Multi-object spectroscopic capability at the Canada France Hawaii telescope: The MSE pathfinder

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ABSTRACT

MSE/CFHT plan to develop an end-to-end Pathfinder or for the Maunakea Spectroscopic Explorer (MSE). The MSE Project office is developing a new massively multiplexed spectroscopic facility on the site of the existing CFHT. MSE has currently passed its externally vetted Conceptual Design Stage. It will be a minimum 11-meter aperture telescope feeding 4000-10,000 fibers mated to a battery of medium and high-resolution spectrographs in the visible and NIR. The goal of the Pathfinder will be to fast-track technology development for MSE by demonstrating on-sky the ability of the major components of MSE and the major software packages in parallel with producing an initial science product that can be shared with the community. Among the primary science goals of the Pathfinder are time-domain astrophysics, specifically spectroscopic follow-up of transients identified by facilities such as Rubin Observatory and Zwicky Transient Factory to optimize their identification and classification; galactic archeology; and the spectroscopy of stars for stellar abundance studies and stellar evolution studies. The end-to-end Pathfinder will be a multi-object spectrograph fed at prime focus from the Canada France Hawaii telescope. It will utilize the same MSE spectrograph design with a multiplexing of ~800-1400 fibers using the same fiber positioner technology as MSE. The Pathfinder will prototype the software architecture for MSE including, scheduling; targeting; data reduction and analysis; and data management, archiving and database manipulation..

Keywords: multi-object spectroscopy, transient follow-up, stellar abundances, Galactic archeology, new facilities, Maunakea, Canada France Hawaii telescope

1. INTRODUCTION

MSE/CFHT plan to develop an end-to-end Pathfinder or for the Maunakea Spectroscopic Explorer. The goal of the Pathfinder will be to fast-track technology development for MSE by demonstrating on-sky the ability of the major components of MSE and the major software packages in parallel with producing an initial science product that can be shared with the community, including community access to this wide field spectroscopic capability. Motivation for the Pathfinder comes also from the recent much-anticipated report from the National Academies, "Pathways to Discovery in Astronomy and Astrophysics for the 2020s" (henceforth referred to as Astro2020). In the Astro 2020 decadal review report Section 7 "Realizing the Opportunities: Medium and Large-scale programs" three funding tracks are called for in order to achieve the science priorities identified by the decadal review panel. Consistent with these priorities, the primary science goals of the Pathfinder are time-domain astrophysics: specifically spectroscopic follow-up in order of transients identified by facilities such as Rubin Observatory and Zwicky Transient Factory to optimize their identification and classification; Galactic archeology; and the spectroscopy of stars for stellar abundance studies and stellar evolution studies. The third track calls specifically for upgrades to existing facilities and community access to additional facilities. The Pathfinder instrument is in direct response to the call from track three.

The end-to-end Pathfinder will include two multi-object spectrographs fed (most likely) at prime focus from the Canada France Hawaii telescope (CFHT). It will utilize the MSE spectrograph design and a fiber positioner that includes the same technology as the fiber positioner for MSE. That positioner will position between 800 and 1400 fibers over a 30-80 arcminute field of view, covering the full V,B,R,I,J,H wavelength bands at a resolution between R=7000 and R=15,000. The Pathfinder project will develop the prototype software architecture for MSE including: scheduling; targeting; data reduction and analysis; and data management, archiving and database manipulation.

