The *HORUS* Observatory - A Next Generation 2.4m UV-Optical Mission To Study Planetary, Stellar And Galactic Formation

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Abstract

The High-ORbit Ultraviolet-visible Satellite (*HORUS*) is a 2.4-meter class UV-optical space telescope that will conduct a comprehensive and systematic study of the astrophysical processes and environments relevant for the births and life cycles of stars and their planetary systems, to investigate and understand the range of environments, feedback mechanisms, and other factors that most affect the outcome of the star and planet formation process. To do so, *HORUS* will provide 100 times greater imaging efficiency and more than 10 times greater UV spectroscopic sensitivity than has existed on the *Hubble Space Telescope* (*HST*). The *HORUS* mission will contribute vital information on how solar systems form and whether habitable planets should be common or rare. It also will investigate the structure, evolution, and destiny of galaxies and universe. This program relies on focused capabilities unique to space that no other planned NASA mission will provide: near-UV/visible (200-1075nm) wide-field, diffraction-limited imaging; and high-sensitivity, high-resolution UV (100-170nm) spectroscopy. *HORUS* is designed to be launched into a semi-stable orbit at Earth-Sun L2. From this vantage *HORUS* will enjoy a stable environment for thermal and pointing control, and long-duration target visibility. The core *HORUS* design will provide wide field of view (WFOV) imagery and high efficiency point source FUV spectroscopy using a novel combination of spectral selection and field sharing. The *HORUS* Optical Telescope Assembly (OTA) design is based on modern light weight mirror technology with a faster primary mirror to shorten the overall package and thereby reduce mass. **The OTA uses a three-mirror anastigmat configuration to provide excellent imagery over a large FOV - and is exactly aligned to use one of the recently released f/1.2 NRO OTAs as part of its design**. The UV/optical Imaging Cameras use two 21k x 21k Focal Plane Arrays (FPAs) consisting of thirty-six Si 3.5k x 3.5k CCD elements each. The FUV spectrometer uses cross strip anode based MCPs improved from *HST-COS* technology. **This poster presents results from the 2010 design update we were asked to do by the NRC Decadal Survey, to reflect updated costs and technology to the original 2004 study. It is now one of the most mature 2.4m UVOIR observatory designs in NASA's portfolio**.

The Science Program

We employ a step-wise approach to our observing program in which both imaging and spectroscopy contribute essential information to our investigation. **Step 1** Conduct a census of all high-mass star formation sites within 2.5 kpc of the Sun to deter-mine how frequently solar systems form and survive, and develop observational criteria con-necting properties of the ionized gas to the underlying stellar population and distribution of protoplanetary disks. **Step 2** Survey all major star forming regions in the Magellanic Clouds, where we can still resolve important physical scales and structures, access starburst analogs, and sample star formation in an initial regime of low metallicity applicable to high-redshift galaxies. **Step 3** Extend the star formation survey to galaxies in the nearby universe in order to increase the range of galaxy interaction and metallicity environments probed. *HORUS* can observe entire galaxies surveyed by *GALEX* and *Spitzer* with 100 times better spatial resolution. **Step 4** Measure star formation and metal production rates in the distant universe to determine how galaxies assemble and the elements critical to life such as C and O are generated and distributed through cosmic time.

Motivation: New Insights into the Sun's Natal Environment

We are on the verge of a revolution in our understanding of the environment in which our Sun and Solar System formed, driven largely by measurements of the decay products of short-lived radionuclides in meteoritic material. Radionuclides such as ^{41}Ca, ^{26}Al, ^{53}Mn, and ^{10}Be have half-lives of ~10^6 years. Meteoritic data show that these nuclides were present in the early Solar System, and hence must have formed close in time to its formation. Meyer et al. (2003) found that the newest supernova nucleosynthesis models can explain all of the abundances of short-lived radionuclides, except for ^{10}Be, which Desch et al. (2004) have subsequently shown can be uniquely attributed to capture of Galactic cosmic rays. The early Solar System also contained significant amounts of the neutron-rich isotope ^{60}Fe (Tachibana & Huss 2003; Mostefaoui et al. 2003), which forms in the proper proportions only in supernovae (Meyer et al. 2003). Thus it is becoming increasingly clear that our Sun and Solar System formed in a region like Orion or M16 that was capable of producing an O star that then went supernova, rather than a low-mass star-forming complex like Taurus-Auriga. The Solar disk was exposed to intense UV radiation and injected with freshly synthesized material after the disk existed, during the few $\times 10^5$ year period over which the short-lived radionuclides formed. Material from a single supernova a few tenths of a parsec away falling on the Solar disk would provide the right amount of newly synthesized material to explain this meteoritic evidence.

