CDIM

Cosmic Dawn Intensity Mapper

A Probe Class Spectro-Imaging Astrophysics Mission for Reionization

A submission to the 2020 Decadal Survey

Theme: Space-based Probe class mission (study supported by NASA Probe Studies)

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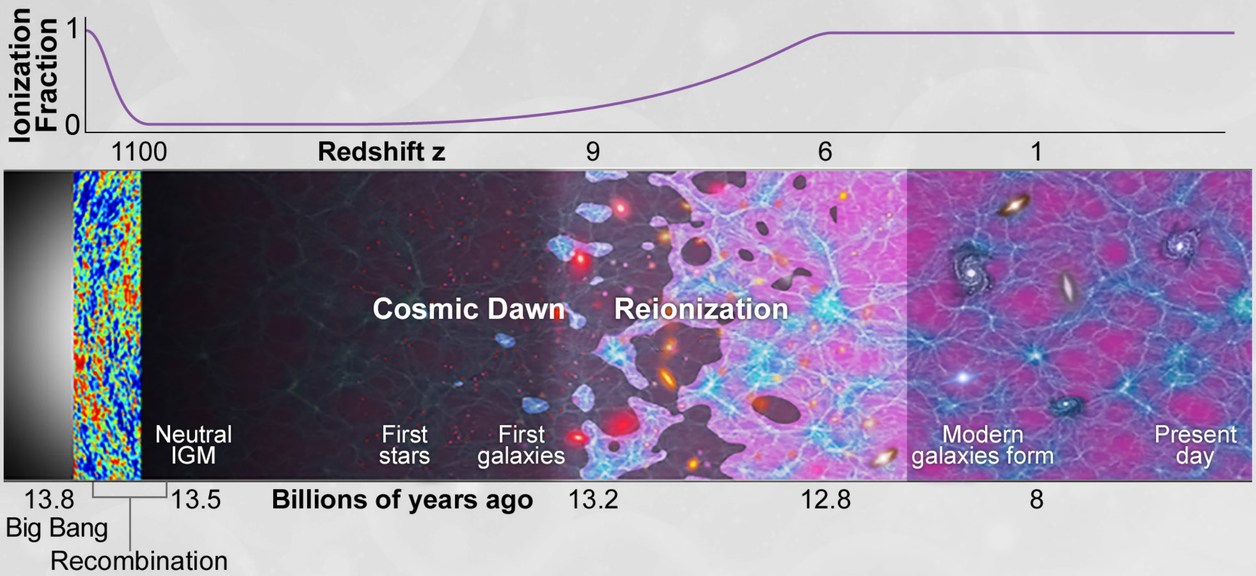
A Probe Class Spectro-Imaging Astrophysics Mission for Reionization

CDIM will transform our understanding of the era of reionization when the universe formed first stars and galaxies, and UV photons ionized the neutral medium.



CDIM FOCUSES ON THREE KEY SCIENCE GOALS

Galaxies

Measuring physical properties to z of 8

AGNs

Finding black holes to z of 8

IGM Tomography

Mapping reionization topology & history from z of 5 to 10

COMPLEMENTING FUTURE MISSIONS

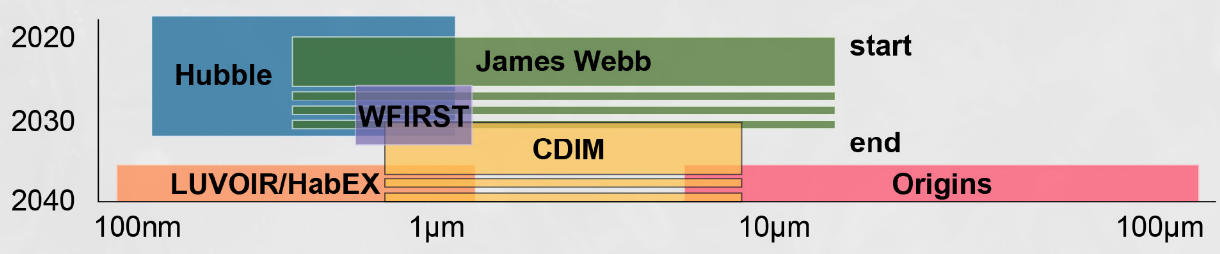


Figure 1. CDIM design and capabilities focus on the needs of detecting faint galaxies and quasars during reionization and intensity fluctuation measurements of key spectral lines, including Lyman-α and Hα radiation from first stars and galaxies. The design is low risk, carries significant science and engineering margins, and makes use of technologies with high technical readiness level for space observations. CDIM will fill the gap between LUVOIR/HabEX operating out to ~1–2 µm and Origins Space Telescope at above 5 µm.

