CFH CANADA · FRANCE · HAWAII TELESCOPE

Maunakea Spectroscopic Explorer

Annex 2
Pathfinder

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1 Pathfinding MSE Science, Culture, and Technology

Annex 2 describes Pathfinder, a Multi-Object Spectrograph (MOS) and/or Integral Field Unit (IFU) instrument that will augment the scientific capabilities of the Canada-France-Hawaiʻi Telescope (CFHT) and further the development of the Maunakea Spectroscopic Explorer (MSE).

Hosted at CFHT, Pathfinder will be a proto-MSE scientific instrument that provides a development platform for innovative technologies that could serve as MSE first-light instruments. With a baseline configuration of ~1,000 multiplexed fibers and two spectrographs, Pathfinder will have two modes: MOS using a fiber positioner at prime focus and a Cassegrain-mounted IFU. The instrument will have a spectroscopic coverage of 0.36 μm to 1 μm at R=2000 to R=5000 moderate resolution (MR). Science capabilities could also include an extended spectral range from visible (VIS) into near-infrared (NIR) *J*- and *H*-band and R=15,000 high resolution (HR mode) in the visible.

The Pathfinder consortium will define the instrument's design specifications and parameters. Figure 1 provides a baseline design as starting point for discussions regarding project partnership and contribution requirements.

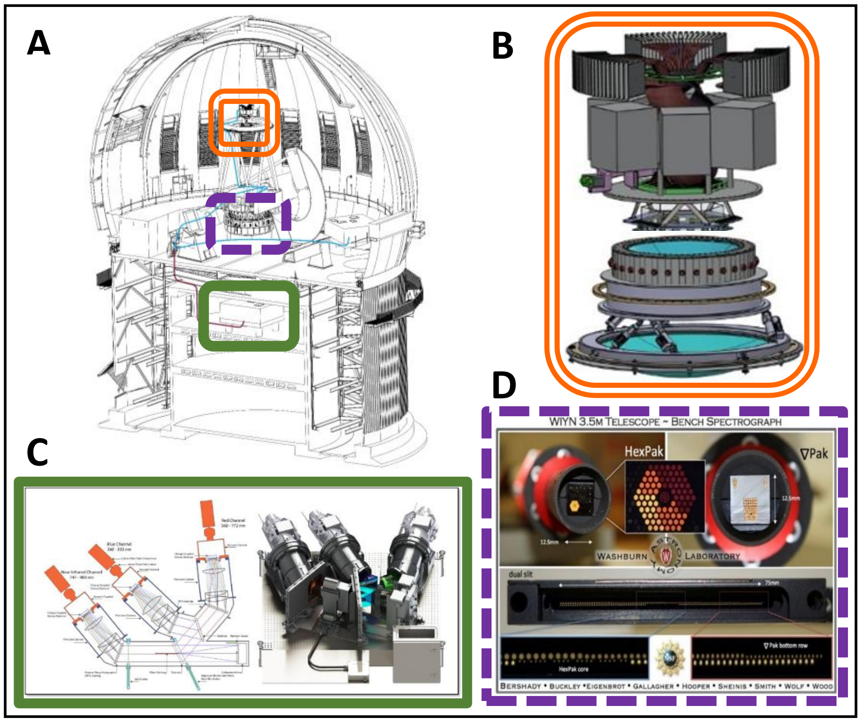

Figure 1: MSE-Pathfinder and representative components
A) CFHT telescope with Pathfinder system
*B) Positioner and wide-field corrector (**compound orange border**)*
*C) Bench-mounted spectrographs, e.g., DESI (DESI Collaboration et al 2022 AJ 164 207) (**solid green border**)*
*D) WIYN telescope IFU similar to Cassegrain mounted pathfinder IFU (Wood et al., 2012) (dotted **purple border**)*
[Credit: S. Barden and B. Small]

Pathfinder also provides a mechanism to demonstrate the principles of community-based astronomy that focuses on the entirety of Maunakea: its cultural sites, e.g., Lake Waiau (Figure 2), its geology, and the endemic fauna and flora dwelling on its slopes. In collaboration with CFHT and the local community, the Pathfinder consortium will further develop a model of astronomy rooted in the cultural values of a diverse society with strong indigenous ties to Maunakea. By establishing innovative ways to include and engage the local community, especially the underserved local and Native Hawaiian communities, the project can create new paradigms for community-based astronomy, creating a model for MSE and other projects and institutions.

