Astro2020 APC White Papers

Setting the Stage for the Planet Formation Imager

Type of Activity: ⊠ Ground Based Project   ☐ Space Based Project
☐ Infrastructure Activity   ⊠ Technological Development Activity
☐ State of the Profession Consideration   ☐ Other _____

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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 taking 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 circumplanetary 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 key technical challenges that must be overcome before the dreams of PFI can be realized within the typical cost envelope of a major observatory. We also suggest activities over the next decade at the flagship US facilities (CHARA, NPOI, MROI) that will help make the Planet Formation Imager facility a reality. **The key takeaway is that infrared interferometry will require new experimental telescope designs that can scale to 8 m-class with the potential to reduce per area costs by $\times 10$, a breakthrough that would also drive major advances across astronomy.**

Key Science Goals and Objectives:

The Planet Formation Imager (PFI) Project (Monnier et al., 2014; Kraus et al., 2014; Ireland and Monnier, 2014) 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 80 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 proto-

Representative Size Scales of protoplanetary disks for nearby star-forming regions

Circumplanetary accretion disk
0.03 AU = 0.2 milliarcseconds

Gaps 5AU
~50 milliarcseconds

Full disk 80AU ~ 0.8"

Based on hydrodynamical models and radiative transfer calculations of Zhaohuan Zhu, Barbara Whitney, Robin Dong
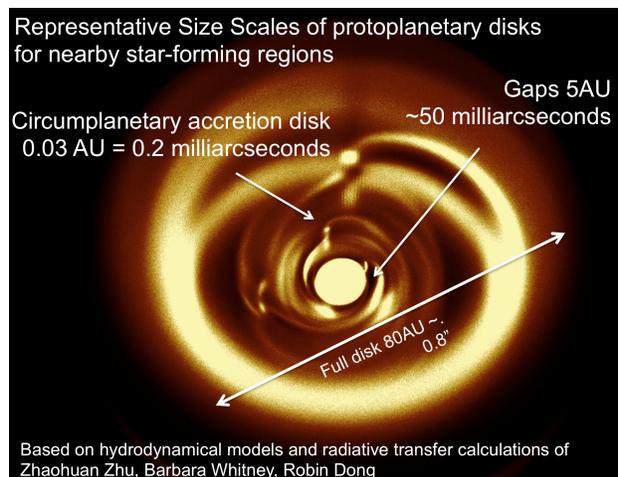
Figure 1: Radiative transfer model for an example planet-forming disk (Monnier et al., 2014; Dong et al., 2015) with the relevant size scales marked. The primary science driver of the Planet Formation Imager (PFI) is to image scales as large as the whole circumstellar accretion disk down to the circumplanetary accretion disks of individual giant planets.

planet (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 requires an infrared interferometer with kilometric baselines.*

Based on the science case for PFI (presented in ASTRO2020 Science White Papers and in the literature), we summarize the PFI top-level science requirements in Table 1. There are hundreds of

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

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 meet these 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 massive 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 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 (Raymond et al., 2006). 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.

With sub-milliarcsecond angular resolution and ground-breaking sensitivity, PFI will also image dust tori around Active Galactic Nuclei, AGB star mass-loss, magnetic spots on main sequence stars, trace stellar orbits around the Galactic Center, measure diameters of young stars themselves, and more. *Additional information on the capabilities of the Planet Formation Imager can be found in a recent paper in* Experimental Astronomy *(Monnier et al., 2018b) and in two submitted AS-TRO2020 White Papers: "Imaging the Key Stages of Planet Formation" (lead: Monnier) and "The Future of Exoplanet Direct Detection" (lead: Monnier).*

Technical Overview:

Members of the PFI Technical Working Group have studied how to best achieve the PFI top-level science requirements (see Table 1) and have presented their work in various SPIE papers (Monnier et al., 2014; Ireland and Monnier, 2014; Monnier et al., 2016; Kraus et al., 2016; Ireland et al., 2016b; Minardi et al., 2016; Mozurkewich et al., 2016; Besser et al., 2016; Petrov et al., 2016; Monnier et al., 2018b,a; Ireland et al., 2018; Zúñiga-Fernández et al., 2018; Defrère et al., 2018b; Quanz et al., 2018; Pedretti et al., 2018; Besser et al., 2018; Michael and Besser, 2018; Tristram and Hönig, 2018). Here we give an overview of our current conclusions regarding the optimal PFI telescope array architectures.

