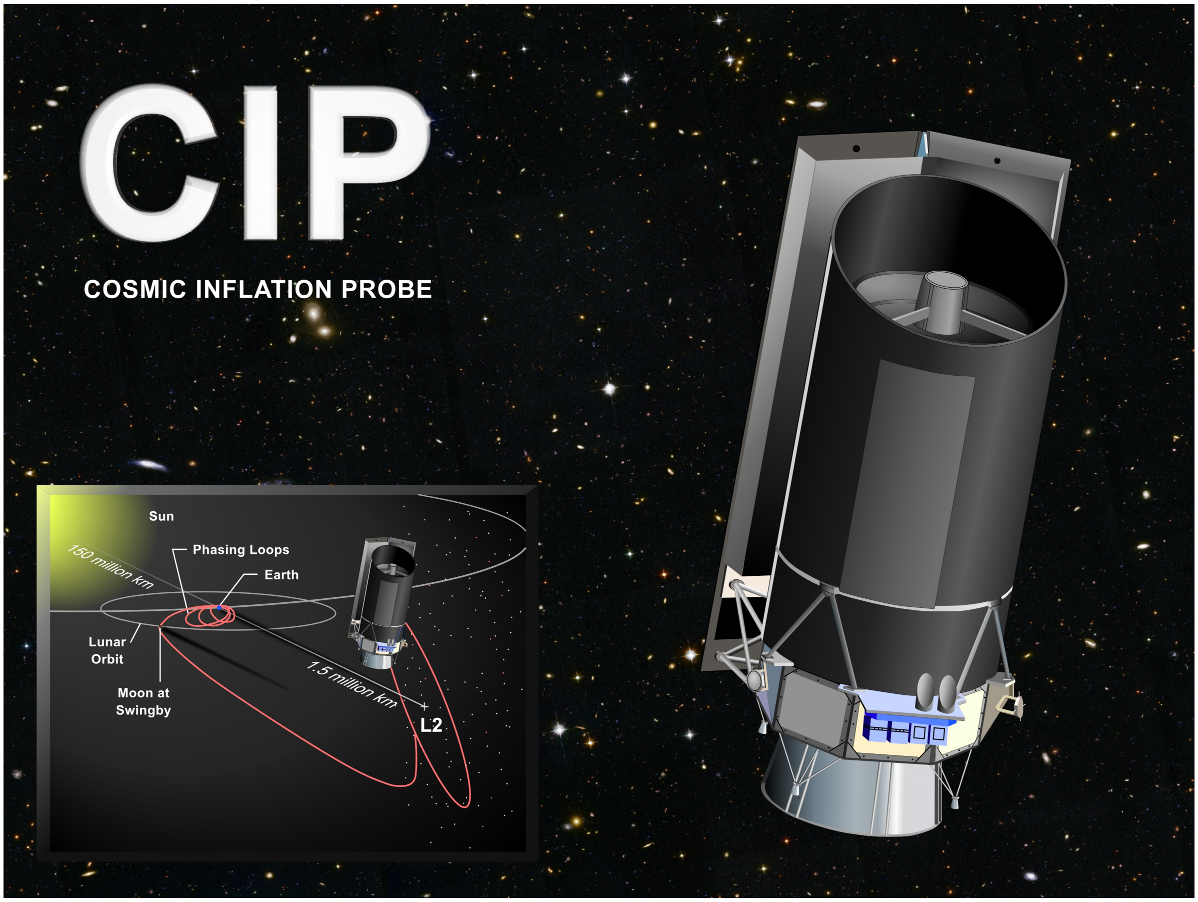
Cosmic Inflation Probe (CIP):

An Astrophysics Strategic Mission Concept Study



Gary J. Melnick[1], Volker Bromm[2], Giovanni G. Fazio[1], Karl Gebhardt[2], Daniel T. Jaffe[2],
Eiichiro Komatsu[2], Avi Loeb[3], Jonathan R. Pritchard[3], Charles Steidel[4],
Volker Tolls[1], Michael W. Werner[5] and Robert A. Woodruff[6]

[1] Smithsonian Astrophysical Observatory, [2] University of Texas, [3] Harvard University,
[4] California Institute of Technology, [5] Jet Propulsion Laboratory, [6] Lockheed Martin Corporation

With industrial partners: Lockheed Martin Corporation, ITT Space Systems,
and Teledyne Scientific & Imaging

and the

Jet Propulsion Laboratory

January 12, 2009

CIP Study Findings

The CIP mission concept has been refined as a result of three extensive design studies – first as a NASA-funded Origins Probe mission concept in 2004-2005, second as a candidate Beyond Einstein Inflation Probe in 2006-2007 and, most recently, as a NASA-funded Astrophysics Strategic Mission Concept Study.

