Thirty Meter Telescope Planet Formation Instrument[1]

B. Martin Levine[ac], Michael Shao[ac], Bruce Macintosh[ab], Mitchell Troy[ac], Rene Doyon[d], James Graham[ae], Kevin Baker[ab], Brian Bauman[ab], Christian Marois[ab], David Palmer[ab], Donald Phillion[ab], Lisa Poyneer[ab], Ian Crossfield[ac], Philip Dumont[ac], Gene Serabyn[ac], Chris Shelton[ac], Gautam Vasisht[ac], James K Wallace[ac], Jean-Francois Lavigne[d], Philippe Valee[d], Neil Rowlands[f], Ken Tam[f], and Daniel Hackett[f]

[a]NSF Center for Adaptive Optics
[b]Lawrence Livermore National Laboratory, 7000 East Ave., Livermore, CA 94551
[c]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109
[d]Universite de Montreal, Department de Physique, Montreal, QC, H3C 3J7, Canada
[e]Department of Astronomy, University of California at Berkeley, Berkeley, CA 94720
[f]Space Science Group, COM DEV, Suite 100, 303 Terry Fox Dr., Ottawa, ON, K2K 3J1, Canada

INTRODUCTION

Direct detection of extrasolar Jovian planets is a major scientific motivation for the construction of future extremely large telescopes such as the Thirty Meter Telescope (TMT). The instrument must be designed to meet specific scientific needs rather than a simple metric such as maximum Strehl ratio. The Planet Formation Imager (PFI) for TMT is a design for such an instrument. It has four key science missions: The first is the study of newly-formed planets on 5–10 AU scales in regions such as Taurus and Ophiucus—this requires very small inner working distances that are only possible with a 30 m or larger telescope. The second is a robust census of extrasolar giant planets orbiting mature nearby stars. The third is detailed spectral characterization of the brightest extrasolar planets. The final targets are circumstellar dust disks, including Zodiacal light analogs in the inner parts of other solar systems. To achieve these requirements, PFI combines advanced wavefront sensors, high-order MEMS deformable mirrors, a nulling coronagraph optimized for a segmented primary mirror, and an integral field spectrograph.[1]

SCIENCE MOTIVATION

Direct imaging of these planets, as opposed to detection of the effects of orbital motion on their parent star, is now feasible, and the first young planet in a wide orbit may have been detected using adaptive optics systems.[2]

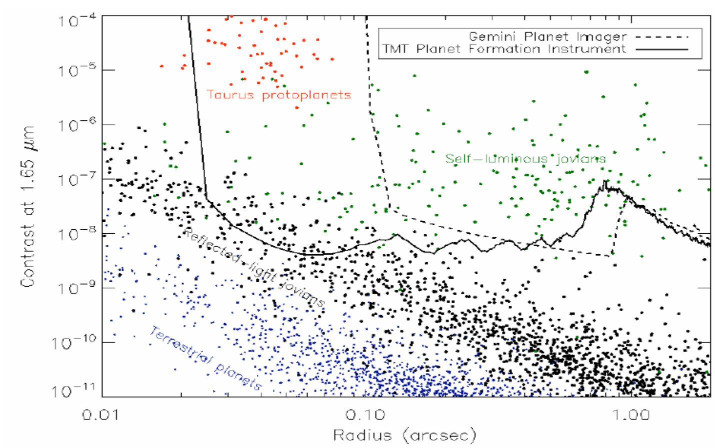

Figure 1: *Contrast-separation plot for a Monte Carlo simulation of a variety of targets in the solar neighborhood. Blue dots are rocky planets, beyond the reach of even TMT. Black dots are mature Jovian planets reflecting sunlight. Green dots are self-luminous Jovian planets, typically those with masses of 3–10 Jupiter masses and ages < 1 Gyr. Red dots are extremely young planets, recently formed or still accreting, e.g., in the Taurus star-forming region. The expected sensitivity of PFI and the Gemini Planet Imager for a bright (4th magnitude) target are overlaid.[1]*

[1] This note is an extract taken from the publication: Bruce Macintosh, et al., "Extreme Adaptive Optics for the Thirty Meter Telescope", Proc. SPIE Vol. 6272, Advances in Adaptive Optics II, B. Ellerbroeck, ed. (2006). This paper was presented at the Coronagraph Workshop 2006, 28–29 September 2006, Pasadena, CA, JPL Publication 07-02, W.A.Traub, editor (2007).