Table 2: Technical Description of Reference PFI Architectures

Parameter	12×3 m PFI	12×8 m PFI
Number of Telescopes	12	12
Telescope Diameter	3 m	8 m
Maximum Baseline	1.2 km	1.2 km
Goal Science Wavelengths	3–13 μm	3–13 μm
Fringe-tracking wavelengths	1.5–2.4 μm	1.5–2.4 μm
Fringe tracking limits (point source)	$m_H <$13	$m_H <$15 (AO-dependent)
Point source Sensitivity (10^4 s integration)	18.1 (L), 12.2 (N)	20.2 (L), 14.3 (N)
Surface Brightness Limit (10^4 s, $B = 1.2$ km)	150 K (N)	125 K (N)
Field-of-view	0.25" (L), 0.7" (N)	0.09" (L), 0.25" (N)
Note	w/ Nulling (2-4 μm)	w/ Nulling (2-4 μm)
Cost estimate*	$250M	$600M**

* Interferometry cost model is site-dependent and generally highly uncertain; assumptions were presented originally by Ireland et al. (2016a) and updated by Monnier et al. (2018b).
** This informal cost estimate is actually for 12×6.5m telescopes, assuming roughly x2 cost reduction from mass-production efficiencies of an existing telescope design (Kingsley et al., 2018).

Ireland et al. (2016b) laid out the basic SNR equations for PFI used in our limiting magnitudes and sensitivity calculations. For background-limited observations (i.e., not limited by systematics or nulling performance), a simplified version of the SNR equation for point source detection is:

$$\text{SNR}_{\text{pt}} \propto \frac{\sqrt{N_t} D^2 \sqrt{t}}{\sqrt{B(T)}}, \tag{1}$$

where N_t is the number of telescopes, D is the telescope diameter, $B(T)$ is the background emissivity (if thermal, T is temperature). Notice that the noise level is independent of the telescope size in the background limit since a diffraction-limited system has constant étendue ($\Delta\Omega A \sim \lambda^2$).

Based on equation (1), the facility sensitivity grows steeply with aperture diameter ($\propto D^2$) and only weakly with number of telescopes ($\propto \sqrt{N_t}$). As a dramatic real-world example, the 4×8 m telescopes of the ESO/VLTI UT array has the same background-limited sensitivity for point source detection as an array of 200×3 m telescopes! Note that this conclusion is subject to some assumptions, as some novel beam combiners (e.g., densified pupil; Pedretti et al., 2000) can recover the SNR$\propto N_t$ scaling under certain conditions. Furthermore, the angular resolution and capability to do nulling depends on the geometry of the array and so an array of many 3 m telescopes with long baselines designed for nulling will have superior capabilities in some ways than a 4×8 m array with shorter baselines. *Regardless of details, one sees that it is critical to push for large apertures for sensitivity and that it is not generally cost-effective to try to compensate aperture with more telescopes.*

One other issue to consider in designing an array is the surface brightness limit for mid-infrared observations. Since the blackbody function peaks in the mid-IR for $T = 300$ K, we recognize that observing dust much cooler than this in young stellar objects will be fighting the exponential