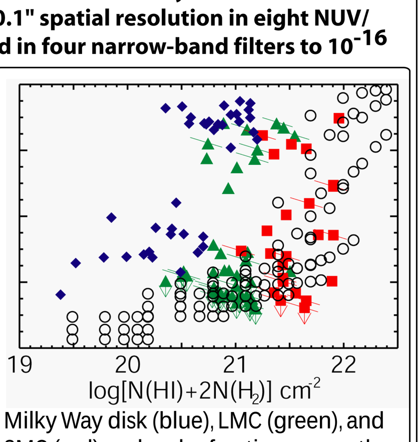
The key to understanding the origins of our Solar System is to understand high-mass star-forming regions - in the Milky Way, nearby galaxies, and the high-redshift universe - to gauge how these environments affect proto-planetary disks and planet formation. We thus describe an observing program and mission concept to trace the complex path from the epoch of galaxy assembly to mature planetary systems.

Step 2 - The Magellanic Clouds: A Bridge to Nearby Galaxies

The second part of the *HORUS* science program extends the high spatial resolution survey to the Magellanic Clouds. This step applies the knowledge derived from the local star forming environment to analogous regions where we can still resolve important physical scales and can also observe star formation over global scales. The study will then be extended to regions that do not have nearby analogs but are common in other external galaxies. **Our systematic, hierarchical approach is pivotal and provides for the first statistically supported application of local star formation knowledge to environments and conditions that do not have analogs in our own Galaxy**.

Low-Mass Star Formation of the MC's: By extending the study to nearby galaxies we will study the effects of more extreme radiation environments, lower metallicities, superbubble boundaries, and so on. We will use the local survey **to infer for the first time the characteristics of low-mass star-forming environments in the Magellanic Clouds.** Bearing in mind the other missions active at the time, we would aim to use complementary IR observations from the ground or using missions such as *JWST* to study the spatial distribution of star forming environments, the rate of subclustering, and the propagation of star formation over large scales (subcluster separation vs age). Finally, we will analyze member clusters to trace the star formation history across larger scales within the Magellanic Clouds to sequence how star formation was triggered and propagated. **In less than 1 year *HORUS* will be able to map both Magellanic Clouds in their entirety at < 0.1" spatial resolution in eight NUV/visible broad-band filters (NUV to Z band) to m_{AB} ~ 26 and in four narrow-band filters to 10^{-16} ergs cm^{-2} s^{-1} $arcsec^{-2}$.**

Molecular Cloud Formation: The spectroscopic component of Step 2 is a **comprehensive study of the origins of molecular clouds using both FUV absorption lines (H_2, CO, and atomic species) and extinction by dust in the LMC and SMC**. *HORUS* will far surpass *FUSE* as a probe of molecular cloud origins at higher extinction using more sources than *FUSE* could access. How do molecular clouds, the precursors of the star formation, coalesce from the diffuse ISM? The physical processes that lead to GMC formation may differ from galaxy to galaxy. *FUSE* has demonstrated that the robust star formation and low metallicity in the Clouds combine to inhibit the formation of H_2 in the diffuse ISM. FUV extinction studies show evidence for a smaller population of dust grains than in our own Galaxy. These recent studies suggest environment affects the diffuse ISM, but not necessarily GMC formation, the star formation rate and efficiency. **Samples of hot stars from the HORUS imaging survey will correlate young stellar populations with the ISM gas and dust to determine how GMCs arise and star formation regulates itself on galactic scales**. This requires both accurate photometry for the stellar populations and a high-throughput FUV spectrograph.