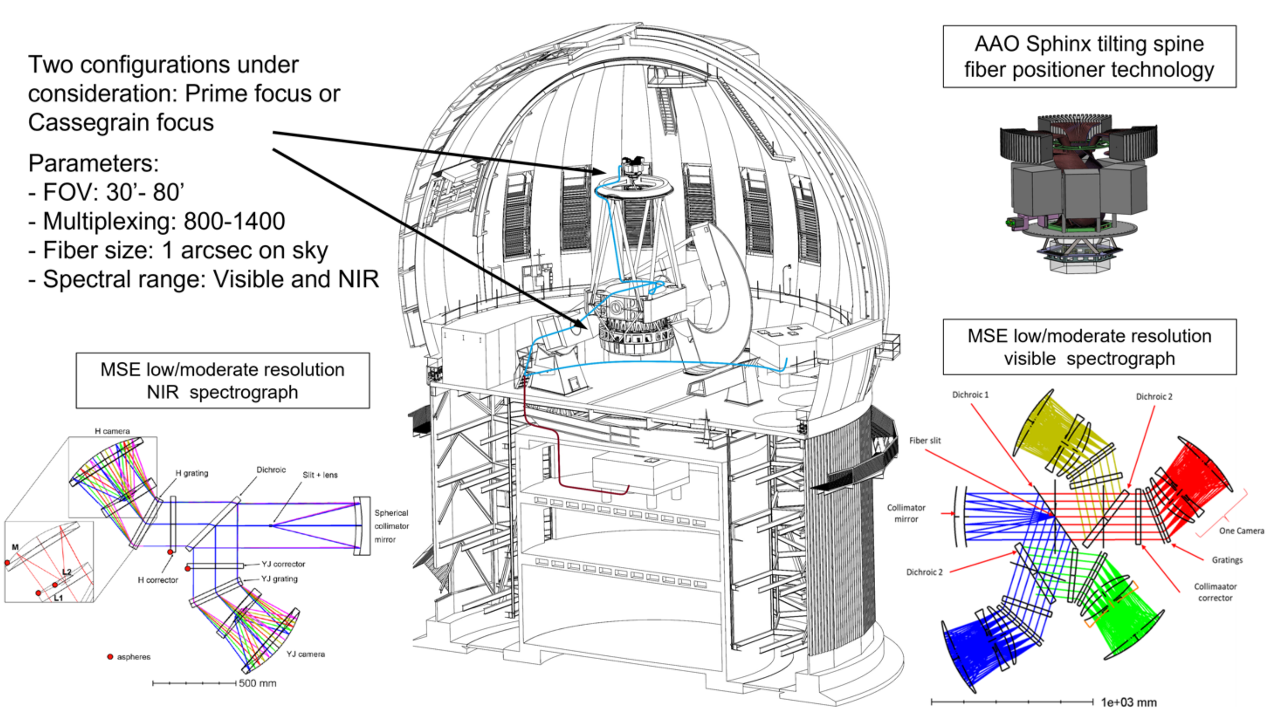


Figure 1. *The MSE Pathfinder Concept.*

2. SCIENCE CASE

The past two decades have seen major advancements in our understanding of the Universe thanks in large part to modern optical and near-IR wide field imaging surveys such as SDSS[1], 2MASS[2], Pan-STARRS[3], the Dark Energy Survey[4], and Gaia[5], Soon the Rubin Observatory[6] will open another new window on the Universe, enabling the discovery and study of stars and galaxies too faint to be studied previously over enormous solid angles. To realize the full scientific potential of these surveys, many (if not most) of the objects discovered in these imaging surveys must be studied in further detail using spectroscopic techniques; this has been emphatically demonstrated by the continued success of SDSS's coupling of a deep imaging survey with copious spectroscopic follow-up activities, resulting in a project that is still scientifically productive decades after its first light.

Furthermore, Astro2020 states that "[m]assively multiplexed spectroscopy is required to fully realize the primary science goals of the VRO, the Roman Space Telescope, Gaia, and other surveys." This observing capability must be widely available to many astronomers, since Rubin and others will soon be producing overwhelming numbers of imaging targets that require spectroscopic follow-up. In opposition to this statement by the Astro 2020 report as shown in Table 1 there is currently no 2 to 8 meter class widefield , spectroscopic survey facilities available to the general US scientific community. Pathfinder satisfies this need in the short term, while the MSE satisfies this need for decades to come. While the field of view is somewhat smaller than the European counterparts WEAVE and 4MOST, the native seeing and the sky transparency are both likely to be better at Maunakea and in particular this will contribute to the infrared capability of the Pathfinder.

Fiber-Fed Spectroscopic Instruments (2-8 meter class)

Instrument	Facility	Hemisphere	Status	Operations Start	M1 Aperture [m]	FOV [deg2]	No. Fibers	Spectral Coverage	IFU	Resolution Modes	North American Astro Community Access
SDSS I/II	APO	N	Completed	1999	2.5	7.1	640	VIS	No	LOW	No
BOSS (SDSS III/IV)	APO	N	Completed	2009	2.5	7.1	1000	VIS	Yes	LOW	No
APOGEE (SDSS III/IV)	APO + LCO	N + S	Completed	2011/2017	2.5	7.1	300	NIR(H)	No	HIGH	No
LAMOST	Guoshoujing	N	Current	2012	4.0	19.6	4000	VIS	No	LOW	No
HERMES	AAT	S	Current	2014	3.9	3.1	392	VIS	No	HIGH	No
BOSS+APOGEE (SDSS V)	APO	N +S	Current	2021	2.5	7.1	500	VIS + NIR (H)	Yes	LOW, HIGH	No
DESI	KPO	N	Current	2020	4.0	8.0	5000	VIS	No	LOW, MED	No
WEAVE	OOCC	N	Build	[2022]	4.2	3.1	1000	VIS	Yes	MED, HIGH	No
MOONS	ESO-Paranal	S	Build	[2022?]	8.2	0.14	1001	VIS*+NIR (YJH)	No	MED, HIGH	No
PFS	Subaru	N	Build	[2023]	8.2	1.3	2400	VIS + NIR (YJ*)	No	LOW, MED	No
4MOST	ESO-Paranal	S	Build	[2024]	4.1	4.4	1624	VIS	No	MED, HIGH	No
MSE Pathfinder	**CFHT**	**N**	**Design**	**[2027]**	**4.0**	**0.5-1.3**	**800-1400**	**VIS + NIR (JH)**	**Potentially**	**MED, HIGH**	**YES**

Table 1 summarizes these facilities. It is worth noting that the decadal survey committee concluded that although existing and near future massively spectroscopic survey facilities will contribute significantly to this science, "[m]ost glaring is the lack of high spectral resolution (R~20,000) multi-object spectrographs."

The scientific impact of the Pathfinder

The Pathfinder will enable a plethora of unique, high impact, and exceptionally diverse transformational science cases. Some examples of science that could be enabled by the instrument are given below:

New Windows on the Dynamic Universe: Multi-messenger time domain astronomy has of late become a focus of observational astronomy: the LIGO-Virgo discovery and localization of neutron star merger GW170817 spectacularly ushered in the era of multi-messenger astrophysics with gravitational waves and has highlighted the immediate need to expand the rapid response capability of follow-up facilities. In the near future, the Rubin Observatory will begin producing overwhelming numbers of transient objects that will require rapid imaging and spectroscopic follow-up. The Pathfinder, with its real-time control software, will enable a new era of rapid-response and time domain astronomy, studying future LIGO events as well as periodic (e.g., binaries/ exoplanets, pulsation), evolutionary (e.g., reverberation mapping[7]) and bursting behavior (e.g., flares, CV novae), on time scales that range from minutes to years.