Gemini and the VLT are building the first generation of high contrast "extreme" adaptive optics (ExAO) systems, which deliver planet-imaging performance at separations > 0.1 arcseconds. These systems will make the first surveys of the outer regions of solar systems by detecting the self-luminous radiation of young planets (1–10 MJ, 10–1000 MYr), but the 8-m ExAO systems cannot see close enough to the host stars to image Doppler-detected or other mature planets in reflected light, and they cannot reach the relatively distant, young clusters and associations where planets are likely to still be forming. The PFI will use the nearly four-fold improved angular resolution of TMT to peer into the inner solar systems of planet bearing stars to yield a unified sample of planets with known Keplerian orbital elements and atmospheric properties. In star formation regions, where T Tauri stars (young solar type stars) are found in abundance, PFI can see into the snow line, where the icy cores of planets like Jupiter must have formed. Thus, TMT could be the first facility to witness the formation of new planets directly. Because of the short lifetimes relative to the Galactic star formation rate, young planet-forming systems are rare and found in significant numbers only in distant (> 150 pc) star forming clouds. The inner working distance required to study planet formation in situ is therefore of order 35 milli arc seconds (5 AU at 150 pc). Since a typical coronagraph has an inner working distance >3–5 λ/D, it is evident that the TMT will be the first facility to enable direct observation of planets emerging from their parent discs. Likewise, to detect nearby mature planets in reflected light, a comparable angular resolution will be needed (30 mas = 0.3 AU at 10 pc). TMT will thus also be the first facility to be able to directly detect a sizable number of reflected light Jovian planets. The unique combination of angular resolution and sensitivity of TMT will thus enable direct images and spectra to be obtained for both young and old planets (Fig. 1). The main instrumental capability needed to take advantage of the TMT, in this regard, is high contrast imaging at an angular separation of a few λ/D from bright stars in the near infrared. This goal is the basic driver for the instrument described here, the Planetary Formation Instrument (PFI).[1]

OVERALL ARCHITECTURE

Current AO systems achieve contrasts on the order of 10^{-5} at angular separations of ~ 1 arcsecond; TMT PFI requires a three order of magnitude improvement in contrast and a factor of twenty in angular separation. The combined requirements of high dynamic range, a wide variety of target brightnesses, very high angular resolution and the need to minimize systematic errors, lead to a multi-stage integrated instrument. A high-speed front AO system, optimized for searching for planets, and achieving extremely high contrast ($>10^{-8}$) on bright targets, requires very high update rates (2–4 kHz) to minimize dynamic atmospheric errors. We have selected as our baseline a variant of the pyramid wavefront sensor run in a quasi-interferometric mode to take advantage of the high Strehl ratio at the wavefront sensing wavelength to achieve measurement errors a factor of 2–4 better than a conventional Shack-Hartmann sensor. Combined with a compact, high-order MEMS DM this system will produce H-band Strehl ratios above 0.9 on bright stars and 0.84 down to I = 9 mag. On dimmer stars, it will provide partial correction to enable the back (interferometric or calibration) wavefront sensor to provide the bulk of the wavefront correction. Unless controlled, light scattered by diffraction from the telescope pupil would completely swamp the signal from a planet. After considerable exploration of alternatives using simulations, we have selected a dual-stage shearing nulling interferometer or "nuller" as the diffraction suppression system (DSS). This combines four offset and phase-shifted copies of the telescope pupil to remove the uniform component of the electromagnetic field that causes diffraction. This has two major advantages over conventional coronagraph architectures. First, it allows for very small inner working angles (IWA)—as small as 3 λ/D—that are needed both to detect nearby planets in reflected starlight and to image young solar systems at distances as great as 150 pc. Second, it is robust against the large secondary obscurations likely to be found in any extremely large telescope. The large aperture of TMT allows PFI to exceed the contrast of 8-m ExAO systems by an order of magnitude, but does nothing to relax the fundamental requirement of sub-nanometer internal static optical errors; since the effect of internal errors is partially independent of telescope size, these requirements are even more exacting to reach the 10^{-8} contrast levels that we are targeting. To overcome this, we will use a dedicated, interferometric (calibration), wavefront sensor that is tightly integrated with the DSS, and controls a second MEMS DM located inside the nuller. Known as the back wavefront sensor, this system is a Mach-Zehnder interferometer combining the bright and dark outputs of the nulling DSS. It has two primary purposes. First, operating at the science wavelength and measuring the dark output of the DSS, it will provide sub-nanometer absolute accuracy and correct these errors through feedback to the front AO or through its own MEMS. Second, especially on very red science targets, it will provide additional rejection of atmospheric turbulence, allowing PFI to reach contrast of 10^{-6} to 10^{-7} on H = 10 mag. young stars.[1]