The four main goals of the most recent study have been an assessment of: (1) the feasibility of extending the wavelength coverage from 2.5–5 μm to 1.8–5 μm through the use of a second spectrometer channel; (2) operating the long-wavelength focal plane detector arrays at 37 K (versus $\sim$45 K, as previously baselined), thus permitting full heritage with identical arrays operating at 37 K on JWST; (3) use of a 1.5-meter diameter primary mirror (versus a 1.8-meter diameter primary mirror previously studied); and, (4) any technology development needs.

The results of the year-long study are:

MAIN CONCEPT STUDY FINDINGS

1) **Demonstrated the feasibility of the dual-channel, passively-cooled CIP comfortably within the cost guidelines specified for a NASA Medium-Class mission.**
2) **Demonstrated the feasibility of achieving a 37 K operating temperature for the 3.1-5 μm focal plane detector arrays, thus allowing the direct use of cost and risk models developed for the JWST detector arrays and reducing CIP risk and cost.**
3) **Demonstrated the feasibility of achieving CIP science goals with a smaller primary mirror than originally envisioned (1.5 vs. 1.8 meters), thus allowing fuller use of heritage development hardware and facilities and reducing risk and cost.**
4) **CIP requires no further technology development; it is ready to move into development now.**

CIP SCIENCE GOALS

Inflation is that brief epoch, lasting between about 10^{-36} and 10^{-34} seconds after $t = 0$, when the Universe underwent faster-than-light expansion and its size grew by a factor of $\sim 10^{43}$ (~ 100 e-foldings). Understanding Inflation is essential to understanding the formation of the Universe because it saves the Big Bang model by providing a natural explanation for the:

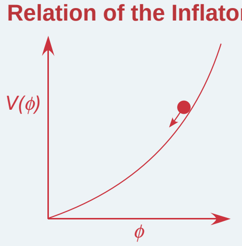
- Isotropy of the cosmic microwave background (CMB) radiation
- Flatness of space
- Initial density fluctuations which provided the seeds for galaxy formation

Yet, despite the indispensable role Inflation plays in our understanding of the Universe, *the physics that drove Inflation remains undetermined and essentially unconstrained.*

A series of phase transitions, occurring as the Universe cools, is believed to govern the way in which Inflation unfolds. A scalar field, referred to as the inflaton field, and its associated potential, $V(\phi)$, control these phase transitions. *The physics that drove Inflation dictates the shape of $V(\phi)$; measure the shape of $V(\phi)$ and it's possible to determine the physics responsible for Inflation.* Because $V(\phi)$ determines the rate at which the Universe expanded during Inflation, the amount of matter clustering on different spatial scales, referred to as the galaxy power spectrum, $P(k)$, is directly related to the shape of the inflaton potential (see below). In this way, the physics that prevailed when the Universe was less than 10^{-34} seconds old has left its imprint on the Universe observed today.

The Cosmic Inflation Probe (CIP) is a Medium-Class mission designed to measure the galaxy power spectrum $P(k)$ to better than 1% over length scales of 1 to 50 Mpc. The goal is to use these data to estimate the shape of the primordial power spectrum, convert it to a scalar potential, and compare this to the predictions made by various Inflation theories. CIP will provide significantly improved constraints on Inflation models using proven observational techniques and a well-studied mission design based on existing technology. Specifically, CIP will conduct a space-based large-area galaxy redshift survey in Hα between 1.8 and 5 μm capable of detecting $> 10^8$ objects between a z of 1.8 and 6.5. Since each spatial scale probes a different epoch in the Inflationary period, it's important to sample as large a range of spatial scales as possible. CIP stands alone in accuracy at small spatial scales. Combining CIP results with WMAP and Planck results at larger spatial scales, it's possible to directly measure the expansion history during Inflation over the broadest range which provides an even more powerful test of Inflation models than CIP or CMB measurements alone.