Milky Way disk (blue), LMC (green), and SMC (red) molecular fraction versus the total H content and compared to numerical models incorporating low dust abundance and high UV radiation fields (black circles). GMC formation may proceed differently in the low-metallicity Magellanic Clouds.

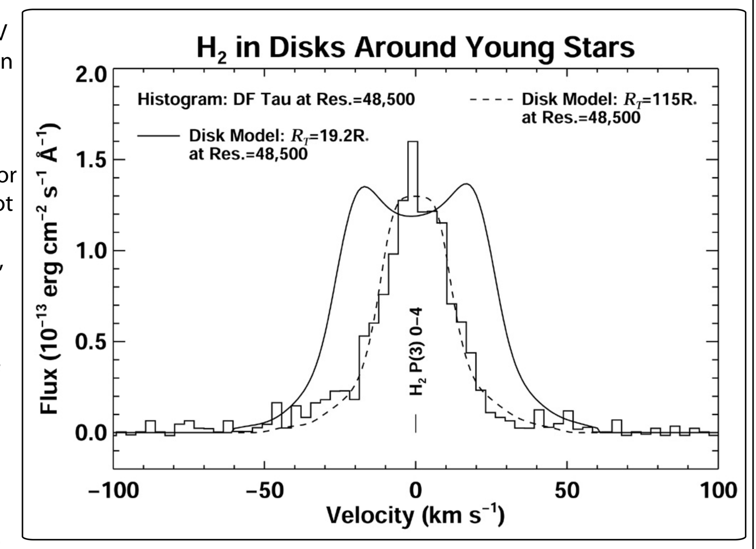
Step 1 - From Protoplanetary Disks to Extrasolar Planets

Imaging Survey: The majority of stars and planetary systems form in HII regions. Step 1 of our program is a near-UV/visible wide-field imaging survey of a significant sample of local massive star-forming environments in emission lines and continuum. **The survey will sample the stellar mass function** from massive stars to the brown dwarf limit. **Required capabilities** are broad wavelength coverage to detect high- and low-mass stars; high spatial resolution to resolve Solar System (~100 AU) scale structures at 2.5 kpc; and wide field of view to cover square-degree areas.

Properties of YSO's: High resolution *HST* images have revealed complex circumstellar environments of exposed young stellar objects (YSOs), their dust properties, and the presence of jets and outflows. *WFPC2* images of a portion of M20 illustrate the richness of fields covering just ~8 square-arcminutes; the ***HORUS* FOV will be 25 times larger and our image mosaics will cover entire nebulae**. The *HORUS* survey will identify protoplanetary systems for further study at other wavelengths to test theories of low-mass star formation. **We will derive** comprehensive numbers, densities, clustering, and other properties of the observed exposed stars, disks, etc. to establish the temporal histories and from there the emergence rate of YSOs and success rate of solar system formation and survival.

UV spectroscopy: This can directly probe the accretion of material onto low-mass stars by which stars are built and disks evolve. With *HORUS*, we can measure line fluxes to study material accreting onto young stars from their accretion disks, as it shocks and is heated to ~10^6 K before radiatively cooling. Such infall is not sufficient to produce X-rays, but the first observable emission from such shocks is from gas at ~10^5 K using lines such as C IV, Si IV, N V, and O VI. This emission represents the least processed radiation produced by accretion and provides direct access to accurate estimates of accretion rates, filling factors, etc.

Planet Formation: The UV probes molecular hydrogen in disks and the near circumstellar environment around T-Tauri stars (TTS). Assembly time estimates for Jupiter-mass planets do not match the measured lifetimes of accretion disks, which implies that gas survival rates are longer. H_2 is expected to be the primary gas constituent of circumstellar disks, so **directly measuring molecular hydrogen** can resolve the disagreement.



Magnetic Field Emission:
When studying accretion shocks with UV lines, we must understand the magnetic origin of the emission from stellar transition regions. We will survey transition-region emission at various stages of stellar evolution in order to separate the accretion-related and magnetic emission. In addition, the flux of near-UV and far-UV emission from young stars is increasingly important for astrobiology questions since photons in these energy ranges have substantial influence on the atmospheric chemistry of young planets.