Probing Dark Matter Physics[8]

Astrophysical observables are critical to constraining models of dark matter across a range of mass scales from 10^{-23} eV to $100M_{sun}$. We will soon enter a new era of high spatial resolution observations and fast sky imaging surveys with James Webb Space Telescope and the Legacy Survey of Space and Time (LSST) at the Vera C. Rubin Observatory. In addition to the imaging surveys, spectroscopic observations are essential to dark matter studies. Astrophysical probes can elucidate the particle nature of dark matter via observations made with multiplexed spectroscopic instruments. With four probes: stellar streams, dwarf galaxies in the

Milky Way and Andromeda Galaxy (M31), Low-redshift ($z < 0{:}05$) dwarf galaxies beyond the Milky Way, and strong gravitational lensing; the Pathfinder could make progress towards a better understanding of the fundamental physics that governs the nearby Universe.

Cosmology:

Though the as-designed MSE Pathfinder will not achieve the same coverage nor number of targets as DESI, the target magnitude reach and signal should be roughly comparable over the visible wavelength regime (in the case of DESI, the wavelength coverage is 360-980 nm). For its cosmological survey, DESI is expected to target three target classes: luminous red galaxies (LRGs) between $0.4 < z < 1$, emission-line galaxies (ELGs) covering $0.6 < z < 1.6$, and Lyα quasars (QSOs) at $z > 2$. According to the DESI Science Requirements Document (SRD) for the three targeted tracers, the BAO cosmic distance scale will be measured to about 0.3% precision over the red shift range $0.0 < z < 1.14$ and to roughly 0.4% precision in the redshift range $1.1 < z < 1.9$. At higher redshifts, Lyα quasars will measure the Hubble parameter over the range $1.9 < z < 3.7$ from the BAO method to approximately 0.8% for the baseline survey.

Accordingly, the potential near infrared coverage of the MSE-Pathfinder will only serve to increase the redshift range over which these cosmological parameters are measured.

3. TECHNICAL HARDWARE DESCRIPTION

System overview

The Pathfinder system consists of a complete spectroscopic survey facility. On the hardware side it includes a wide-field corrector; fiber positioning system; fiber management system; and visible and near infrared low/medium resolution spectrographs. On the software end it includes all of the proposal handling tools; scheduling and targeting software; target of opportunity tools; data acquisition analysis and reduction software packages; as well as all of the data management tools for building the searchable database that is consistent with that developed for Rubin, WFIRST, Roman etc….