Imaging young giant exoplanets can be done with a PFI 12x3m telescope array...
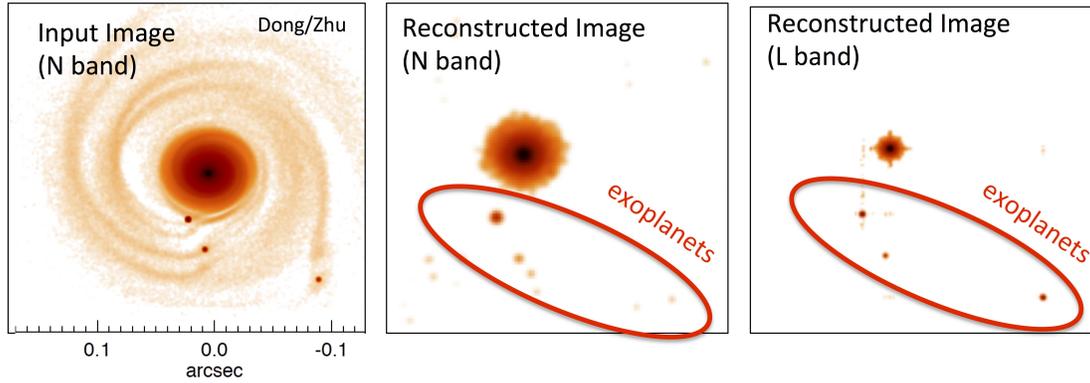
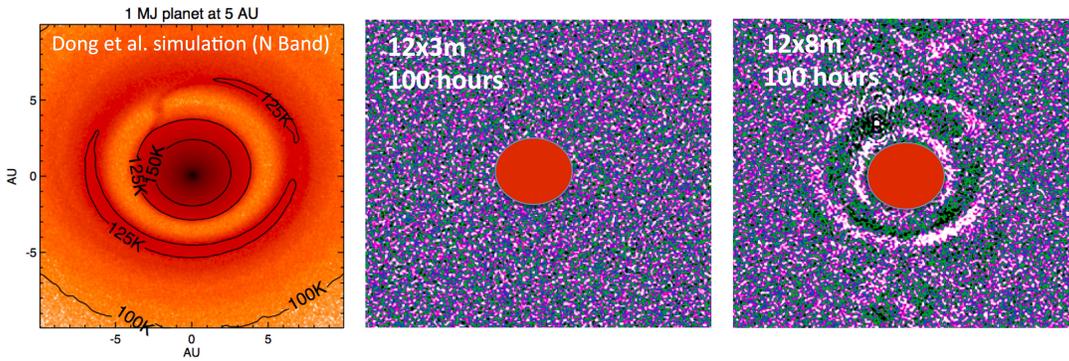... but imaging a gap caused by Jupiter analogue requires PFI 12x8m telescope array

Figure 2: The PFI Science and Technical Working Groups have simulated performance for both 12x3 m and 12x8 m PFI architectures. (top row) Monnier et al. (2016) demonstrated that an equivalent 12x3 m PFI (in 25 hours) can detect young giant exoplanets at both L and N bands ("hot start" models shown here) but cannot see the warm dust in this 4-planet simulation by Dong et al. (2015). (bottom row) Monnier et al. (2018b) found that a 12x8 m PFI array would be able to image gap formation in solar analogues found in nearby star forming regions, a stunning capability bringing ALMA-like performance to the inner solar system where terrestrial planets form.

Wien's tail of the Planck function. Quantitatively, emission at $T = 150\,\mathrm{K}$ is $\sim 1\%$ of the emission at $T = 300K$ in the mid-IR. Indeed, going further to $T = 125\,\mathrm{K}$ is another factor of 7 in flux. Based on this physics, it is not practical to observe thermal emission of dust much below $T < 125\,\mathrm{K}$ in the mid-infrared at high angular resolution, especially from the ground. Fortunately, the water iceline occurs at T$\sim 150\,\mathrm{K}$, opening up observing opportunities for PFI.

Here we motivate the facility characteristics adopted for our PFI reference architectures:

- 1.2 km maximum baseline chosen to attain 0.2 au mid-IR resolution at 140 pc: a) to resolve a planet-opened gap from a Jupiter at 1 au, b) to resolve diameters of circumplanetary disks for exo-Jupiter ($1\,\mathrm{M}_J$ @ 5 au)

- $12 \times 3\,\mathrm{m}$ diameter array chosen to have $T = 150\,\mathrm{K}$ surface brightness (3-σ) in 10,000 s: Sensitivity to dust at $T = 150\,\mathrm{K}$, the temperature for the water iceline for typical disks

- $12 \times 8\,\mathrm{m}$ diameter array chosen for enhanced surface brightness limit ($T = 125\,\mathrm{K}$) to see gaps and dust structures for giant planets forming as far out as 5 au, and an enhanced exoplanet yield.