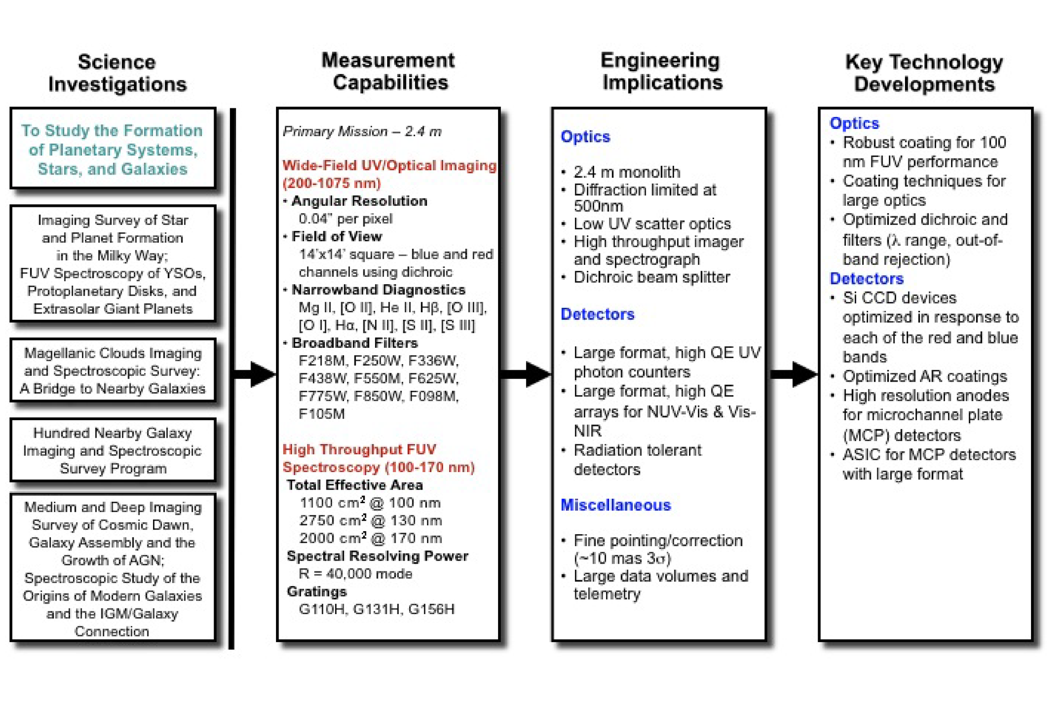
Understanding the Mechanics of Accretion Disks: The R ~ 40,000 spectral resolution provided by *HORUS* allows the study of both H_2 and accretion shock emission. Line profiles of accretion shock diagnostic features constrain the geometry and velocity of the accreting gas and how much hot gas is present in the winds driven from these stars. For studies of H_2 **the spectral resolution combined with the 100-170 nm wavelength coverage of the FUV band allows us to map the temperature of the H_2 gas** in TTS disks. Velocity broadening of the line indicates the distance of the gas relative to the star, allowing comparison with expectations from Keplerian disks. The H_2 gas is observed to be fairly warm (>2000 K) at AU scales, which constrains theories of disk temperature profiles and heating mechanisms. Narrow H_2 lines are also observed, implying emission at large distances from the central star in cases like DF Tau. ***HORUS* will be able to set better constraints on the distribution of the H_2 component of disks and to extend our reach to YSOs in HII regions**.