Positioner

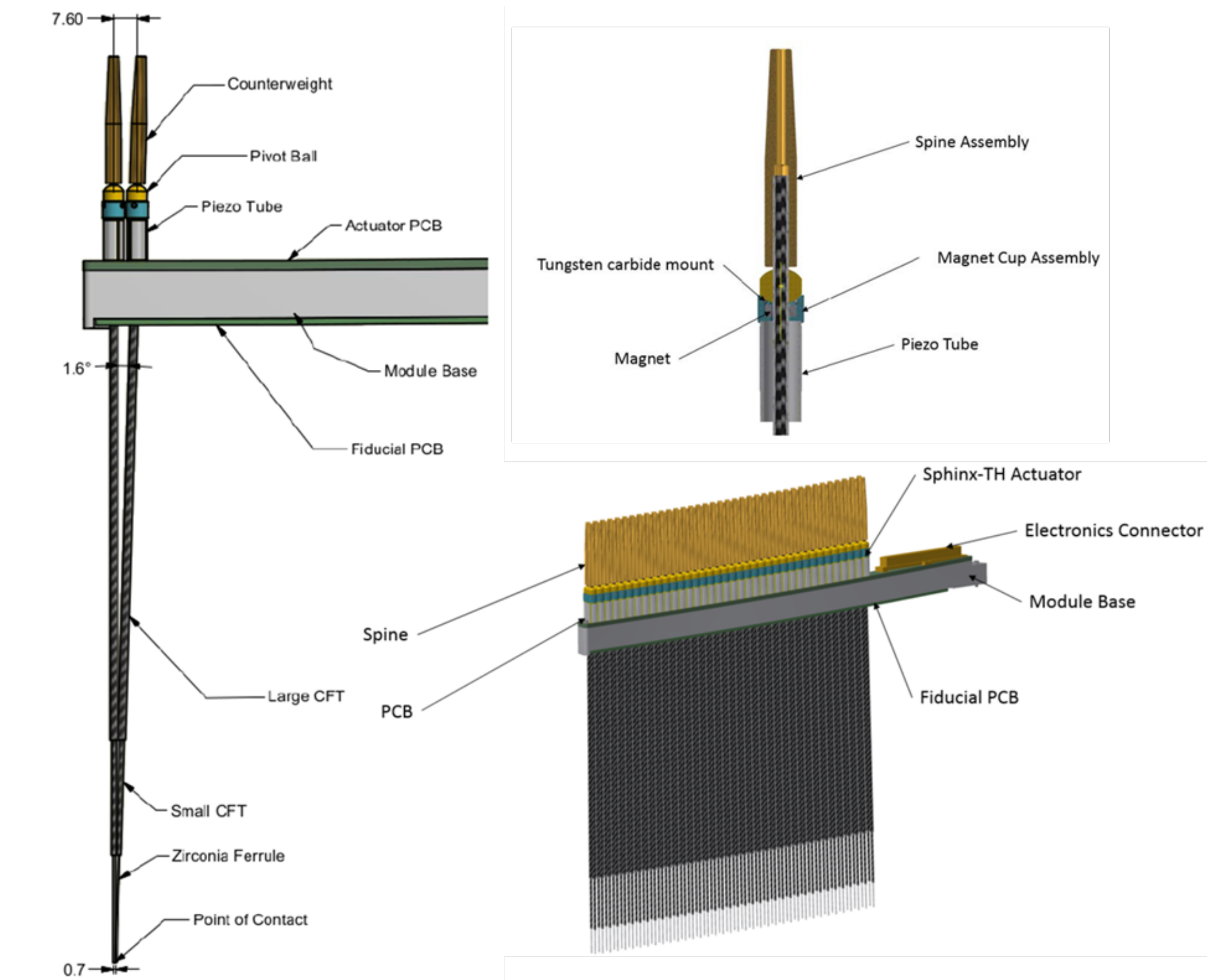


Figure 2: Sphinx fiber positioner module—Each module carries 76 spines, with 57 LMR and 19 HR fibers (bottom right), two adjacent spine assemblies (left) and a close-up of the piezo actuator (top right).

The MSE Pathfinder system will use the tilting spine positioner technology for its positioner system[9]. This is the same technology that will be used for MSE.

The tilting spine positioner technology was developed by the Anglo-Australian Observatory (now Australian Astronomical Optics, AAO) initially for WFMOS[10], which was a massively multiplexed wide-field spectroscopic survey instrument initially envisaged for Gemini or Subaru observatory. The tilting spine technology found its first home in the FMOS Echidna system at the Subaru telescope, where it was fielded for

approximately 10 years from 2008 to 2018 and is currently being deployed on the 4MOST widefield spectroscopic survey facility being developed by the European Southern Observatory, where it demonstrates the ability to position all fibers in parallel leading to positioning times in under 2 minutes.
The technology was chosen because it demonstrates a significant advantage in targeting crowded fields. That is primarily because the patrol radius for each Echidna spine (containing a fiber) is greater than the pitch separating the individual spines. The end result is that this feature allows every single point within the field of view to be accessed by between three and five individual fibers, and it is this feature that allows for more flexibility in fiber assignment.
The number of fibers facilitated by this positioner are up to 800 if a 30-arcminute field of view is chosen and up to 1400 if an 80-arcminute field of view is chosen. The 30-arcminute field of view corresponds to reusing and existing wide-field corrector that resides at CFHT as a spare, but would require refurbishment and recoating of the corrector. The 80-arcminute field of view corresponds to the maximum field of view that could be reasonably developed for CFHT if an entirely new wide-field corrector was developed.

Fiber Transmission System (FTS) description.

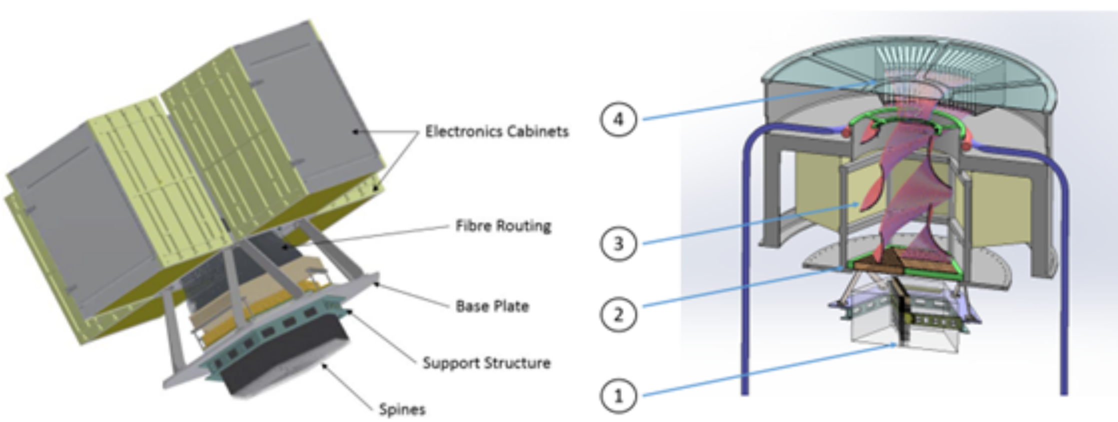


Figure 3: PosS (left) and FiTS (right) at the top end: (1) Positioning system (simplified), (2) fiber combiner, (3) helical tubes, (4) loop boxes, which share space with the electronic PosS cabinets.

The Pathfinder FTS duplicates the optical fiber bundles, fiber management system, and the specialized metrology system (hardware software and procedure) to characterize, verify and monitor FTS' performance. The fiber bundles is the optical relay that links the instrument focal surface delivered by the Telescope to the spectrograph slit inputs. FTS contains the fibers used for science targets and sky background, including spares, linking the positioner inputs to the spectrograph slit inputs. To maximize throughput and ensure system stability, FTS is designated to have continuous fiber link from positioners to spectrographs without using connectors. The construction of the fiber bundle protects the optical fibers and is optimized to reduce the telescope-motion induced cable strain in sag, stretch, bending, twisting, etc.