UNIQUE SENSITIVITY TO DETECT OPTICAL EMISSION LINES

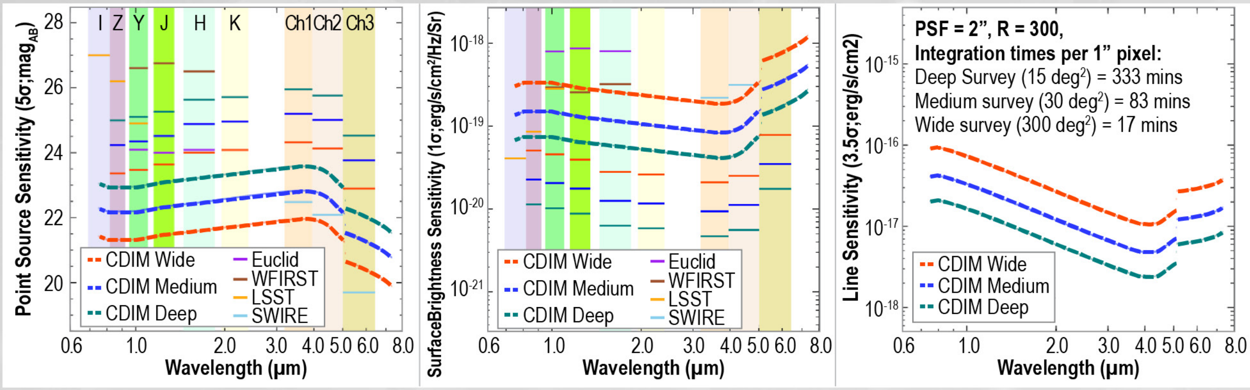


Figure 2. With a three-tiered survey designed to match science requirements, CDIM is uniquely sensitive to detect rest-frame optical emission lines or the aggregate intensity in emission lines over the entire cosmic history of galaxy formation and evolution, and out to the beginning of cosmic dawn ($z \sim 10$)

LINEAR VARIABLE FILTER (LVF) OBSERVATIONS

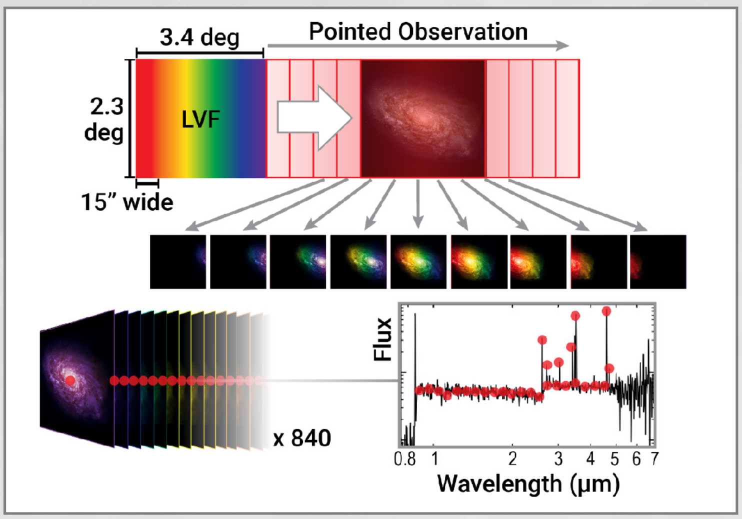
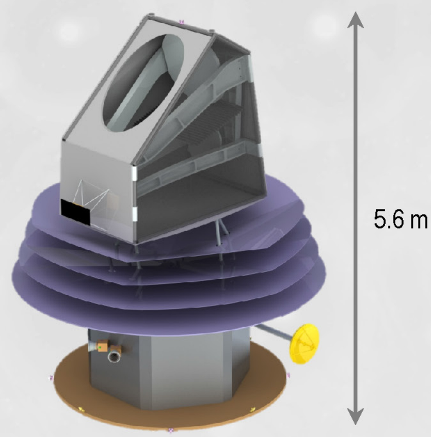


Figure 3. The full spectra are obtained by moving the telescope in small discrete steps corresponding to the CDIM spectral resolution across the dispersion direction of the LVF.

INSTITUTIONS

JPL, University of California Irvine, RIT, Ball Aerospace, Princeton University, IPAC, Caltech, University of Arizona, Harvard, Scuola Normale Superiore Pisa, UT Austin, Osaka University, University of Oslo, Carnegie Mellon, Ohio State University, University of Utah

CDIM FLIGHT SYSTEM

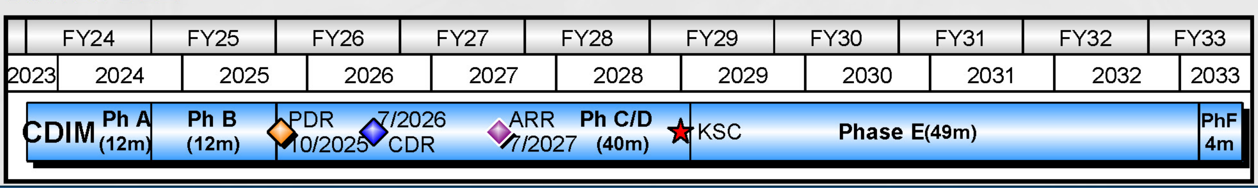


- 3-mirror all-reflective design with 0.83-m clear aperture
- Linear Variable Filters over 0.75–7.5 μm in 840 bands at R = 300
- V-groove radiators, passive cooling at T < 35 K in L2 halo orbit
- 4×6 H2RG detectors
- Data rate ~400 Gbit/day; 1 hr/day downlink
- 4-year survey for key sciences; plus extended mission for community observations