Relation of the Inflaton Potential, V(ϕ), to the Primordial Power Spectrum, P(k)



ε: slope $(V'/V)^2$

η: curvature (V''/V)

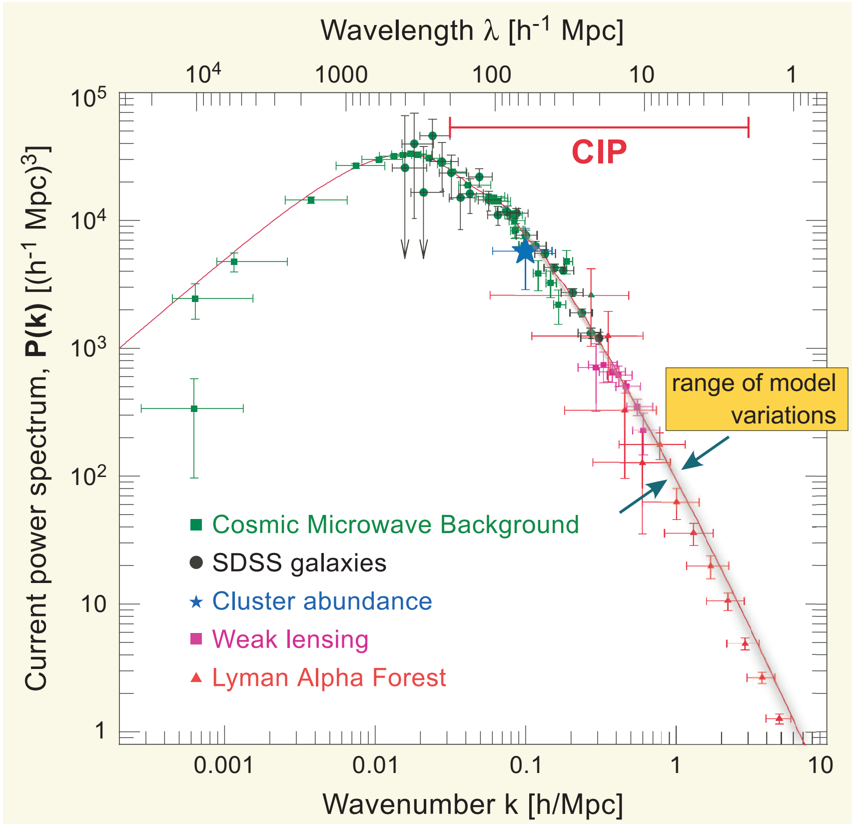
ξ: jerk $(V'/V)(V'''/V)$

$$\ln P_{prim}(k) = A + \left[n_s + \frac{1}{2}\alpha_s \ln\left(\frac{k}{k_o}\right)\right] \ln\left(\frac{k}{k_o}\right)$$

$$n_s = 1 - 6\varepsilon + 2\eta \quad \textbf{: Tilt}$$

$$\alpha_s = -2\xi + 16\varepsilon\eta - 24\varepsilon^2 \quad \textbf{: Running}$$

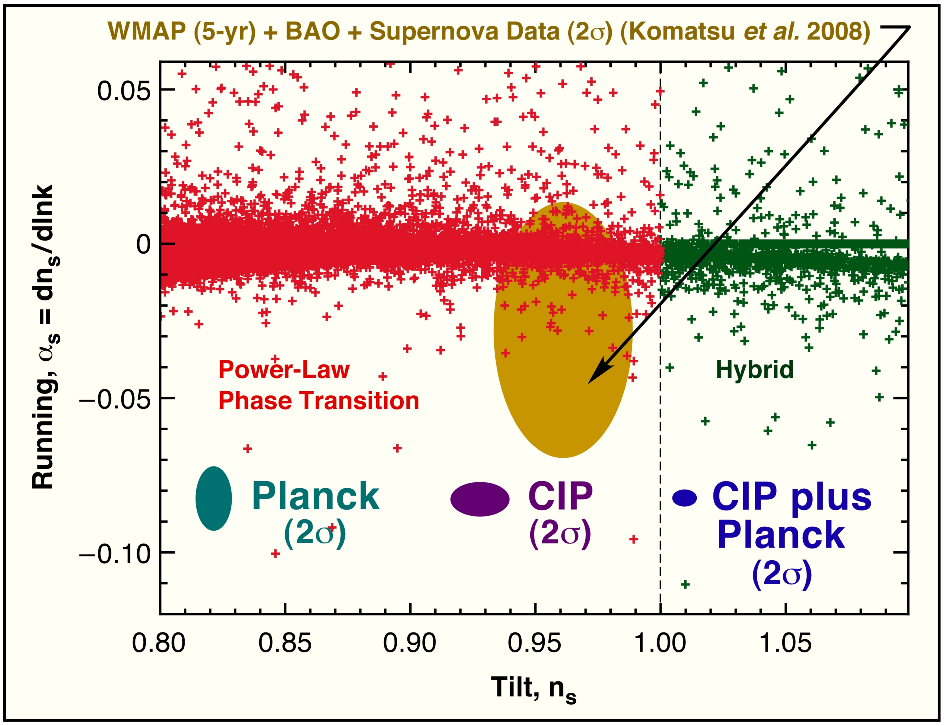
Unfortunately, because the hundreds of Inflation models make similar, but not identical, predictions for the shape of $V(\phi)$ and thus $P(k)$, these models are often treated in a phenomenological way as "perturbations" around the average power spectrum, often parameterized by two terms – tilt and running.