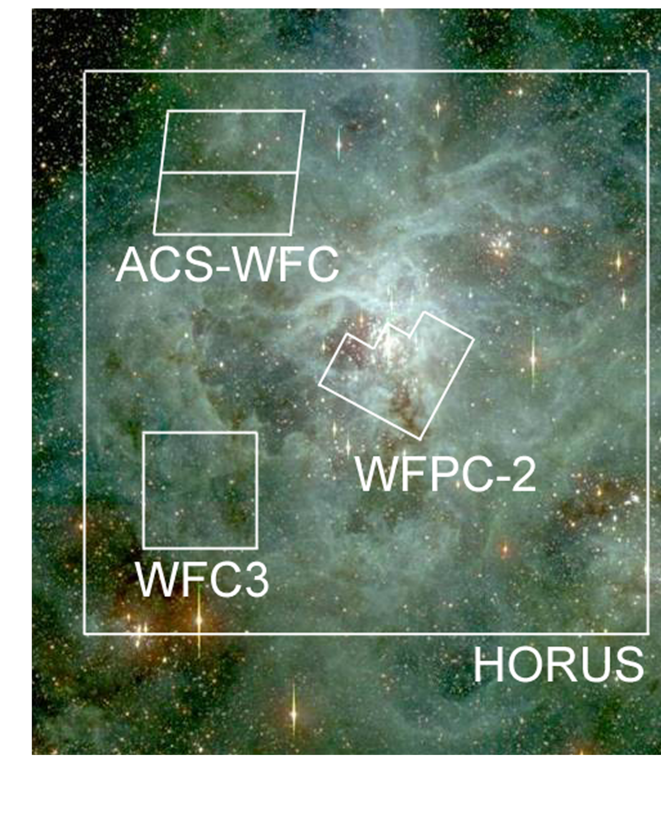
Detection of Extrasolar Planets: An added benefit of the combination of the 100-170 nm wavelength coverage for spectroscopy is that ***HORUS* will be able to perform an in-depth study of transiting extrasolar planet atmospheres via their measurable absorption** of the numerous strong stellar emission lines in this wavelength region (potential lines include Si III 120.6, H I 121.6, N V 123.9 and 124.3, O I 130.2, C II 133.5, Si IV 139.4 and 140.3, S I 147.4, Si II 152.7, C IV 154.7 and 155.1, and C I 156.0 and 165.7). **The *HORUS* low spectral resolution mode will capture all of these diagnostics in a single exposure.** This technique has been used to detect absorption by Na at visible wavelengths and O and H in the UV in the atmosphere of the transiting planet HD 209458B (nicknamed "Osiris").

UV measurements are particularly effective because the O and H absorption depth in transit is of order 15% due to the very extended atmosphere of close-in planets, which may be overfilling its Roche lobe. **The 100-170 nm coverage of *HORUS* will allow searches to be made for many different species in the planetary upper atmospheres**. *HORUS* will provide a unique follow-up capability to quantify the atmospheres of hot-Jupiter or hot-Saturn class transiting planets discovered by the *KEPLER* mission.

Detection of Primordial Gas and Cometary Infall: *HORUS* high resolution spectroscopy of molecular gases can be used to measure the volatiles in young planetary systems. The bulk of the material out of which stars and giant planets form is gas (the typical interstellar gas-to-dust ratio is 100:1). In this primordial gas, the most abundant species is H_2, which is also the primary constituent of Jovian-type planets. Once removed from a protoplanetary disk (by photo-dissociation and/or incorporation into gas giant planets), **H_2 is difficult to reform and is therefore the best tracer of the evolution of primordial gas.** Studying the primordial gas dissipation timescale in circumstellar (CS) disks has already led to a reevaluation of theories of giant planet formation; the core accretion model may not be able to form giant planets quickly enough, forcing a revisit of direct gravitational collapse models.

In older CS disks where planetesimals have already formed, **sensitive spectroscopy of the gases can provide information on the composition of the bodies.** In the case of the debris disk of β Pictoris, the large CO/H_2 ratio indicates that the source of the CO gas is evaporation of icy, comet-like bodies. Such disks provide information on the formation of terrestrial planets and their early evolution, since most of the volatile content of the Earth's surface was delivered during the debris phase by the impact of water-rich planetesimals. *FUSE* has already shown the importance of UV absorption spectroscopy of debris disks, for measuring physical conditions such as temperature and density. The rapid depletion of gas in disks relative to the dust requires new observations of the strong far-UV transitions of H_2 to accurately trace the evolution of the gas.





Step 3 - Star Formation in Nearby Galaxy Environments

The third part of the *HORUS* science program will survey a representative sample of nearby external galaxies, such as those mapped by *GALEX* or in the SINGS program from *Spitzer*, using the same emission lines and continuum filters used to characterize nearby star formation regions. The intent of this phase is to **map the distribution of star-forming region types as a function of the galactic environment in which they reside** for galaxies out to at least 5 Mpc, where we can still resolve internal structure within individual HII regions.