Figure 2: Venus setting over Lake Waiau, a site of deep cultural significance to many Native Hawaiians [Credit: B. Mahoney]

2 Science Motivation

Pathfinder's MOS and IFU instrument capabilities will enable a wide range of science cases from cosmology to stellar astrophysics, including

- Time Domain and Transients
- Galactic Science
- Cosmology
- High-Energy
- Galaxy Evolution

Pathfinder's spectroscopic data will enhance the science return from a variety of space- and ground-based facilities. Its observations will complement space missions such as Gaia, eROSITA, Euclid, Plato, TESS, Roman, and JWST. Pathfinder spectroscopic follow-up will augment the data and science return from several current and future ground-based facilities including ZTF, Pan-STARRS, Rubin, PTF, KIDS, DESI, and SKA, as well as existing CFHT data sets such as NGVS, UNIONS, and Pristine. Enabling the science cases as outlined in Table 1, Pathfinder will generate 2D (MOS) and 3D (IFU) fully reduced and calibrated spectra and measurements of stellar atmospheric parameters, line ratios, element abundance ratios, radial velocities, and redshifts.

Science Area	Facility Follow-Up / Target Population	Science Goal / Science Area	Pathfinder Mode
Time Domain	LSST, Time Critical	SNe + Galaxy Hosts	MOS+IFU
	LSST, Time Critical	TDE	IFU
	LSST, Time Critical	GRB	IFU
	LSST, Time Critical	Blazar	IFU
	LSST, Non-Time Sensitive	Eclipsing Binaries	MOS
	LSST, Non-Time Sensitive	Brown Dwarfs	MOS
	LSST, Non-Time Sensitive	Pulsating Stars	MOS
	LSST, Non-Time Sensitive	Exoplanet Hosts	MOS
Galactic Archaeology / Near Field Cosmology	Gaia; target: MW Halo	Inner/outer halo distinction	MOS
	Gaia; target: MW Halo	Accretion and in situ formation history of Milky Way stellar halo	MOS
	Gaia; target: MW Halo	3D dark matter halo potential of Milky Way and its substructure	MOS
	Gaia + OS; target: MW Bulge	Formation scenarios: accretion vs. disk instability bulge formation	MOS
	Gaia + OS; target: MW Bulge	Transition regions	MOS
	Gaia + OS; target: MW Disk	Dynamics of bar and spiral arms to constrain stellar mass distribution	MOS
	Gaia + OS; target: MW Disk	Stellar radial migration importance	MOS
	Gaia + OS; target: MW Disk	Origin of thin and thick disks	MOS
	Gaia + OS; target: MW Disk	Chemical enrichment history of disk	MOS
	Gaia Faint End	MW populations' chemodynamics	MOS
Cosmology / Galaxy Evolution	Euclid, Roman, LSST, SKA	Dark energy/dark matter (BAO, RSD, Ly alpha Forest)	MOS
	Euclid, Roman, LSST, SKA	Dark energy/dark matter (Lensing)	MOS+IFU
	Euclid, Roman, LSST, SKA	Transients (SNe Ia, SNe CC, exotic SNe)	MOS+IFU
High Energy Sky	eROSITA	Cosmology with X-ray Clusters to z~0.8	MOS+IFU
	eROSITA	X-ray AGN/galaxy evolution and cosmology to z~5	MOS+IFU
	eROSITA	Galactic X-ray Sources, Resolving the Galactic Edge	MOS
Galaxy Evolution	SKA PF, SKA, Roman, LSST, Euclid	Galaxy Evolution (Galaxies)	MOS+IFU
	SKA PF, SKA, Roman, LSST, Euclid	Galaxy Evolution (Clusters)	MOS+IFU

Table 1: Representative science cases for Pathfinder MOS and IFU

3 Pathfinder Perspectives and Advantages

Observational and Site Perspective: Located on the summit of Maunakea (Figure 3), CFHT provides exceptional seeing and site quality. From its location in the Northern Hemisphere, CFHT accesses M31, M33, a large fraction of the Galactic Disk (especially the second disk quadrant), part of the Galactic Bulge, and various Milky Way stellar populations and satellites.