The above power spectrum (after Tegmark *et al.* 2004) has been modified to show the k-range sampled by various techniques, including the range that would be covered by CIP, along with existing measurements. The fit used as an illustration in the Tegmark figure is based on WMAP first-year data and other existing data at higher k. It is necessary to measure $P(k)$ to 1% in order to distinguish between nearly identical models, which is the goal of CIP. (Note: Tegmark *et al.* use a convention wherein $k = \pi$/length-scale.)

Since successful inflationary models must have a nearly flat potential, they generally predict tilt ~ 1 and a running of ~ 0. Precise measurements of the deviation from these values are the key to discriminating between different inflationary models. The figure on the next page shows predicted values of tilt and running from a sample of Inflation models (e.g., Power-Law, Hybrid, Phase Transition) characterized by a single scalar field and which make the Universe flat (or nearly flat). The constraints set by WMAP (5-year) + SDSS BAO + supernovae data and by CIP are shown and illustrates how the proposed CIP mission can better distinguish between models. Combined with the CMB data, which samples different spatial scales and thus different epochs of Inflation, CIP will test if running $= 0$ to unprecedented accuracy. If running $\neq 0$, the implication is profound and will challenge the simplest model of inflation. (The placement of CIP and Planck constraint ellipses in this figure are arbitrary.)

CIP will also contribute to our ability to distinguish between Inflation models through its ability to measure primordial non-Gaussianity. The current limit from WMAP (5-year) is $f_{\rm NL} = 51 \pm 30$ (Komatsu *et al.* 2008). The Planck mission is expected reach $\Delta f_{\rm NL} \sim 3$ (Yadav, Komatsu, and Wandelt 2007). CIP is expected to achieve $\Delta f_{\rm NL} \sim 2.4$ (Sefusatti and Komatsu 2007) using the bispectrum, with further reductions possible using the shape of the power spectrum.



THE CIP SURVEY

The CIP survey will cover 1,000 contiguous square degrees in the vicinity of the north ecliptic pole. The total integration time per $18' \times 18'$ field-of-view of approximately 5,000 seconds will be obtained in segments of $\sim$500 seconds at 10 different position angles on the sky. By changing the dispersion direction on the sky, it becomes possible to solve for the relative position of the frames, the roll angle of the spacecraft for each exposure, and the position and wavelength scale for each point source in the field. It also becomes possible to deconvolve any sources that overlap at some position angles.

CIP ANCILLARY SCIENCE

The CIP instrumentation and mission design have been optimized for one purpose: to provide an as-accurate-as-possible representation of the galaxy power spectrum between redshift 1.8 and 6.5 to constrain the Inflation history of the Universe. Nevertheless, without any modifications to the mission, the CIP survey data will have powerful ancillary science benefits, including:

Star Formation History of the Universe: Hα has proved to be a remarkably robust indicator of star formation rates, at high redshifts as well as low, even in the presence of extinction. With over 10^8 Hα measures from $1.8 < z < 6.5$, CIP will provide the most accurate picture of star formation over the most critical epochs for galaxy formation.

Dark Energy: CIP will measure distance indicators and the growth of structure using the shape of galaxy power spectrum at high-z. If dark energy is important at high-z (i.e., not a cosmological constant) CIP will measure this.