MISSION COST ESTIMATE

Total cost (including reserves): $905M (FY18)

SCHEDULE



1 EXECUTIVE SUMMARY

The Cosmic Dawn Intensity Mapper (CDIM) will transform our understanding of the era of reionization when the Universe formed first stars and galaxies, and UV photons ionized the neutral intergalactic medium. CDIM goes beyond the capabilities of upcoming facilities by carrying out wide area spectro-imaging surveys, providing redshifts of galaxies and quasars during reionization, and by measuring spectral lines that trace physical properties. CDIM will make use of unprecedented sensitivity to surface brightness to measure the intensity fluctuations of reionization to provide a valuable and complementary dataset to 21-cm experiments. The baseline mission concept is an 83-cm (effective aperture) infrared telescope equipped with a focal plane of 24×2048^2 detectors capable of R = 300 spectro-imaging observations over the wavelength range of 0.75 to 7.5 μm using Linear Variable Filters (LVFs). The large 7.8 deg^2 field of view allow efficient wide area surveys, and instead of moving instrumental components, spectroscopic mapping is obtained through a spacecraft shift-and-stare strategy. The design is low risk, carries significant science and engineering margins, and makes use of technologies with high technical readiness level for space observations.

2 KEY SCIENCE GOALS AND OBJECTIVES

The development of a comprehensive understanding of the physics that led to the formation of first stars and galaxies is challenging, but remains a fundamental goal of extragalactic astrophysics and cosmology. Over the next decade, multi-wavelength observations of the first galaxies and the early intergalactic medium will yield significant new clues in our quest to develop a fundamental understanding of the physics of the epoch of reionization (EoR). Though a great deal has been learned in the past two decades, and more information will be forthcoming with JWST and WFIRST over the coming decade, many key questions will remain unanswered, including: **(i) what is the history of stellar, dust and metal build-up in early galaxies during reionization?; (ii) what is the contribution of quasars to the reionization history of the Universe?; and (iii) what is the exact reionization history of the Universe?**

One reason for this limitation in our science understanding of reionization is that JWST extragalactic surveys will be likely limited to a handful of deep fields, with a total area of several hundred arcmin^2 (Salvaterra et al., 2011). While WFIRST will be capable of wide area surveys, due to the lack of spectroscopic capability beyond 1.8 μm, spectroscopic studies involving Hα will be limited to $z < 2$; JWST and WFIRST will not be definitive missions to complete our understanding of reionization – leaving open critical questions on the rate at which first galaxies formed their stars, dust and metals, the role of active galactic nuclei (AGN) in reionization, and the history and topology of reionization.

A Probe-class mission optimized for reionization studies will need to expand both imaging and spectroscopic capabilities over the expectations from JWST and WFIRST. The Cosmic Dawn Intensity Mapper (CDIM) is designed with an improved understanding of reionization as the primary science goal. The science program is directly linked to two of the NASA top-level goals in astrophysics (2018 NASA Strategic Plan and 2014 NASA Science Mission Directorate Plan): how does the Universe work? And how did we get here?

CDIM survey data will allow us to address the above three questions and many more, through the science program outlined in **Table 1**. In particular, CDIM spectro-imaging data with a spectral resolving power $R=\lambda/\Delta\lambda$ of 300 can be used to: (i) determine the spectroscopic redshifts of WFIRST-detected Lyman-break galaxies (LBGs) out to $z \sim 8$–9; (ii) conduct a complete census of first-light galaxies in over 2–3 decades of stellar mass by establishing their mass, metal abundance, and dust content by spectrally separating [NII] from Hα, and by detecting both Hβ and OIII; (iii) establish the environmental dependence of star-formation during reionization through clustering measurements; (iv) detect Lyα emission from individual bright first-light galaxies and combine with Hα line detections of the same galaxies for studies of variations of Lyα escape fraction with

Table 1. Science Program of the CDIM Probe Mission

NASA Science Goals	**How does the Universe work? How did we get here? (from *2014 NASA SMD Strategy Document*)**		
CDIM Science Themes	Galaxy Formation and Evolution at $5 < z < 8$	Active galactic nuclei at $5 < z < 8$	Reionization history through Lyman-α intensity
CDIM Science Goals	Trace the stellar mass buildup, dust production, and metal enrichment history during cosmic reionization.	Establish the role of active galactic nuclei (AGN) in cosmic reionization	Establish the progression and topology of reionization from cosmic dawn at z=10 to the end of reionization at z < 6.
CDIM Scientific Objectives	Determine if the rate of growth of metals and dust corresponds to the growth of stellar mass at $5 < z < 8$.	Determine the fractional contribution of super-massive black hole/AGNs to reionization photon budget.	Determine the progress of reionization by measuring the ionization fraction in at least 10 redshift bins at $5 < z < 10$, with accuracy better than 10%.

environment and other physical properties; and (v) use the redshift-evolution of spectral-line intensity fluctuations to determine the reionization history of the Universe.