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- Sufficient point source sensitivity to detect young giant exoplanets for a range of models.

- Sufficient fringe tracking margin (H band magnitude limit at least 13) to observe solar-type stars in nearby star forming regions.

Table 2 contains information on two reference facility architectures for PFI, one is a 12×3 m array and the other a 12×8 m array. Figure 2 shows examples of the science capabilities of the arrays. The main difference is a factor of 7 in sensitivity that is crucial for imaging warm dust at 5 au and for a more complete census of giant planets in young disks. During the PFI Community Meeting held during the 2018 SPIE meeting, a straw poll of those in attendance overwhelmingly favored pursuing the 12×8 m architecture over the 12×3 m version based on the increased science capabilities.

Note that the PFI 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.

Technology Drivers:

The PFI Technical Working Group has developed a Technology Roadmap containing technologies identified as strategic and key investments for PFI (see Table 3). We will focus on a few of the most important technology areas next while we refer the interested reader to the recent SPIE summary by Monnier et al. (2018a) for more details.

Technology Driver 1: Inexpensive Telescopes

The most crucial technical advance needed to make PFI both supremely powerful and affordable is less-expensive large-aperture telescopes. The cost of "traditional" telescopes scale as $D^{2.5}$ (van Belle et al., 2004) – roughly $5M for a 2 m aperture, $\sim$$40M for a 4 m aperture – thus, an array of a dozen or more large telescopes rapidly becomes cost-prohibitive. A goal of the PFI Technology Program is to attain an order-of-magnitude cost reductions in telescope construction.
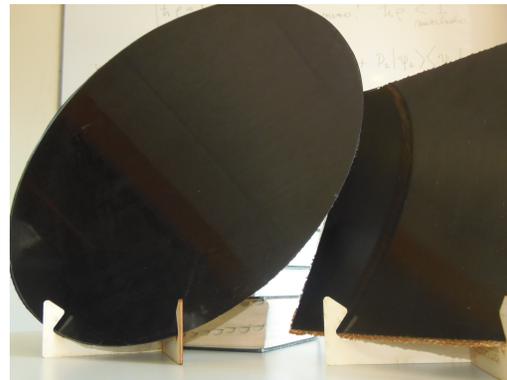

Figure 3: New technologies to allow mass-production of inexpensive 8 m class telescopes are essential for the viability of the PFI project long-term. Here we see 0.5m spherical curvature carbon fiber prototypes made from a stainless steel mandrel under fabrication in Chile (Zúñiga-Fernández et al., 2018). Credit: Amelia Bayo

There are three key concepts that drive our optimism that such a breakthrough is possible:

1. Advances in lightweight and new "smart" materials

2. Integration of "active" and "adaptive" optics systems into telescope architecture, enabling imaging within a narrow field-of-view on an intrinsically "floppy" structure

3. Replication savings from mass-production

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Table 3: PFI Technology Roadmap

Critical Technology	Considerations

Inexpensive telescopes	Possible key technologies:
	    Replicated parabolic or spherical mirrors,
	    lightweight structures with AO correction
	Partner with industry, engineers
	New telescopes for existing arrays (CHARA,NPOI,MROI)

L/M band Integrated Optics combiners	Needed for high precision calibration, Explore Chalcogenide integrated optics. **Pilot nulling instruments with VLTI/Hi-5 or MROI**
Wavelength-bootstrapped fringe tracking	L band imaging require 10^6:1 dynamic range imaging, ultra-accurate fringe tracking in L based on H-band, **VLTI/GRA4MAT mode** **New "high sensitivity" fringe tracker (e.g., VLTI/Heimdallr)**
Mid-IR laser comb heterodyne	Possible "add-on" to L/M band **Develop combs, detectors, digital processing**
Low-cost operations model	Demonstrate as part of new 3-telescope Array **e.g., *Gaia*/TESS follow-up interferometer (3x3m)**
Space interferometry	Longer-term future for high sensitivity Demonstrate formation flying with Cubesats **Support new formation flying missions using smallSats**