Total Neutrino Mass: Non-relativistic neutrinos suppress the growth of structure on the scales that are smaller than the velocity dispersion of neutrinos times the Hubble time. An accurate measurement of the power spectrum can illuminate neutrino properties in two ways: the amplitude of suppression is sensitive to the total *mass* of all non-relativistic neutrino species, while the shape is sensitive to the *number* of non-relativistic neutrino species.

Current measurements from neutrino oscillation experiments place a lower bound on the neutrino mass of 0.05 eV. The CIP 2σ uncertainty on the mass will be 0.05 eV. CIP will therefore be able to measure the total neutrino mass (*not just a lower limit*) to better than 2σ. In addition, the data contained within the CIP survey can be used to address the question of whether all of three – or just two – neutrino species are non-relativistic.

Space Curvature: Very small curvature is a robust prediction of Inflation. Current constraints are derived from determinations of the angular-diameter distance to the CMB last-scattering surface, which is limited by our understanding of the dark energy. Measurements of luminosity or angular-diameter distances to redshifts in the matter-dominated era can greatly reduce this uncertainty. With a 0.2% measurement of the distance to $z = 3$ provided by CIP, combined with CMB data, it's possible to measure or constrain curvature to better than 7×10^{-4} – more than a factor of 10 below the WMAP-set limit of 10^{-2}. Detection of any curvature at the 10^{-3} level would rule out the standard models of Inflation, and detection of a positive curvature (i.e., a closed universe) would rule out Inflation models arising from String Landscape. Conversely, detection of a slight negative curvature would confirm the String Landscape prediction and establish String Theory as a leading candidate to explain Inflation.

Brown Dwarfs: CIP will take $\lambda/\Delta\lambda = 600$ 1.8–5 μm spectra of a significant sample of cool brown dwarfs.

Supernovae: CIP will observe each position within the 1,000 sq. degree survey area every $\sim$40 days. This cadence will permit the detection of hundreds of Type Ia SNe with IR spectra.

General Data Set: CIP will produce infrared spectra for over 10^8 objects in a 1,000-sq. degree area at the north ecliptic pole. This public database will include faint galactic and extragalactic objects and will be useful in finding extreme and interesting objects for study with JWST, for finding the highest redshift galaxies, and for finding cool dwarfs in the galactic halo, among many other possible projects.

CIP OBSERVATORY

To carry out these scientific goals we have studied an extremely simple and straightforward observatory concept consisting of a 1.5-meter diameter telescope coupled to two wide field-of-view slitless grating spectrographs, each possessing a 3×3 mosaiced array of Hawaii-2RG HgCdTe arrays. Identical arrays are currently being flight qualified for JWST's NIRSpec instrument. The instrument has no moving parts other than a one-time-use secondary mirror focus adjustment mechanism. Due to the inherently low thermal background of the proposed Earth-Sun L2 orbit, no liquid cryogens or refrigerators are required to ensure that CIP is background limited throughout the 1.8–5 micron range.

Telescope/Spectrometers/Detectors

A fully-baffled wide field-of-view all-reflective telescope images the full field onto the entrance of each imaging spectrometer. The spectrometers then disperse the light, re-imaging the dispersed field onto their respective focal plane array. The all-reflective concentric spectrometer design provides wide field coverage over a wide spectral region using a convex spherical diffraction grating. The telescope