While the primary focus is EoR, CDIM is also designed to study galaxy formation and evolution throughout cosmic history. It will map out, for example, Hα emission from $z = 0.2$ to 10 and will detect Lyα emission from galaxies present during reionization. Wide area spectral mapping with CDIM will allow searches for rare sources, such as bright quasars, active galactic nuclei (AGN), and galaxies that make up the bright-end of the luminosity functions. CDIM surveys will provide three-dimensional view of the star-formation history, its environmental dependence, and clustering over 90% of the age of the Universe.

For the first theme, using galaxy samples and their exquisite spectra from CDIM we will address the rate of growth of metals and dust during reionization. The same CDIM data can also be used to address whether the initial mass function (IMF) of stars in reionizing galaxies at $z > 6$ is different from the IMF of stars in galaxies today. The difference could be attributed to differences in the physical properties of stars during reionization, which are likely to be metal poor and, on average, have masses that are higher than the stars in galaxies at low redshifts.

With AGN or quasar samples, our second theme seeks to address if they make a substantial contribution to the UV photon density budget during reionization. Current expectations are that galaxies are primarily responsible for reionization, but uncertainties remain on the role played by quasars and AGNs.

For the third theme, CDIM is capable of detecting Lyα emission from bright galaxies present throughout the full history of reionization, without the restrictions of ground-based narrow-band Lyα emitter surveys that are only limited to a handful of redshifts allowed by the atmospheric window. When combined with Hα and UV continuum detections of the same galaxies, CDIM will allow a complete statistical study of the escape fraction of ionizing radiation, relating galaxy properties to their environment. For the fainter population undetected as individual galaxies, CDIM is capable of sensitive surface brightness measurements leading to intensity mapping of spectral lines, including Lyα during reionization. These line intensity maps will be compared with 21-cm fluctuations that trace neutral hydrogen. Galaxies bright in Lyα emission are expected to have a relatively high ionizing photon emissivity, leading to a larger size for their surrounding

Table 2. CDIM survey requirements summary

CDIM Science Themes	Galaxy Formation and Evolution at $5 < z < 8$	Active galactic nuclei at $5 < z < 8$	Reionization history through Lyman-α intensity
CDIM key Technical Requirement	Wavelength range of 0.75–7.5 μm to detect Lyα and Hα. Spectral resolution R > 300 to separate [NII] from Hα for metallicity measurements. Line flux sensitivity to detect Hα below L^* at $z = 6$ in a deep survey of 15 deg^2.	Large 300 deg^2 survey area to probe adequate cosmic volume (wide survey). Point source sensitivity down to K band magnitude of 23.5.	Large field of view to map sufficient areas on the sky for large-scale reionization topology, overlapping with wide epoch of reionization 21-cm surveys (medium survey). Sufficient surface brightness sensitivity to detect Lyα at a minimum signal-to-noise ratio of 500 in a medium survey of 30 deg^2.

ionized bubbles than the bubbles of Lyα-deficient galaxies. Therefore, galaxies bright in Lyα emission should be anti-correlated with the 21-cm emission from the intergalactic medium (IGM) on scales smaller than their bubbles. This anti-correlation provides ways to establish the bubble sizes during reionization as a function of redshift. The two in combination also allow reionization history to be determined, improving over the current uncertainties by an order of magnitude or more, while not subject to systematics that can negatively impact 21-cm alone measurements.

Currently prioritized science programs, conducted over four years, will be accomplished with a three-tiered wedding-cake survey with the shallowest spanning 300 deg^2 and the deepest tier of about 15 deg^2. **Table 2** summarizes survey requirements, while **Table 3** lists the surveys anticipated to meet the requirements. The sensitivity levels are summarized in **Fact Sheet Figure 2**. We plan to overlap the deep survey with one of the deep fields of WFIRST and/or Euclid surveys located in either the North Ecliptic Pole (NEP) or the South Ecliptic Pole (SEP) for synergistic science. The medium survey is chosen to overlap with one of the SKA1-LOW deep fields, likely the Extended Chandra Deep Field-South (ECDF-S), which will also overlap with the 21-cm EoR survey of the Hydrogen Epoch of Reionization Array (HERA). The wide survey is designed to surround the deep survey to optimize observing efficiency in either the NEP or SEP, which is visible year-round from L2 for ease of scheduling. The integration time per LVF step is 250 seconds, ensuring that photon-noise dominates, and the total integration time per spatial pixel per spectral resolution element are 333.3 minutes, 83.3 minutes and 16.7 minutes each for deep, medium wide surveys, respectively. In practice the surveys will be completed with multiple surveys (visits) over the same areas, with a redundancy of 80, 20, and 4 visits for the deep, medium and wide surveys, respectively. The redundancy is used for cross-checks on systematics and to minimize effects of Zodiacal light, among others, and allows Nyquist-sampling of the spectral resolution by a spatial offset of the pointing position per visit of half the LVF step size.

