Setting the Stage for The Planet Formation Imager

John D. Monnier, Stefan Kraus, Michael J. Ireland,
and the PFI Technical and Science Working Groups

Abstract

An international group of scientists has begun planning for the Planet Formation Imager (PFI, www.planetformationimager.org), a next-generation infrared interferometer array with the primary goal of imaging the active phases of planet formation in nearby star forming regions and to take planetary system "snapshots" of young systems to understand exoplanet architectures. PFI will be sensitive to warm dust emission using mid-infrared capabilities made possible by precise fringe tracking in the near-infrared. An L/M band beam combiner will be especially sensitive to thermal emission from young exoplanets (and their disks) with a high spectral resolution mode to probe the kinematics of CO and H_2O gas. In this brief White Paper, we summarize the main science goals of PFI, define a baseline PFI architecture that can achieve those goals, and identify remaining technical challenges. We suggest activities that NOAO might support through further developments over the next decade at the flagship US facilities (NPOI, CHARA, MROI) that will help make the Planet Formation Imager facility a reality.

1 Science Goals of PFI

The Planet Formation Imager (PFI) Project [10, 6, 4] was started in 2013 to radically advance the field of planet formation, to image the sub-au spatial scales sufficient to resolve disk gaps cleared by single planets, to detect accretion streams, and to follow the dust and gas all the way down to scales of individual exoplanet Hill Spheres, where disk material is accreted onto young planets themselves. We introduce the PFI science goals by looking at a radiative transfer image of a planet-forming disk in the thermal infrared (see Figure 1). The protoplanetary disk is approximately 100 au across, with gaps and structures on the scale of ∼5 au. We expect a circumplanetary disk to form on scales of 0.03 au, matching the Hill Sphere for each accreting protoplanet (for a Jupiter-mass planet on a 5 au radius orbit). The mid-IR wavelength range efficiently traces emission from small grains from 0.1-10 au in the disk, complementing mm-wave/radio observations of the large grains. In the mid-IR, probing scales of 0.1 au at the distance of even the nearest star forming regions is far beyond the capabilities of a single telescope and we explore potential of an infrared interferometer with kilometric baselines.

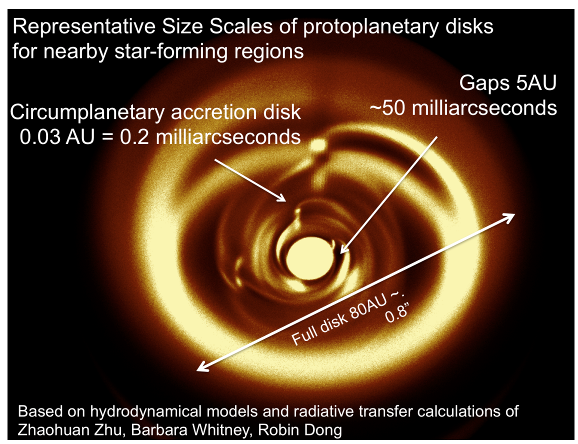

Figure 1: Radiative transfer model for an example planet-forming disk [10, 3] with the relevant size scales marked. The primary science driver of the Planet Formation Imager (PFI) is to image scales as large as the whole circumstellar accretion disk down to the circumplanetary accretion disks of individual giant planets.

Having reviewed the typical characteristics of key science targets, we summarize the PFI top-level science requirements in Table 1. There are hundreds of young stellar objects with disks that satisfy these requirements within 200 pc and thousands if we move out to the distance of Orion. In the next section, we propose a specific facility architecture that can achieve most of the top level science requirements at the cost of a typical major astronomical facility.

For the stars in this sample, PFI will be able to detect planets at all stellocentric radii, providing a complete census of the exoplanet population (down to a certain mass limit). The objects in this sample cover a wide range of evolutionary stages, from the pre-main-sequence (∼ 0.1 Myr), transitional disk (∼ 10 Myr), to the debris disk phase (∼ 100 Myr). It is expected that planetary systems undergo

Table 1: Top-level Science Requirements (Minimum Goals)

Parameter	Dust Imaging	Young Exoplanets
Wavelengths	5-13 μm	3-5 μm
Typical Source Distance	140 pc	50-500 pc
Spatial Resolution	2 mas $\equiv$ 0.3 AU	0.7 mas $\equiv$ 0.1 AU
Sensitivity	Integrated $m_N \sim 7$	$m_L \sim 18.5$ (Point source @5σ)
Goal Surface Brightness (K)	150 K	$--$
Spectral Resolving Power	R$>$ 100	R$>$ 100 and R$>$ 10^5 (spectroscopy)
Field-of-view	$>$ 0.15"	$>$ 0.15"
Fringe tracking limit	$m_H > 9$	$m_H > 9$
Fringe tracking star	$\phi < 0.15$ mas	$\phi < 0.15$ mas

dramatic changes during this age range, with planets forming in the outer disk and then migrating inwards and outwards due to planet-disk interaction, and planets being rearranged or ejected due to resonances and planet-planet scattering [13]. By observing planetary systems at different evolutionary stages, PFI will be able to observe directly how these processes alter the exoplanet populations with time. This will provide much-needed input for constraining exoplanet population synthesis models and unveil the dynamical processes that determine the architecture of exoplanetary systems and that shaped also our own solar system.

The Science Working Group is also very interested in science cases beyond planet formation. Imaging dust tori around Active Galactic Nuclei, stellar orbits around the Galactic Center, AGB stars mass-loss, diameters of young stars themselves, magnetic spots on main sequence stars, and more are all possible with PFI – but the baseline design is focused on the planet formation case to define the required facility architecture.