PFI's science instrument is a dedicated Integral Field Spectrograph unit (IFS or IFU) optimized for high-contrast imaging, maximum scientific return, and for spectral follow-up of extrasolar planets. This combines moderate spectral resolution ($R = \lambda/\Delta\lambda \sim 70$) with a 2 × 2 arc second Nyquist-sampled field of view and spectral coverage from 1–5 μm. Carefully designed to minimize chromatic errors, this allows planets to be distinguished from artifact speckles by their differing behavior as a function of wavelength. The instrument also includes an R = 500 mode that can be used for followup of previously-detected planets. A dual-channel imaging polarimeter mode will be available to study circumstellar disks and distinguish disk structure from the planets embedded in them. Figure 2 shows a block diagram of the PFI system.[1]

PERFORMANCE SIMULATIONS

We ran a series of end-to-end simulations of PFI incorporating all the subsystems except the science instrument (only monochromatic PSFs were generated.) Typical simulation exposure times were 2–4 seconds, sufficient for 1–4 atmospheric speckle lifetimes[4]. These simulations correctly predict contrast due to atmospheric effects (including scintillation and propagation chromaticity) but are too short to show the effects of static wavefront

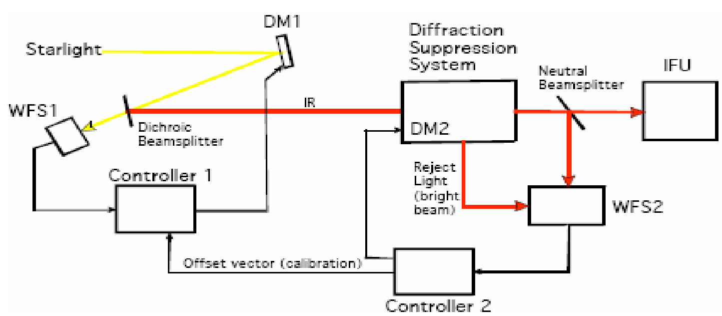

Figure 2: *Block diagram of the TMT Planet Formation Instrument[1]*

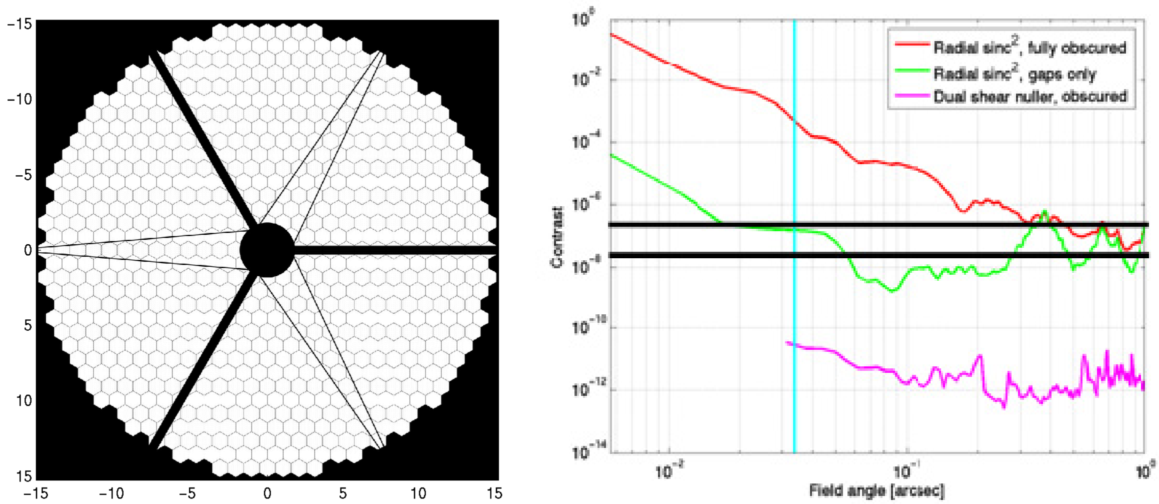

Figure 3: *Left, the segmented and obscured TMT pupil[1]. Right, results of achievable contrast from PFI due to the pupil as compared to other coronagraph types[3]. The segmented primary mirror does not adversely effects the resultant contrast, however, the obscuration grossly affects performance. The nulling coronagraph suffers no such loss of contrast.*

errors. Separate simulations of static effects were used to evaluate their magnitude and set instrument requirements. If these are met, sensitivity can then be extrapolated to 1–2 hour exposures. Additional post-processing suppression of speckle noise by a factor of 5–10 should be possible by the calibration wavefront sensor.[1]