The primary science goal addressed by the deep survey is pioneering observations of the Lyα, Hα and other spectral lines from individual galaxies throughout the cosmic history, but especially from the first generation of distant, faint galaxies when the Universe was less than 800 million years old. Deep survey/instrumental requirement will be line sensitivity of better than 1×10^{-17} erg s^{-1} cm^{-2} at 1.0 μm, with spectral resolving power of 300 to separate Hα and [NII] for accurate metallicity measurements and galaxy/AGN separation. The medium survey aims for three-dimensional tomographic view of EoR mapping Lyα emission from galaxies and the intergalactic medium (IGM), with a surface brightness sensitivity requirement of 1.3×10^{-18} erg s^{-1} cm^{-2} Hz^{-1} sr^{-1} at 1.1 μm. The wide survey requirement will be K-band AB mag = 23.5 to capture quasars at $z > 6$. Table 3 shows the sensitivities achieved by the current mission and survey design.

	Table 3. Proposed CDIM Surveys							
Survey	**Area (deg^2)**		**Sky location**	**Total Integration Time for full survey area (days)**	**Point source depth** (K-band AB mag; 5σ)	**Spectral line flux detection limit** (1 μm at R = 300; 3.5σ) [10^{-17} erg/s/cm^2]	**Surface brightness sensitivity** (1.1μm at R = 300; 1σ) [10^{-19} erg s^{-1} cm^{-2} Hz^{-1} sr^{-1}]	**Scientific drivers**
	Reqt.	Survey Design						
Deep	15	15.6	SEP or NEP	584	25.7	1.5	0.70	Galaxies – stellar mass, dust, and metallicity
Medium	30	31.1	ECDF-S	292	25.0	3.2	1.5	Reionization history through Lyman-α intensity
Wide	300	311	SEP or NEP	428	24.0	8.0	3.3	Quasars/AGNs

The difference between requirement numbers quoted above and the sensitivities shown is the science margin that we carry for any technical changes during mission formulation.

Astro2020 Science White Papers overlapping with CDIM: The science case related to CDIM appears in the reionization overview (Cooray et al. 2019), intensity mapping sciences (Chang et al. 2019; Kovetz et al. 2019), and galaxy redshift surveys for cross-correlations with 21-cm data (Furlanetto et al. 2019). An example GO science case with a mission such as CDIM is the discovery of cold brown dwarfs (Leggett et al. 2019).

3 TECHNICAL OVERVIEW

CDIM is an infrared survey mission that will provide spectra from 0.75 to 7.5 μm at R=300 for fields as wide as 300 deg^2. The instrument employs a 1.1-m cryogenically cooled telescope to image a 9 deg^2 instantaneous field of view. An array of Teledyne H2RG detectors provides sky-limited imaging while linear variable filters select the wavelengths with high efficiency. Spectra are constructed for each object by repointing the spacecraft to move the instantaneous field in a series of small steps across the detector array.

The proposed NASA Probe Class Mission Cosmic Dawn Intensity Mapper (CDIM) is an 83-cm effective aperture (1.1-m physical aperture), passively cooled telescope (down to 35 K), designed to meet NASA's Class B mission requirements (Figure 1). CDIM is capable of three-dimensional spectro-imaging observations over the wavelength range of 0.75 to 7.5 μm, at a spectral resolving power $R=\lambda/\Delta\lambda$ of 300. The focal plane is made up of 24 × 2048^2 detectors, leading to an instantaneous field-of-view (FoV) of 3.4 × 2.3 = 7.8 deg^2 with 1″ pixels.

CDIM will make use of fixed linear variable filters (LVFs) to image the sky at narrow Δλ wavelengths, rather than a using a dispersing element or a grism. This design has no moving parts, and is ideally suited to measuring spectra across a wide-field focal plane. An integral field spectrograph for such a large focal plane is not feasible on a Probe-mission budget.

CDIM will cover the spectral range between 0.75 and 7.5 μm with 840 independent spectral channels (**Fact Sheet Figure 2**). A fully Nyquist-sampled spectrum then requires 1680 individual pointings towards a given line of sight, with pointings offset by an angle that is δθ/2 of the LVF width δθ on the sky. The LVF varies in wavelength along the 3.4° direction with a width of δθ at 15″. To ensure uniform spectral sampling the step size must be accurate to about 0.5″. Even though a survey requires 1680 individual pointings in each sky position, CDIM is designed to be very efficient; current best estimate for design and operations shows an efficiency of 93%. The key science programs build on a survey strategy that requires 250 seconds of integration at each LVF position in the shallowest team, while deeper surveys interleave multiple visits at the same integration time. The spacecraft operations for an individual shift of the LVF across a given sky position involve an overhead with less than 10 seconds to slew and settle. This ca be compared to 250 seconds of integration.

