circumplanetary disk
  - T Tauri star \(N_{\text{mag}} = 7.5\)
  - Best case circumplanetary disk: \(N_{\text{mag}} = 11\)

- Also should image exoplanets themselves for <100 Myr clusters to probe dynamical relaxation of giant planet architectures
  - 10Myr: \(1 M_{\text{Jup}} = N_{\text{mag}} \approx 15.7\)
  - 100MYr: \(1 M_{\text{Jup}} N_{\text{mag}} \approx 18.5\)

- Very complex scenes... Like 400x400 pixel imaging
Architecture Overview

1. NIR/MIR Conventional Direct Detection Interferometer
2. MIR Heterodyne Interferometer
3. MIR/FIR Space Interferometer
4. ALMA ++
5. Coronagraph, Occulter
Architecture 1:
Conventional ground-based interferometer design

- Basics
  - 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: Conventional ground-based interferometer design

- 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, \( N_{mag} = -2 \)
  – 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 \( \rightarrow \text{SNR} \propto \sqrt{N} \)
  (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 – worth a second look
  - 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
  - Resolution $\propto \sqrt{\frac{\lambda}{d}}$
    ➔ Distance between spacecraft and shade: 30AU
      (and 10km shade – use asteroid?)
The PFI Technical Working Group (TWG)

Identifies the key technologies and develops a technology roadmap

**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

Interested scientists are welcome to join ➔ www.planetformationimager.org
Learn more and join us at: www.planetformationimager.org
(Series of SPIE papers can be found in the "Resources" section)