FTS also contains a fiber management system with attachment points for individual optical fibers as they exit the positioners and transition into sub-bundles and into cables as they exit the focal surface. The fiber management system includes structural support design that organizes the distribution and routing of the fibers through the telescope to the spectrograph to minimize fiber strain and loop boxes to facilitate repair and replacement of broken fibers with spares within the cables..

Spectrographs

It is envisioned that the two spectrographs developed for the Pathfinder will be identical to those designed for MSE and will serve as the first-light instruments for MSE after the Pathfinder has completed its science mission. Both a visible and near infrared spectrograph will be developed based on the MSE designs. The spectrographs will feed two different diameter fibers. For sky subtraction experiments the fibers will match the physical fiber size chosen for MSE, but because of the smaller aperture telescope those fibers will subtend about 3 arcseconds on the sky. For science observations, the Spectrographs will be fed by the same fiber size on the sky, one arc second, but because of the smaller aperture of CFHT will be physically 1/3 the size of those for MSE. The net result is that spectrographs will be pixel-limited in their resolution. Current spectrograph designs show the possibility of two times the resolution on CFHT as compared to MSE depending on the availability of detectors with smaller pixels. MSE design resolution is approximately R=7500 which brings the CFHT resolution up to R=15,000. The possibility of using smaller pixeled detectors for CFHT is currently being studied.

This is shown in the following equation, which relates the spectrograph resolving power to the spectrograph and telescope parameters[11].

$$R\phi = D_{Coll} \cdot 2\tan(\theta_{blaze})\,/D_{Tel} \qquad (1)$$

where $R=\lambda/\delta\lambda$ is the spectral resolving power, ϕ=fiber diameter in radians, θ is the grating angle, D_{tel} is the telescope diameter and D_{coll} is the diameter of the collimated beam within the spectrograph. Clearly as one increases the diameter of the telescope, keeping the spectrograph parameters unchanged the result will either be an increase in spectral resolution or an increase in fiber diameter on the sky.

NIR Spectrograph

The NIR spectrograph is currently being designed for MSE by the Laboratory for Astrophysics in Marseille (LAM) as an in-kind contribution. That spectrograph follows the basic design of the MOONS spectrographs, which were also developed by LAM for ESO. The spectrograph is a two-armed J and H band spectrograph utilizing a reflective collimator, two VPH gratings and a pair of obscured Schmidt cameras operating on axis, utilizing nominally 2 Hawaii H4RG detectors.

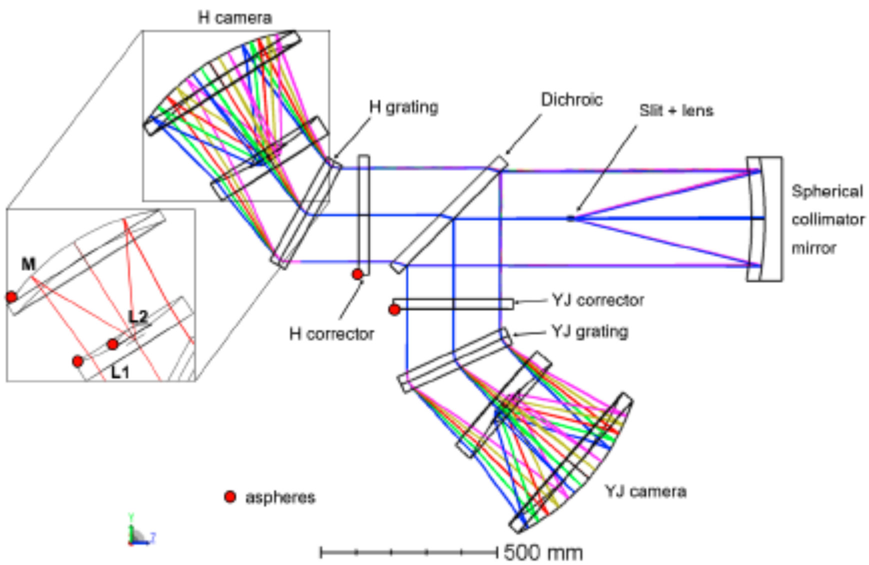


Figure 4: Optical layout of the proposed NIR design for the LMR

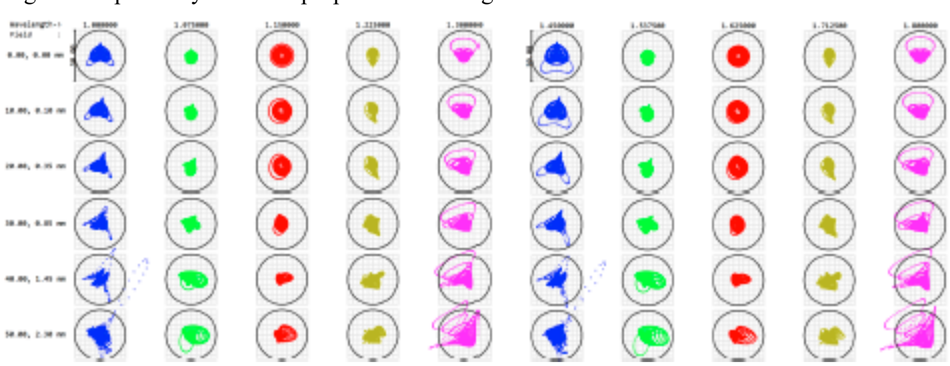
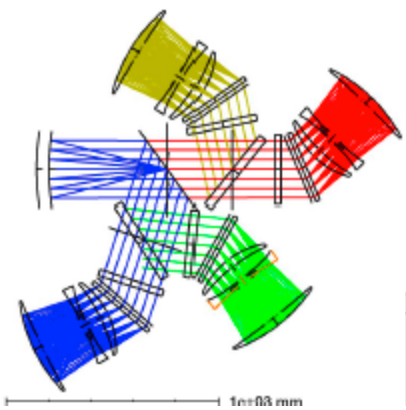


Figure 5: Spot diagram matrix of the proposed catadioptric NIR design for the LMR. The different wavelengths and fiber positions span the horizontal and vertical axes, respectively. The projected fiber core diameter is represented as a black circle, for comparison.