CDIM builds on the existing heritage of using LVFs for spectral mapping on the sky. Past successes include WFPC2 on HST, OVIRS on OSIRIS-Rex and LEISA on New Horizons. By taking repeated images, the spectrum is constructed in the data analysis process. CDIM is a natural follow-up mission to SPHEREx, an explorer class mission that utilizes R = 35–130 LVFs to map the whole sky between 0.75 and 5 μm using a 20-cm aperture telescope. While the focus on SPHEREx is all-sky cosmological measurements using shallow depths to cover the spatial distribution of galaxies out to z of 1.5, by going deeper on 15–300 deg^2 patches on the sky, CDIM aims to focus on the era of reionization.

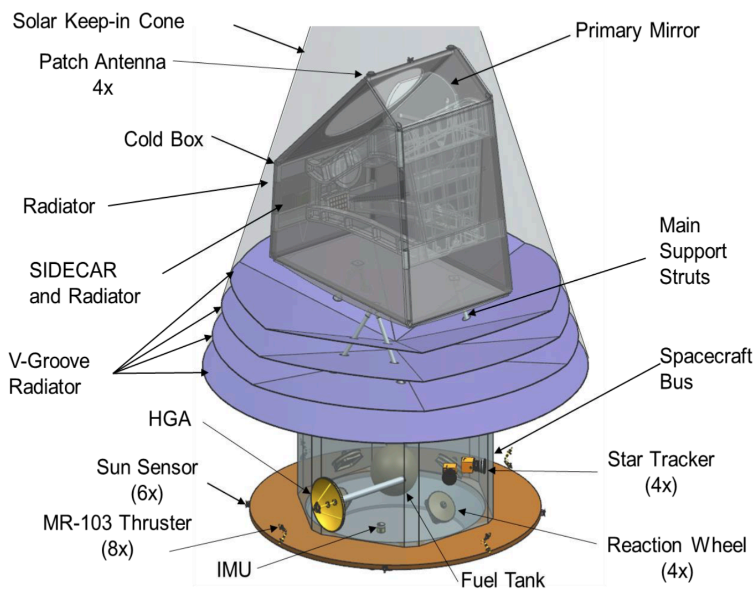


Figure 1. CDIM's telescope is mounted on V-groove radiators above the spacecraft bus to enable passive cooling and maximize observation time.

While the CDIM concept proposed here assumes four years of operations to meet the key scientific objectives, the mission lifetime is limited primarily by consumables. The design allows science operations that could last substantially longer than the four years necessary for the key science identified in the report. Thus, CDIM is fully capable of functioning as a general-purpose observatory, enabling substantial community-led observing campaigns, to be selected via the usual peer-review process. These could be in the form of mapping the Galactic plane to targeted studies of near-by galaxies, or other deep cosmological fields, for example. Due to its large FoV and rapid mapping capability, CDIM can also function as a transient source identifier for time-domain sciences. Of interest in 2030s will be identification of electromagnetic counterparts to gravitational-wave sources, especially super-massive black hole merger events detected by the LISA gravitational-wave space observatory. CDIM is capable of rapid scanning of LISA error boxes, expected to be in the order of 10 to 100 deg^2. A future study will be necessary to properly work out the requirements for such an transient survey observational campaign with CDIM.

4 Technology Drivers

The CDIM instrument is a simple high-throughput design that relies on established technologies for the telescope and most of the focal plane. Areas of required development are the 7.5 μm H2RG sensor and the linear variable filter elements (both currently assessed at TRL 4). Investments by NASA can readily advance the state of the art in these areas. Our plans leverage these investments and provide three-year programs to advance TRL to 6 in advance of flight development.

CDIM is low-risk. The two key technology development items are the production of LVFs to meet the requirements on filter shape and out-of-band leakage and the H2RG detectors that allow imaging out to the longest wavelengths covered by CDIM of 7.5 μm. The LVF technology already has substantial development already by industry, while substantial work is underway to space qualify long-wavelength H2RGs as part of NASA concept missions such as NEOCAM. The CDIM telescope and other technical components are already commercially available and are already flight qualified or will be flight qualified. This includes components such as Teledyne SIDECAR ASICs that will be qualified as part of Euclid.

The CDIM design takes advantage of heritage in the following hardware items:

CDIM mirrors. The CDIM beryllium mirrors are of a freeform figure, modest radius of curvature, and smaller in diameter than JWST mirrors (Lightsey, 2007) and comparable to Spitzer 85-cm Be mirror.

H2RG detectors. Widely used in the IR community and currently available from Teledyne, with flight versions for JWST (Rauscher et al., 2011) and Euclid (Waczynski et al., 2016).

Linear Variable Filters. LVFs in near-IR have been flown in New Horizons/LEISA (with R=240 and 560; Baker, 2007; Reuter et al. 2008) and OSIRIS-Rex at asteroid Bennu; its OVIRS instrument (Reuter et al., 2018) covers 0.4–4.3μm in 3 bands with R = 125–200.