Immediate Target-of-Opportunity Follow-Up: With Rubin, Euclid, Roman, and similar surveys fully underway, Pathfinder will dedicate a fraction of fiber hours to pursue rapid target of opportunity (ToO) spectroscopic follow-up. With CFHT's unique longitudinal position, Pathfinder will be able to execute follow-up observations of time-sensitive signals, augment time series data, and perform immediate spectroscopic observations of newly detected astrophysical events. In addition, the instrument's IFU and MOS components will be able to provide immediate ToO follow-up observations.

Figure 3: CFHT at the summit of Maunakea [Credit: CFHT]

Survey Start and External Survey Overlap: Because of its expedited development plan, Pathfinder surveys will overlap with Euclid, Roman, and Rubin surveys. For target selection, Pathfinder survey programs will be able to leverage substantial external data and well-established candidate targets, some with long baseline data.

Crowded Field Performance: To enhance Pathfinder's performance in crowded fields with high target densities of sufficient brightness for the CFHT 3.6-m telescope, Pathfinder aims to employ a fiber positioning system that can achieve close separation between neighboring fibers. We anticipate that multiple fibers can reach any one science target, enabling high fiber allocation efficiency.

4 Top Level Requirements

Detailed below are the associated technical flow-down requirements for Pathfinder's science cases. These requirements assume a minimal baseline configuration for the Pathfinder: a 1,000-fiber MOS at prime focus and a 1,000-fiber IFU at Cassegrain focus feeding DESI-like spectrographs.

- Wavelength Coverage: λ = 0.36-0.98 μm
- Sky Background Subtraction: Poisson-limited performance (goal)
- Spatial Resolution: 1.0', Goal 0.65', (median seeing of the CFHT site)
- Spectral Resolution: (R ~ 4000 at 0.6563 μm)
- Kinematic/Velocity Precision: 10 km s^{-1}
- Chemical/Abundance Precision: less than 0.2 dex for stellar atmospheric parameter and individual element abundance determinations
- Absolute Spectrophotometric Calibration: better than 5%

5 Pathfinder System Architecture

As a fiber-fed, wide-field MOS and IFU, Pathfinder will complement CFHT's existing suite of instrumentation detailed in Annex 1. In addition to capitalizing on studies and designs from the MSE project, Pathfinder's preliminary concept leverages existing technologies, building upon the experience of current and upcoming MOS instruments such as DESI, WEAVE, 4MOST, VIRUS, PFS, and MOONS.

MOS System

Pathfinder MOS mode consists of a visible, moderate-resolution spectrograph fed by a positioning system (Figure 1B) mounted at prime focus (Figure 4). Additional options include NIR medium resolution and visible high-resolution spectrographs. The top-end assembly at the prime focus is comprised of a fiber positioner assembly (FPA), an acquisition and guide system (AGS), a wide-field corrector (WFC) with an atmospheric dispersion corrector (ADC), and a hexapod. The FPA has a 1.17-degree circular field of view (FOV) with 1,000 movable 1'' fibers providing full field coverage of targets. Cameras mounted around the periphery of the fiber plate execute target acquisition and guiding functions. The hexapod assembly, with its six degrees of freedom, provides the focus, tip/tilt, and field de-rotation functions.

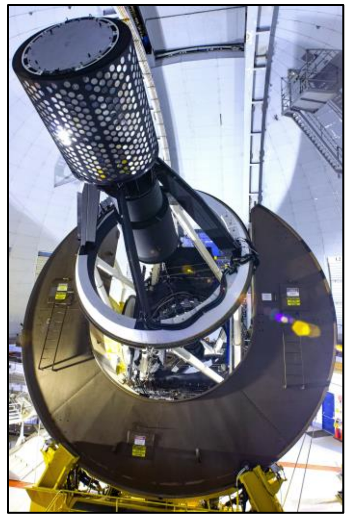

Figure 4: CFHT Prime Focus [Credit: T. Benedict]

IFU System

Pathfinder's IFU mode consists of an IFU at the Cassegrain port (Figure 5), supporting a wide range of science cases, notably ToO follow-up. Similar to the University of Wisconsin's Hexpak and GradPak (Figure 1D), the permanently-mounted IFU will have a 31'' X 31'' FOV and will be accessible whenever the telescope is in the Cassegrain configuration (nominally 50% of the time). A new instrument, VISION, will allow for rapid changes between the IFU and one or both of CFHT's high-resolution spectropolarimeters: SPIRou and ESPaDOnS (see Annex 1 for more detail). The combined spectra from SPIRou and ESPaDOnS will allow for high-resolution spectra from the UV through the thermal IR (0.37-2.5 µm) at a spectral resolution above 70,000.