VIS Spectrograph

The VIS spectrograph is currently being designed for MSE by WinLight in partnership with the Laboratory for Astrophysics in Marseille (LAM). That spectrograph is a 4-armed VBRI-band spectrograph utilizing a reflective collimator, four VPH gratings and four obscured Schmidt cameras operating on axis and 4 individual silicon detectors.



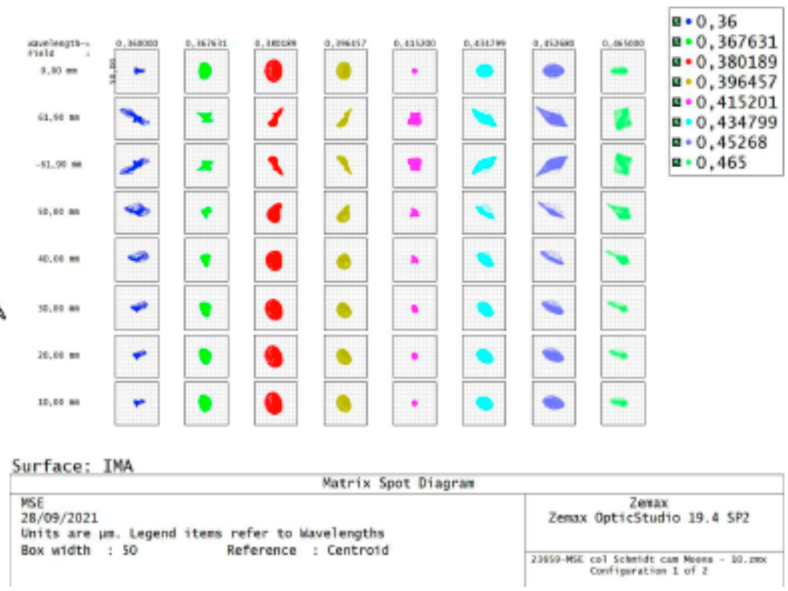


Figure 6 (Left)Optical layout of the proposed VIS design for the LMR spectrograph.

Figure 7 (Right) Spot diagram matrix of the proposed catadioptric VIS design for the LMR spectrograph. The different wavelengths and fiber positions span the horizontal and vertical axes, respectively.

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4. TECHNICAL SOFTWARE DESCRITPTION

The Program Execution System Architecture (PESA) is being developed for MSE and led by the consortium. The effort to develop the PESA package for the Pathfinder will follow the same development plan and can serve as the prototype package for MSE. The PESA end-to-end high-level software that the Execution System (ExeSys) directs the overall science operations of the observatory beginning from proposals submission and ending at the distribution of science products. PESA contains the science data processing and analytical tools along with the associated user interfaces for the MSE staff and scientific community. PESA's subsystems are derived based on the workflow envisaged in the MSE Operations Concept Document for science operations. The workflow of science operations is illustrated Figure 8 with the pre-observations and post-observations domains under the supervision of the Execution System and facilitated by the Object Model data structure to provide context to the PESA products

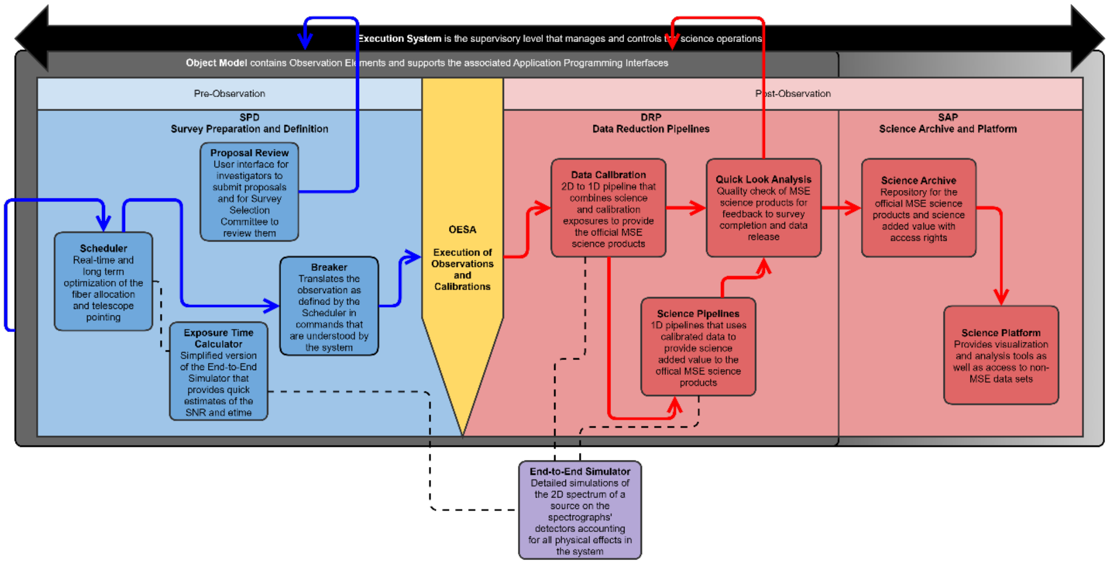

Figure 8: Workflow of science operations for the PESA software packages

PESA includes the user interfaces and Application Programming Interfaces (APIs) to enable the scientific users to perform science operations such as design and submit surveys, schedule and verify observations, reduce and validate data, distribute and access science products, etc. Pathfinder will share following MSE PESA products:

Execution System (.ExeSys) : The Execution System product is the supervisor that directs science operations among the PESA products to coordinate and execute observations. ExeSys also provides common tools that facilitate manipulation of science data from survey definition to official release.
Object Model (ObjMod): The Object Model product is the backbone connecting the pre-observations and the post-observations domains. It contains the target definition, observing status and science data information of every science target as it progresses through the survey program
Survey Preparation and Definition (SPD) :The Survey Preparation and Definition (SPD) product refers to the steps and tools by which survey teams prepare proposals, a.k.a. survey programs, to observe large samples of targets, and with their scientific and technical justifications verified. SPD supports the workflow and functionalities needed to propose, prepare, schedule, queue and monitor observations
Proposal Review (SPD.PROP): PROP processes survey programs collected from call for proposals that is coordinated by the observatory and selected by the Survey Selection Committee (SSC) at regular intervals.
Scheduler (SPD.SCH): The primary objective of the Scheduler (SCH) product is to optimize science observations by taking into account the overall priorities and requirements set by MSE/Pathfinder of the combined survey programs, while incorporating the observational constraints, i.e., weather, current spectrographs configuration, and provides both short-term and long-term schedules in the upcoming night and upcoming year.
Breaker (SPD.BRK): Pathfinders will have its unique Breaker,
Quick Look Analysis (DRP.QLA): The Quick Look Analysis (QLA) enables quality check of Level 0, 1 and 2 data. During observation, QLA operates in real-time and provides performance feedback to the Data Pipelines in order to facilitate monitoring of survey progress and its data quality. This enables Data Pipelines to interact with the Scheduler to maintain an optimal observing schedule dynamically, and the interaction is described in the next section.
Data Pipelines (DRP.DATAP): Once the Level 0 data are acquired, Data Pipelines (DATAP) reduces the science exposures by applying calibration algorithms and generating calibrated science data products at Level 1 and 2. Specifically, DATAP is responsible to develop the algorithms by implementing the techniques and procedures stated in the Science Calibration Plan, and utilize the calibration data, i.e., various science detector readouts, provided by the Science Calibration System. In addition, DATAP provides real-time feedback to SCH via the ObjMod in order to adjust the exposure time, as needed, and runs in parallel during observations.