Thermal design. The simple thermal design is based on the successful Planck mission (Leroy et al., 2006), leading to < 35K for the focal plane. The thermal design has substantial margins, possibly allowing one of the v-groove panels to be eliminated (future design trade).

Spacecraft. CDIM uses the Ball Configurable Platform (BCP) spacecraft with 12 missions on orbit. All spacecraft share a core architecture that has evolved over 20+ years. Past programs span Earth sciences, remote sensing, including DoD operational, and commercial imaging.

4.1 7.5 μm H2RG sensors

Five of the six CDIM bands for the focal plane are accommodated by existing, off-the-shelf detector products (TRL 9) from Teledyne that currently meet the mission requirements. The sixth band has a cutoff wavelength of 7.5 μm to reach redshifted Hα 656 nm at $z = 10$ (7.2 μm) and some development is required to enter a flight qualification program for the long wavelength detector. NEOCAM, funded by NASA, is already working with Teledyne to extend the cutoff wavelength. H1RG 1k×1k test products are already available with cutoff wavelengths as long as 13 μm (McMurtry et al., 2016a). Devices with a 10 μm cutoff produced for the NEOCAM study have been substrate-thinned to 30 μm and exhibit dark current (>80% of pixels) of under 0.2 $e^{-}s^{-1}$ at 35 K (McMurty et al., 2013), meeting the science requirements of CDIM.

We propose a three-year plan to work with Teledyne to develop the required 2kx2k sensors for CDIM with operability > 95%, optimize quantum efficiency, and radiation testing to verify requirements. Our budget estimate for this work is $8M.

4.2 LVF Technology

The current state of the art of LVFs has been demonstrated by industry: Omega, Viavi (OCLI), Materion (Barr Associates) and by research labs between 0.4μm to 4μm (over several octaves) with 2 to 100 nm/mm spectral gradient. These LVFs have in-band transmission > 85% and have out-of-band rejection 3 to 5 Optical Density (OD). The CDIM filter requirements are to fabricate 4 × 6 (LVF) filter matrix architecture and mounted in front of the CDIM detector focal plane assembly. These LVFs for the CDIM are required to have 6 segments covering 0.75 μm to 7.5 μm spectral range, have an out-of-band rejection of OD-5, and kept thermally stable at 35 K. The LVF will have $R = \lambda/\Delta\lambda \geq 300$ and the size of each filter segment will be 40 mm × 40 mm.

The main challenges with the LVF for the CDIM are: extending the spectral range of the LVF > 4 μm to 7.5 μm (coating materials); achieving out-of-band rejection at ≥ OD-5 and controlling induced stress of the coating layers and substrates. We plan to work with Omega Optical to develop processes to use known IR coating materials in the 4 μm to 8 μm spectral range (Ge, Si, ZnS, and YF3); develop processes for the FeOx and ITO materials to improve blocking for all segments.

OD-5 out-of-band rejection can also be achieved by adding a second air-spaced (gradient) blocking filter
to the light path. To achieve TRL 6, we will follow flight environmental testing requirements and procedures on LVF prototypes – including multiple thermal cycles to the operating temperature of 35 K. Our budget estimate for this work is $4M.

5 Cost Assessment

The Cosmic Dawn Intensity Mapper (CDIM) fits within the cost guideline for a Probe-class mission, with an estimated total cost of $905M (incl. launch vehicle, 30% development reserves, and 15% operations reserves).

The costs presented in Table 4 are ROM estimates from JPL Team X; they are not point estimates or cost commitments. It is likely that each estimate could range from as much as 20% percent higher to 10% lower. The costs presented are also based on Pre-Phase A design information, which is subject to change. All costs quoted in are in $FY18, as estimated in Nov 2018.

The CDIM team substituted costs where team's estimates are higher fidelity than the corresponding model cost. It is likely that each estimate could range from as much as 20% percent higher to 10% lower. The costs presented are based on Pre-Phase A design information, which is subject to change. All costs quoted in this Report are in $FY18.

Team X used two models to estimate the cost of the Instrument (Telescope, thermal control system, and focal plane, and cold electronics) selected for which best captures the cost for its respective subsystem.

- Optical Telescope Assembly (OTA) – using multivariable parametric telescope cost model by Stahl & Henrichs (2016): $15M including reserves.
- Focal Plane – Team X adopted the higher-fidelity (and much-higher) CDIM Team cost estimate ($70M). This was estimated by scaling from the costs already incurred by the Euclid and NEOCam projects to develop and fabricate the CDIM's 24-detector focal plane.