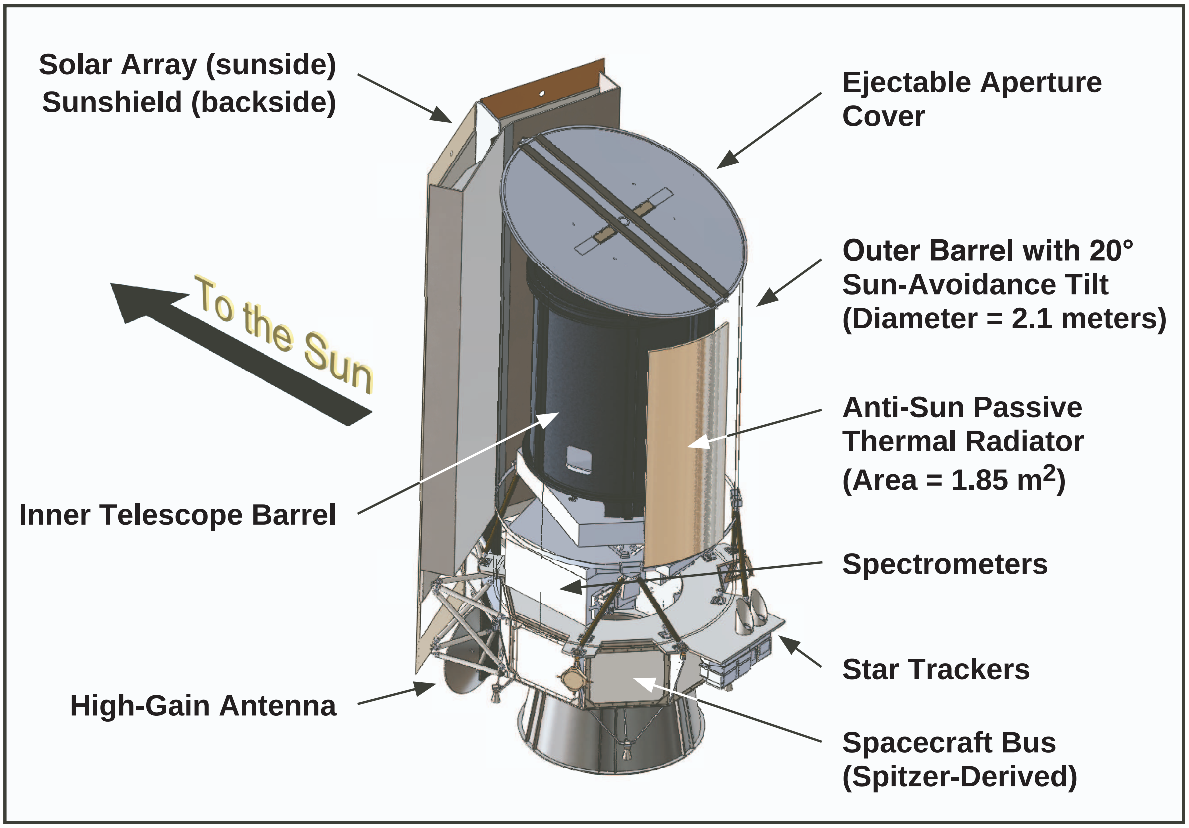
CIP Mission Summary	
Telescope diameter	1.5-meters
Spectral range	1.8 - 5 microns in 2 bands (1.8 - 2.9 and 3.1 - 5 microns)
Spectrometer type/res.	Two slitless gratings ($\lambda/\Delta\lambda$ = 600)
Pixel Size/Field-of-view	0.172" / 18.4' x 18.8'
Detector type	Two 3 x 3 mosaics of Rockwell Hawaii-2RG 2k x 2k HgCdTe SCAs
Pointing accuracy/stability	2.5" (1σ) / 88 mas in 500 s (2σ)
Optics temperature	90 ± 10 K
Detector temperature	37 K (same as JWST) & 60 K
Cooling method	Passive
Integration time per FOV	~ 1.4 hrs in 500-sec integrations
Data generation per day	13.7 GBytes
Downlink time every 2 days	37 min.@100 Mbps
Observatory launch mass	1814 kg (w/propellant)
Launch vehicle capability	3488 kg (Atlas V 401); 48% margin
Orbit	Earth-Moon L2
Baseline mission	3 years (5-year goal)