2 Technical Description of the PFI Array

After the 2014 SPIE meeting where the PFI project was introduced, a Science Working Group (SWG; headed by Stefan Kraus) and a Technical Working Group (TWG; headed first by David Buscher, and now Michael Ireland) were formed involving around one hundred astronomers around the world. Based on the early top-level science requirements first outlined in 2014, the 2016 SPIE meeting in Edinburgh saw even more contributions which explored technical solutions to achieve these science goals [9, 7, 5, 8, 11, 1, 12].

The infrared surface brightness sensitivity for PFI is mostly determined by the size of the individual apertures and not the number of telescopes – this pushes the design towards large-area unit telescopes which drives the cost. A simple cost model was introduced by Ireland et al. [5] which informed the baseline architecture described now where fewer large telescopes were preferred over many more small apertures (at fixed cost).

In order to achieve the minimum top-level science requirements and still cost less than $250M, **PFI consists of twelve 3-m class telescopes arranged in either a "Y-array" or "ring array" with maximum baselines of 1.2 km.** With this geometry, fringe tracking down to $H = 14$mag can be done using the shorter spanning baselines while the longest baselines provide an angular resolution of 0.6 / 1.7 milliarcsecond resolution at L band (3.5μm) / N band (10μ), which corresponds to spatial resolution of 0.08 au / 0.25 au at 140 pc. The L/M band angular resolution and a high spectral resolution mode should allow spectro-astrometric detection of CO/H_2O gas kinematics in circumplanetary disks when bright enough. Reliable calculations of the molecular gas emission are not yet available and are being pursued by our Science Working Group to evaluate this science goal more soberly.

The Science Working Group determined that a mid-latitude site is near-essential for PFI due to the limited number of star-forming regions observable from high-latitude sites, which removes the High Antarctic Plateau from consideration. The PFI Project has identified the Flagstaff (Arizona, USA) Navy Precision Optical Interferometer (NPOI) site and the ALMA site (Chajnantor Plateau, Chile) as locations with sufficient accessible area and existing infrastructure to merit further consideration.

3 Setting the Stage for PFI

The PFI Technical Working Group has identified key technologies needed to lower technical and financial risk before a facility is constructed – see Table 2. We highlight that much of this work, such as telescope and combiner technologies, can be incrementally funded and tested at the existing powerful US-based interferometers: NPOI, CHARA, and (soon) MROI.

Table 2: PFI Technology Roadmap: Opportunities to use NPOI, CHARA, and MROI facilities as testbeds

Critical Technology	Considerations
Inexpensive telescopes	Explore new technologies Lightweight structures with exquisite AO **Partner with industry, engineers** **Test with existing arrays**
L/M band IO combiners	Needed for high precision calibration, **Chalcogenide integrated optics on-sky**
Mid-IR laser comb (heterodyne)	Possible "add-on" to L/M band **Develop mid-IR combs, detectors, ...**
Low-cost operations model	**New array of limited scope,** **e.g., pathfinder SMILES array**

The most crucial technical advance needed to make PFI both supremely powerful and affordable is less-expensive medium-aperture telescopes. Multiple concepts are being explored, including spherical primaries, carbon-fiber reinforced polymers for mirror replication and/or for lightweight supports, and more. Such narrow-field, AO-corrected telescopes would also be useful for upcoming RV surveys of bright stars searching for exo-Earths. Natural allies for this technical development include governments interested in imaging geostationary satellites and telecommunication companies interested in narrow-field, diffraction-limited applications such as laser communication (to/from space or ground stations). Work is ongoing in Chile (Valparaiso), USA (Flagstaff, Michigan), and Australia (Canberra) to seek funding and new partnerships. For instance, a spherical primary with a highly-aspheric Gregorian secondary produces a Gaussian-like apodization of the pupil with diffraction-limited performance over a small field-of-view [10, 5].

PFI should also seek to operate in a stream-lined, efficient, and low-cost manner. The Palomar Testbed Interferometer (PTI) [2] was a famously efficient system which collected data on thousands of objects over many years with a low operations budget. PFI should be considering operations modelling as planning moves towards a Phase A study.

A new interferometric array of limited scope could be a powerful vehicle to debut the core technologies needed to build the full PFI. For instance, a 3-telescope array using new 3-5 m class telescopes with kilometric baselines could test the new "cheap telescopes" in practice, test kilometer-length delay line technology, validate high-throughput beam train design, commission a high-sensitivity fringe tracker, and adopt a low-cost operations model. Such an instrument could survey 10000+ binary systems with astrometric and RV orbits from GAIA and other large scale surveys. By resolving these binaries with an interferometer at even a single epoch, masses can be determined for all components, unlocking powerful avenues to probe stellar structure and evolution with powerful application to Galactic archeology. Such a facility – Stellar Multiplicity Interferometer Large Experimental Survey (SMILES) – could be a powerful achievable goal during the next decade. Further, if built at a location compatible with the full PFI, some of the SMILES infrastructure could potentially become part of PFI.

4 Conclusion

The Planet Formation Imager Project has spent the last 4 years defining realistic science goals and defining a practical facility to achieve them. Actually imaging the major stages of planet formation – *as they are happening live* – is a realizable dream using today's infrared interferometric technologies. New technologies could lower the cost of PFI and make the capabilities even more powerful over the next decade. In addition to purely technological development, we have also identified pathfinder instruments and a possible new limited-scope facility that can yield exciting short/medium-term science while laying the groundwork for the ambitious PFI facility at the end of the next decade.

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