Data Management

In [29]:
```
cluster = 'SPT0205'
image_filter='i'
zmaglim = np.array([23.5, 23.0])
zfluxlim = 10.**(-0.4*(zmaglim-25.))

#objs = matched_table.query('(SPECID=="{}")'.format(211060584))
objs = matched_table.query('(cluster=="{}") & (redshift_quality == {}) & (z_tot >= {}) & (z_tot <= {})'.f

for obj_index in objs.index.values:
    print ('Generating plot for specid ',matched_table.loc[obj_index,'specid'])
    plotspecinspect(matched_table,obj_index,filter=image_filter)
    #break
```

```
Generating plot for specid  101000184
Generating plot for specid  101000354
Generating plot for specid  101000677
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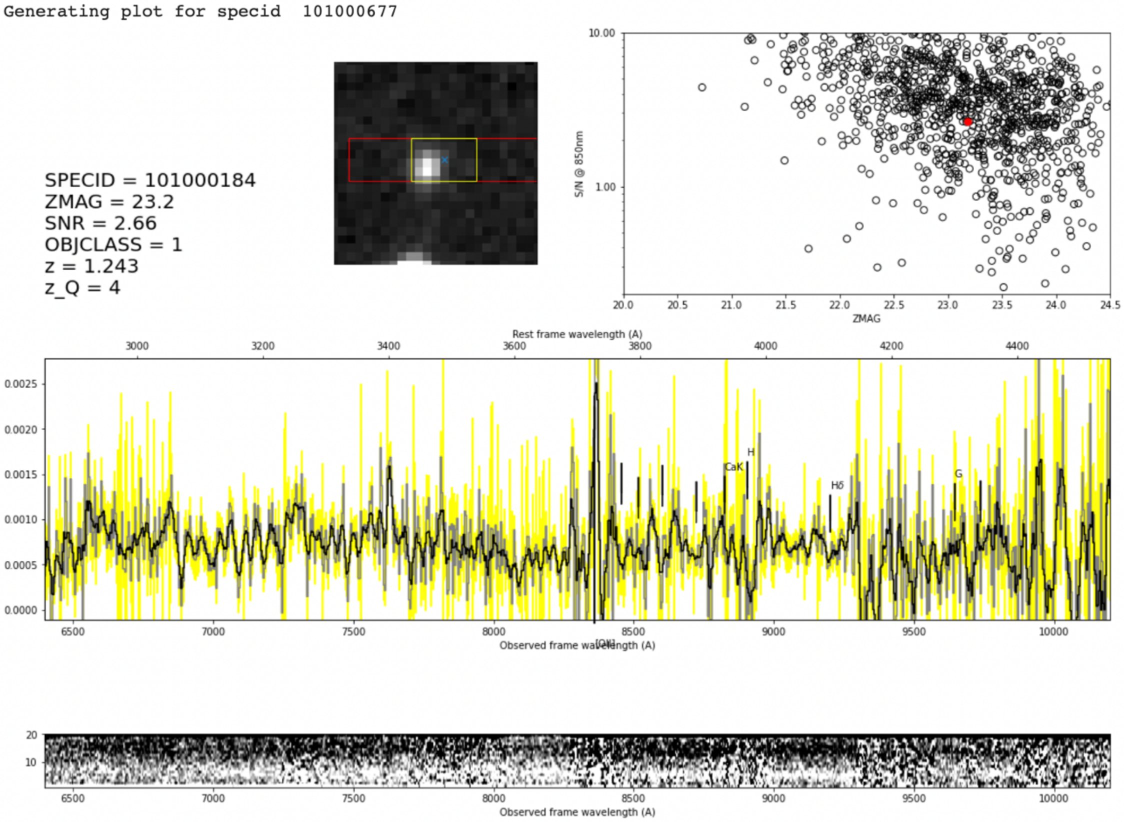

Figure 9: An example Jupyer notebook-based environment for analysis and visualization of spectroscopic data from the Gemini Observations of Galaxies in Rich Early Environments survey[12], hosted through the Astro Data Lab science platform at NSF's NOIRLab (https://datalab.noirlab.edu). Using interactive Python code and scripts, archival researchers can view image cutouts, one- and two-dimensional spectra, and plots of the physical parameters of individual galaxies in the context of the survey sample. Figure Credit: M. Balogh & R. Nikutta.

Data management for the MSF Pathfinder will be provided by NSF's NOIRLab, building on experience with multiple telescopes and instruments, and adapting software tools and techniques for multi-object fiber spectroscopy developed for the Dark Energy Spectroscopic Instrument[13]. This includes target selection and fiber assignment, real-time quality assurance, data transfer and archiving, data calibration and reduction, spectroscopic classification and parameter measurement, data-product distribution, and online platforms for high-level scientific analysis such as NOIRLab's Astro Data Lab[14].

The DESI spectroscopic data processing system[15], has been developed by the DESI collaboration with funding primarily from the US Department of Energy. Requirements for this system are driven by DESI's key project to constrain the nature of dark energy by measuring the baryon acoustic oscillation feature in the large-scale structure of the universe as traced by galaxies over cosmic time. To measure redshifts for faint emission-line galaxies, DESI requires precision sky subtraction, which is achieved using the algorithm of Bolton & Schlegel[16] that employs the two-dimensional spectrograph point-spread function to extract spectra by building an accurate forward-model of the raw CCD data. Since DESI will measure redshifts for approximately 40 million galaxies, quasars, and stars over its 5-year primary mission, a high degree of automation is also implemented by the DESI pipeline. Adopting the precision and automation of the DESI pipeline will directly benefit the scientific reach of the MSE pathfinder.

Open-access observing time on the MSE pathfinder would be provided under the terms of a proposal for NSF funding of the instrument. NOIRLab would manage the allocation of this time through its existing Time Allocation Committee (TAC) process, which provides peer review of proposals for all NSF-funded ground-based optical-infrared observing time. Given that the MSE pathfinder will be a survey-optimized instrument, it is expected that most of this time will be allocated through the NOIRLab Survey program, which enables large multi-semester programs and includes an explicit focus on delivering data sets of significant legacy value. A fraction of time will also be available through the regular TAC process every six months for smaller and more opportunistic proposals. The NOIRLab allocation of US observing time will also include a mechanism for coordination with larger collaborative projects spanning multiple partner communities.

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5. FAST-TRACK TECHNOLOGY DEVELOPMENT

MSE technology to be fast-tracked with Pathfinder include:

Targeting and scheduling software to allow the system to interleave multiple large programs, along with PI programs, along with targets of opportunity into each pointing of the telescope in a way that produces the most science for open shutter time while satisfying the need to reach the completeness for the large programs.

Understanding and developing a proper sky subtraction techniques to compensate for errors possibly introduced at an extremely low level by the tilting spine technology, by aberrations within the spectrograph, by improper mode mixing within the fibers, and by temporal and spatial variations in the sky spectra that are sparsely sampled across the field.

Understanding and developing the data management and data analysis tools in a way that introduces the data archive to a large searchable database managed by NOIR labs.

6. COMMUNITY BENEFIT

Pathfinder will define a community benefit program which will be centered on NOIR labs becoming an Associate Partner of CFHT through the existing Associate Partner program. This would allow for a portion of the time on the pathfinder instrument at CFHT to be available to the entire U S community through the NOIR partnership. NOIR would handle all of the logistics associated with US observers i.e. they would provide their own TAC and proposal review process as well as time allocation.

7. SCHEDULE

Pathfinder is being developed in parallel with MSE. As a result, much of the design work has already been completed in particular the positioning system, both spectrographs, and the PESA software have all been developed to concept-review level. Expected first light will be in 2027.

8. CONCLUSION

Pathfinder will provide a unique capability to the US community to provide spectroscopic follow-up for time domain astrophysics as well as generalized spectroscopy including Galactic archaeology and spectroscopy of stars in order to better understand stellar evolution. It will be comprised of an instrumental upgrade to the Canada France Hawaii telescope that will provide a unique capability compared to what is currently available to the entire U S community, and with an infrared capability will be unique. The expectation is first light by 2027.

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