The Role of Galactic Environment: In this part of the study we will focus on the influence of galactic interactions in the star formation process, investigating the correlation between star formation mode (or intensity) with the metallicity of the ISM (which depends on galaxy mass). We will also correlate SF type with morphological galactic structure such as bars, spiral arms, resonant rings, bulges, and nuclear activity. In particular we will assess **the evidence for SF propagation over large (kpc) scales to see if global modes exist that can influence the star formation process across an entire galactic system**. Along these lines we intend to quantify the star formation rate (SFR) vs. galactic radius, as well as the SFR vs. galaxy morphological type. We will also infer the distribution and history of low-mass star formation over galactic scales, by identifying the regions in which low-mass stars and planetary systems are most likely to form, correlating their relative spatial location and apparent age. Finally, as in Step 2, we will characterize the local and global stellar content and star formation history of galaxies, and relate these results to the current observed star-forming environments.

Sampling the ISM in Other Galaxies: The spectroscopic component of Step 3 **extends the intensive study of interstellar conditions in Step 2 to diverse galaxies in the Local Group**. We will study differences in GMC origins in galaxies of varying morphology, metallicity, and SF history. ***HORUS* will be capable of obtaining S/N > 10 spectra of all O-stars in the Local Group**, thereby extending to nearby galaxies our knowledge about the ISM of the Galaxy and the Magellanic Clouds from Step 2. This technique may reveal strong dependencies of molecular cloud formation on galactic morphology or metallicity. These resolved studies of individual stars and sightlines in chemically primitive environments will provide the basis for understanding star formation in the more distant galaxies we observe in Step 4.

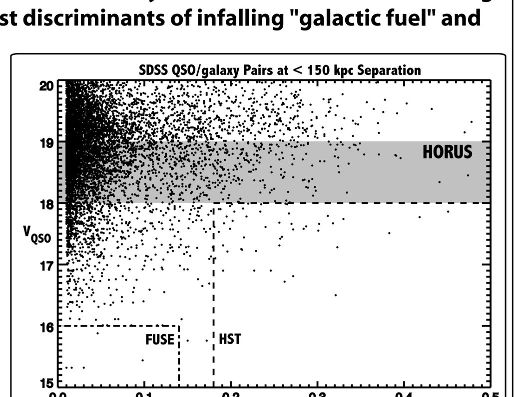
Step 4 - Galaxy Formation and the IGM/Galaxy Connection

In Step 4 of our program, we will use **the *HORUS* wide-field imaging and FUV spectroscopic capabilities to study galaxy assembly and the nature of the intergalactic medium (IGM)**. The symbiotic connection between galaxies and their environment is the next great objective of IGM studies. *HST* and *FUSE* opened this frontier by revealing interface regions, 0.1-1 Mpc in scale, that bear the imprint of continuous IGM infall, galactic outflows driven by star formation, shocks triggered by mergers and interactions, and mixing of the fuel and products of galactic star formation over billions of years. These processes and their UV absorption-line tracers (Si II-IV, C II-IV, N V, O VI, Ne VIII) are central to our understanding of the co-evolution of galaxies and the IGM. These processes have been studied in the Galactic halo, Local Group, and serendipitous extragalactic cases, but they are still poorly understood. **With high sensitivity and access to the FUV, *HORUS* will enable precise measurements with unprecedented statistics on galaxy properties and their relation to the surrounding IGM**.

FUSE has recently posed a major mystery that neatly illustrates the class of problems *HORUS* will address. Using O VI λλ 1032,1038 (tracing ionized gas at T ~ 300,000 K), *FUSE* found widespread high-velocity O VI that appears to arise in diverse environments, such as Galactic fountain outflows, intragroup material, and the interface between in-falling photoionized gas and the Galactic halo. Conversely, the O VI (from *FUSE*) and O VIII seen by *Chandra* may co-exist in a single-phase, hot (T = 10^{6-7} K), low-density medium that fills the Local Group. Such a diffuse, Mpc-scale medium, if common to all galaxy groups, could hold a major reservoir of the long-sought "missing baryons" that are predicted to reside in the diffuse, shock-heated IGM.