Multiple concepts are being explored that take advantage of these principles, including spherical primaries, carbon-fiber reinforced polymers for mirror replication and/or for lightweight supports, slumped glass, 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 (see Figure 3 and Zúñiga-Fernández et al., 2018), USA (Lowell Observatory & U. Michigan), and Australia (ANU) 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 (Monnier et al., 2014; Ireland et al., 2016b). In addition, there could be significant cost reductions even using today's technology through mass production (Kingsley et al., 2018) of proven designs, such as the MMT or Magellan telescopes.

Technology Driver 2: Focus on instruments and intermediate facilities

Over the past two years, a few new proposals for instruments and facilities have been developed that could act as pathfinders for PFI. Nulling interferometry is needed for detection of exoplanets with PFI at short wavelengths and the Hi-5 project is a science-driven international initiative to develop a new VLTI instrument optimized for high dynamic range observations (Defrère et al.,

2018a). Reaching 1:10,000 or higher dynamic range in the thermal near-infrared (L and M bands) would be extremely valuable to directly detect forming and young giant exoplanets. Nulling interferometry on the ground also requires advances in highly-accurate fringe tracking and VLTI could demonstrate this with the proposed Heimdallr instrument (PI: Ireland). While no comparable instruments have been proposed yet for US facilities, an L/M band nulling instrument could potentially be interesting at MROI using 4 telescopes before the full 10-telescope array is available.

MATISSE is a L/M/N band 4-telescope combiner for VLTI that was just commissioned (Lopez et al., 2018). MATISSE should be able to be used with GRAVITY in fringe-tracking mode (GRA4MAT) and reach very high sensitivity, although with much lower angular resolution than PFI. While VLTI has relatively short baselines (120 m instead of 1200 m needed for PFI), the sensitivity of 4x8 m telescopes is unrivaled – this "mini-PFI" could be an amazing testbed for future PFI technology developments and science instruments. The PFI Project strongly advocates developing the VLTI-UT interferometric capabilities during the 2020s, ideally with involvement from USA astronomers.

Technology Driver 3: Gaia/TESS follow-up with a new 3×3 m facility with 1 km baselines

While exoplanet science and thermal dust imaging of cool dust requires large aperture telescopes, a small array of 3×3 m telescopes with ~1 km baselines could test key PFI technologies such as cheap telescopes, long delay lines, and low-budget operations model while achieving impressive science goals. In particular, *Gaia* and TESS will identify millions of nearby binary stars and red giants that need additional data. By measuring the separation of *Gaia* binaries with photocenter orbits, a 3×3 m interferometer would measure thousands of new masses for a wide range of stars in the solar neighborhood. Furthermore, diameters of TESS red giants with asteroseismic radii from precision photometry will allow independent calibration of this key technique.

To illustrate this, we have estimated source counts using the Casagrande simulation (Ireland et al., in prep.), applying the following se-
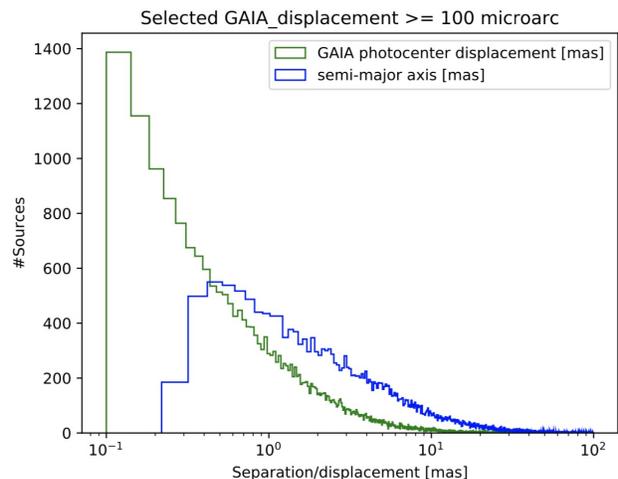