Figure 5: Pathfinder IFU will be mounted at Cassegrain [Credit: T. Benedict]

6 Project Definition

The Pathfinder project is forming a scientific consortium to

- Design, build, and commission the Pathfinder instrument on CFHT
- Plan and conduct user-selected spectroscopic surveys, including time-domain observations
- Produce and distribute science-ready data products for Pathfinder astronomy communities

Opportunities to contribute as a consortium member to activities listed in the Work Breakdown Structure (Figure 6) include

- Financial contributions
- In-kind contributions
  - Instrumentation: hardware, existing or to-be-developed
  - Software design: development and/or equipment
  - Personnel: scientific, engineering, and project management

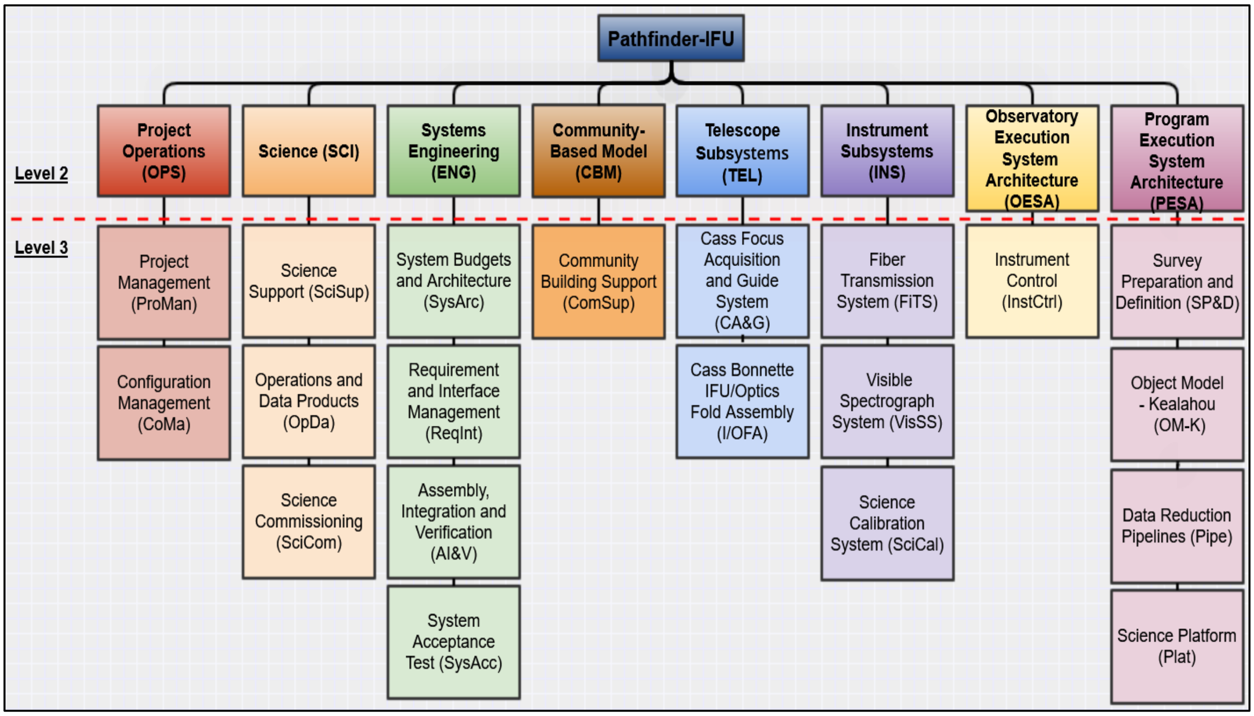

Figure 6: Pathfinder Work Breakdown Structure