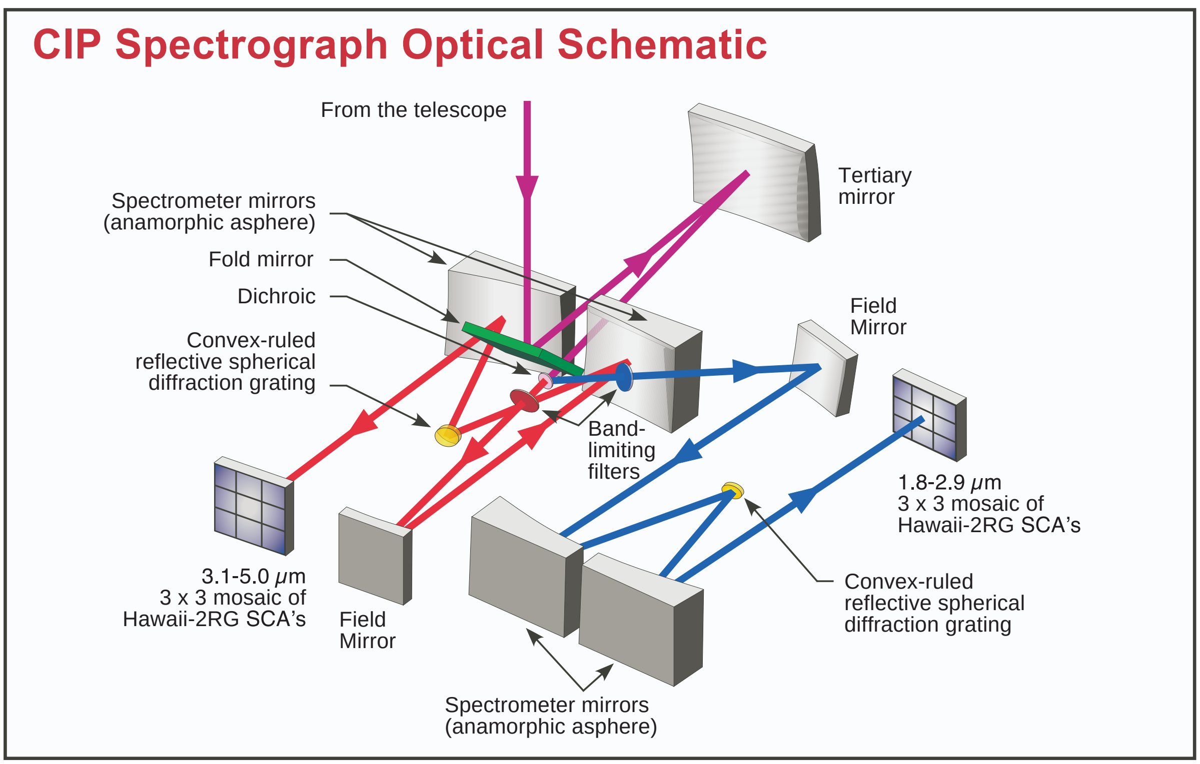
exit pupil is imaged at the gratings to provide the needed symmetry in the design. The gratings are blazed for first order and operate from 1.8 to 2.9 and 3.1 to 5 microns with higher orders eliminated by longpass filters. In a slitless instrument, the diffraction-limited image size determines both the width and resolution of the spectrum. For the baseline design, the spectrum is Nyquist sampled for $\lambda/\Delta\lambda = 600$. The three-mirror anastigmat camera produces good images across the entire field of each spectrograph.

Each spectrograph uses a 3×3 mosaic of the Teledyne Hawaii-2RG HgCdTe arrays with 2048×2048 pixels per detector and an 18 micron-pixel pitch. At the detector operating temperature of 60 K for the short-wavelength channel and 37 K for the long-wavelength channel, the dark current is 0.01 e^-/pixel/s. Pixel sampling is 172 mas, corresponding to $\lambda/(2D)$ critical sampling for wavelength $\lambda = 2.50$ micron.

Orbit

In the L2 orbit, the observatory presents a largely unchanging view to the Earth, Moon, and Sun, greatly simplifying the thermal design. With no Earth/Moon/Sun emission visible behind the sunshield, the heat load on the payload is substantially eliminated. (This configuration is used on the Spitzer Space Telescope, where the outer shell, behind the sunshield, is passively cooled to ~ 35 K.) For CIP, the design will be tailored to maintain the telescope and optics at ≤ 90 K. The configuration also contains a focal plane radiator that views only deep space, and will be used to provide a heat sink that allows the FPAs to operate at 37 and 60 K.


Solar Array (sunside)
Sunshield (backside)
Ejectable Aperture Cover
To the Sun
Outer Barrel with 20° Sun-Avoidance Tilt (Diameter = 2.1 meters)
Anti-Sun Passive Thermal Radiator (Area = 1.85 m2)
Inner Telescope Barrel
Spectrometers
Star Trackers
High-Gain Antenna
Spacecraft Bus (Spitzer-Derived)


CIP Spectrograph Optical Schematic
From the telescope
Tertiary mirror
Spectrometer mirrors (anamorphic asphere)
Fold mirror
Dichroic
Convex-ruled reflective spherical diffraction grating
Field Mirror
Band-limiting filters
1.8-2.9 μm 3 x 3 mosaic of Hawaii-2RG SCA's
3.1-5.0 μm 3 x 3 mosaic of Hawaii-2RG SCA's
Field Mirror
Convex-ruled reflective spherical diffraction grating
Spectrometer mirrors (anamorphic asphere)