Figure 4: Using a Galactic structure simulation, we can estimate the binary properties detected by *Gaia*. From this, we can estimate the angular resolution needed for a ground-based interferometer to resolve these systems – thus providing absolute masses for both components. We see there are *tens of thousands* of objects that can by resolved even with current facilities (Ireland et al., in prep).

lection criteria: (1) period < 10 years, (2) $R < 15$ mag (apparent magnitude), (3) *Gaia* photocenter displacement > 100 microarcsec (i.e. SNR≈ 10 detection of photocenter displacement). In total, there are 27,464 sources that match these criteria and 26,332 have semi-major axis > 0.5 mas (i.e. in range of current CHARA and VLTI facilities). A new VLTI instrument, BIFROST, operating at $1\,\mu$m is being proposed (Kraus, Ireland) to observe the wider *Gaia* binaries. A new facility with kilometric baselines will resolve additional binaries at smaller separations and permit robust effective temperature calibrations across the HR diagram, including stars with very low metallicity.

Technology Driver 4: Space Interferometry

Lastly, space interferometry has the potential to extend "PFI science" to the low-mass (possibly Earth-mass) planetary mass regime. In addition, through cooled apertures, "Space-PFI" has the potential to fully explore the 5–20 au regime where disk gaps remain resolution-limited for ALMA and sensitivity-limited for a ground-based PFI. The PFI project strongly supports taking some steps in the next few years to explore Cubesat formation flying missions, to launch a low-cost space interferometer demonstration, and to participate in NASA/ESA planning processes to explore the massive advantages of developing interferometric space capabilities for missions from far-infrared to x-rays. *There will be other ASTRO2020 Technical White Papers on this topic "A Realistic Roadmap to Formation Flying Space Interferometer" (Lead: Monnier) and "A Long-Term Vision for Space-Based Interferometry" (Lead: Rinehart).*

Organization, Partnerships, and Current Status:

The Planet Formation Imager Project is international with various collaborations already formed to work on PFI technology. In the context of the USA ASTRO2020 Decadal Survey, we emphasize that US-led projects can take advantage of the longest interferometer baselines in the world at CHARA, NPOI, and MROI, and these facilities have pioneered many new technologies, from new telescope designs to new beam combiners to new delay line designs.

Schedule:

As we are proposing technology development, we do not advocate a detailed timeline for construction of the Planet Formation Imager (PFI) as a full facility. The most critical advance required for PFI is less expensive 5+m apertures. As a goal for this decade, we would like to see inexpensive 3 m-class telescopes ($< \$2M$ each) built from technologies traceable up to 8 m class. This kind of order-of-magnitude reduction in cost would make PFI a competitive project for ASTRO2030.

A medium-scale project this decade to build a 3x3 m telescope facility with kilometric baselines would tackle *Gaia*/TESS follow-up science while simultaneously demonstrating key aspects of PFI – inexpensive telescopes, kilometric baseline beam combination, and low-cost operations.

Cost Estimates:

Many technologies for PFI can be developed through normal NSF programs. However, developing new telescope technologies will require close academic-industry ties, requiring larger than usual budgets involving skilled engineers. $10M would allow serious prototyping of one or two different design concepts at the 1 m class with a goal of selecting a technology concept for a 3 m diameter demonstrator at the end of the decade. We note again that other areas of astronomy would benefit from inexpensive 3 m class diffraction-limited, narrow-field telescopes, such as next-generation ambitious exoplanet RV surveys.

The cost of a new facility with 3x3 m telescopes with kilometric baselines depends on many factors. Adding telescopes to existing facilities is one possibility though geographical site limitations and limited delay line lengths pose serious issues for all current facilities. Our cost model (Ireland et al., 2016a) for a new facility includes: 3 delay lines ($2.5M), 3 AO systems ($3.4M), beam combiners ($6M), other infrastructure ($1M), and 3x3 m telescopes (cost from $6M to $26M, depending on cost model). With 10% management and 20% contingency, we arrive at a facility cost estimate ranging from $25M to $50M, with up to half the cost in telescopes alone if no breakthroughs in telescope costs can be achieved this decade. Such a project would benefit from international partnerships to share cost.

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