Table 4. CDIM mission cost from Team X and CDIM Team

Work Breakdown Structure (WBS) Elements	Team X Cost Estimate ($FY18)	CDIM Team Cost Estimate ($FY18)
Development Cost (Phases A-D)	$690M	$666M
1.0, 2.0, & 3.0 Management, Systems Engineering, and Mission Assurance	$51M	$51M
4.0 Science	$25M	$25M
5.0 Payload System	$170M	$170M
5.01 Payload Management	$2.0M	$2.0M
5.02 Payload Engineering	$1.5M	$1.5M
5.04 Telescope (incl. II&T)	$167M	$167M
5.04.01 Instrument (IR Spectrometer)	$152M	$152M
5.04.02 Optical Telescope Assembly	$15M	$15M
6.0 Flight System	$220M	$190M
7.0 Mission Operations Preparation	$16M	$16M
9.0 Ground Data Systems	$23M	$23M
10.0 Assembly, Test, and Launch Operations (ATLO)	$25M	$34M
12.0 Mission and Navigation Design	$0.0M	$4M
Development Reserves (30%)	$160M	$154M
Operations Cost (Phase E)	$89M	$89M
1.0 Management	$4.5M	$4.5M
4.0 Science	$40M	$40M
7.0 Mission Operations	$24M	$24M
9.0 Ground Data Systems	$10M	$10M
Operations Reserves (15%)	$11M	$11M
Launch Vehicle	$150M	$150M
Total Cost (including Launch Vehicle)	$930M	$905M

Table 4 reflects the Stahl telescope model and the CDIM Team estimate for the focal plane.

The spacecraft cost was estimated by Team X using JPL institutional cost models for an 'out of house' build, using design parameters provided by the CDIM team. The Team X estimate was

$245M (WBS 6+10). Separately, the CDIM Team worked with our spacecraft partner Ball Aerospace to develop an independent estimate of the spacecraft cost. Ball used SEER, based on the MEL and other design data in the Team X Report. Ball also estimated these costs using actual cost data from previous Ball spacecraft developed to Class B standards, and parameterized according to bus mass. The CDIM team adopted Ball-SEER as the best estimate for WBS 6 and 10 with a cost of $190M (WBS 6) and $34M (WBS 10).

Costs for Science Team and Analysis were estimated by analogy with experience with WISE and Planck. Team X adopted the CDIM Team's estimates for WBS 4 with Phase B-D: $25M and Phases E-F: $40M.

Total Mission costs are estimated primarily from the output of the Team X models. Reserves on Phases A-D are carried at 30% and Phases E-F Reserves are 15%, per JPL flight project guidelines. (No reserves are carried on Launch Vehicle and spacecraft tracking). E&PO costs (WBS 11) are not included. The CDIM Team’s best estimate of total mission cost is **$905M**.

6 MANAGEMENT AND SCHEDULE

Management of the CDIM Mission would be governed primarily by the management guidelines outlined in a NASA Announcement of Opportunity (AO) for a Probe-class astrophysics mission. For this study, we assumed a specific management approach for the purposes of estimating mission costs. We assume that the mission would be PI-led, in a similar way to a New Frontiers mission in NASA's Planetary Science Division of the Science Directorate. In a future competition, the management structure would be proposed in response to the AO, and could different from the outline assumed in this Report.

Management of the mission would be the ultimate responsibility of the PI. Team X cost models (§5) assume JPL manages most elements, except the spacecraft and ATLO which would be subcontracted to a major partner, which we assume in this Report to be Ball Aerospace. JPL would be responsible for Management, System Engineering, Mission Assurance, Payload (including thermal design and I&T), Mission Operations, Ground Data System, and Mission Operations. Ball Aerospace would be responsible for the spacecraft bus, payload integration to the bus, and ATLO. NASA would be responsible for providing the launch vehicle and launch services. Elements of the payload would be sub-contracted: the telescope, focal plane design and fabrication, detectors, and LVFs. The Science Data Center would be hosted at IPAC, where several NASA infrared missions (including WISE and Spitzer) have their Centers. The PI would be responsible for assembling a Science Team, and managing that Team's activities both pre-launch and post launch (delivering data products to the community).

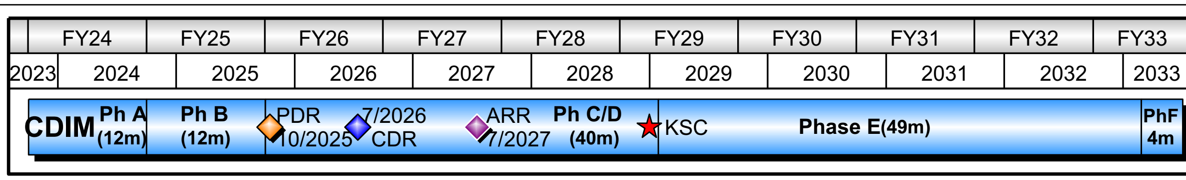


Figure 2. Development and operations schedule for CDIM. Phase E taken to be 4 years Any Extended Mission can be added to Phase E. CDIM is capable of a substantial community-led General Observing (GO) campaign.

6.1 Schedule

Team X costed the CDIM Mission assuming a 64-month development phase (A-D), with durations appropriate for a New Frontiers-class mission (Figure 2). The schedule makes the normal assumption about the technological readiness of the proposed mission: all elements must be at TRL 6 by the end of Phase B (PDR). For CDIM, there are two technology developments that must achieve TRL 6 by PDR (see §4); the technology development plan is consistent with this schedule.

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