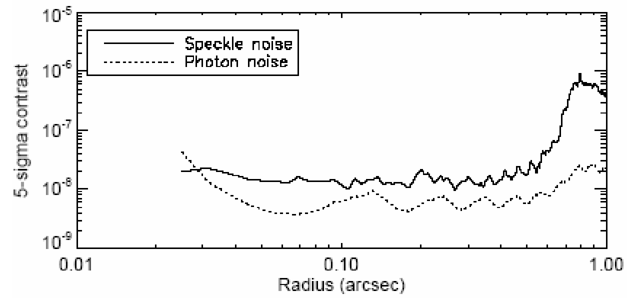

Figure 4: The speckle and photon noise contrast is shown as a function of field angle for a G5 star at 10 pc. The simulation was run for 1.5 seconds and the results scaled to obtain the contrast in 2 hrs, assuming systematic errors are controlled.[1]

SUMMARY

We have identified key science missions—the study of mature planets and of young protoplanets in starforming regions—in which future 30-m-class telescopes will have unique capabilities, in particular their small inner working angle. We have produced a science-driven design, practical using near-term technologies, that can carry out these science missions, with the emphasis on performance at 3–5 λ/D. Such an instrument will build upon the technological and scientific heritage of the 8-m class ExAO systems such as the Gemini Planet Imager, and will produce both a uniform census of extrasolar planets and the first images and spectra of planets in the process of formation.[1]

REFERENCES

1. Bruce Macintosh, et al., “Extreme Adaptive Optics for the Thirty Meter Telescope”, Proc. SPIE Vol. 6272, Advances in Adaptive Optics II, B. Ellerbroeck, ed. (2006).
2. G. Chauvin, et al., “A giant planet candidate near a young brown dwarf. Direct VLT/NACO observations using IR wavefront sensing”, A&A 425, L29 (2004)
3. M. Troy, et al., “Effects of diffraction and static wavefront errors on high-contrast imaging from the thirty meter telescope”, Proc. SPIE Vol. 6272, 62722C, Advances in Adaptive Optics II, B. Ellerbroeck, ed. (2006), and presentation viewgraphs therein.
4. B. Macintosh, et al., “Speckle lifetimes in high contrast optics”, Proc. SPIE, Vol. 5903, 170, (2005).
5. D. Phillion, et al., “Two-sided pyramid wavefront sensor in the direct phase mode”, Proc. SPIE Vol. 6272, 627228, Advances in Adaptive Optics II, B. Ellerbroeck, ed. (2006).
6. G. Vasisht, et al., “Post-coronagraph wavefront sensing for the TMT Planet Formation Imager”, Proc. SPIE Vol. 6272, 627253, Advances in Adaptive Optics II, B. Ellerbroeck, ed. (2006).