A systematic study of FUV metal-line absorption associated with galaxies, groups, and large-scale filaments can solve this mystery. Links to broader theories cannot be made without statistical evidence - currently lacking - that other galaxies possess these interfaces. The handful of O VI systems seen in external halos and groups towards bright (V ~ 15) quasars provide the first tantalizing clues that complicated IGM interfaces enshroud all galaxies, but these rare systems also prove that single, serendipitous sightlines do not suffice. **Good statistics on other systems will extend our knowledge of local conditions by revealing statistically robust discriminants of infalling "galactic fuel" and the metal-enriched products of star formation**.

Most of the discovery space lies with quasars too faint for *FUSE* and with galaxies at redshift too low for *HST-STIS* to detect O VI. ***HORUS* opens the 100-170 nm region where hundreds of SDSS galaxies at z > 0.2 will show absorption**. With access to V~18 quasars at R~40,000 *HORUS* will enable comprehensive studies of local Galactic conditions and extragalactic analogs with a single optimized sample of preselected sightlines with excellent statistics on galaxy properties (SFR, morphology, and red-shift).



Another component of Step 4 will be the ability to **use *HORUS* to address the star formation history of the universe**. The UDF data show that the faint-end slope of the galaxy LF may be steeper than α = 1.6, and if so dwarf-galaxies can collectively produce enough UV-photons to finish the reionization of the universe by z~6. Only one *NICMOS* UDF z~7 candidate has been found which implies that the amplitude of the LF at z > 7 LF from the UDF *NICMOS* data could be significantly lower than at z > 6. These *HST* results are currently limited by the FOV at z > 6-6.5. **A critical part of the *HORUS* mission will be to cover a significantly larger FOV with good sensitivity out to 1.07 μm, in order to get a much larger sample of galaxies at z > 6-7.5**. The main goal here is to see if the drop in the UDF LF at z~7 is heralding the dawn of galaxy formation. In *WMAP* cosmology, the time interval between z=7 to z=6 is only 0.16 Gyr, which is the lifetime of the B-stars whose UV-flux (together with co-eval O-stars) finished reionization at z~6. ***HORUS* will measure the expected significant drop in the amplitude of the LF from z~6 to z~7**. While Population III star clusters and first light objects will be the exclusive domain of *JWST*, *HORUS* will be able to add significant FOV and redshift depth (z~8) to the existing *HST* data. *HORUS* should find at least several 100 z > 7.5 objects to AB(1.05 μm)=27-28 mag, about 1000 at z ~ 7, and several thousand at z=6.0-6.5.

Observatory Properties

Operating Wavelengths	Imaging: 200-1075nm (Si sensitivity passband) Spectroscopy: 100-170nm (FUV)
Imaging Observing Channels	Blue (200-517nm); Red (517-1075nm)
Imaging Broad-band Filters	F218M, F250W, F336W, F438W, F550M, F625W, F775W, F850W, F098M, F105M
Imaging Narrow-band Filters	Mg II, [O II], He II, Hβ, [O III], [O I], Hα, [N II], [S II], [S III]
Imaging Exposure Times	0.1 up to 2000 seconds
Imaging Detectors	LBL "SNAP" 3.5k square CCDs
Imaging Pixel Size	10.5 μm = 40 mas
Imaging Field Size	14' × 14' ≅ 6 × 6 CCDs = 21k × 21k pixels
Imaging Dark Noise	< 10 e-/pix/hr
Imaging Read Noise	< 3 e-
Imaging Gain	2 e-/ADU
Imaging Full Well Capacity	130,000 e-
Imaging Operational Temperature	175 K
Spectroscopy Detectors	Si MCP CsI w/ cross-strip readout
Spectroscopy Size	220 mm long, 15μm pores
Spectroscopy Resolution	R = 40,000
Spectroscopy Slit	0.5" × 5"
Pointing Accuracy (w/ FSM)	< ¼ pixel over 2000 seconds
Orbit	Earth-Sun L2
Cost (inc. 30% reserve)	$1.48B FY 2009
Observatory Lifetime	5-yr baseline, 10-yr design
Single Field Exposure Image Size	0.9 GB × 2 channels
On-board capacity	2.2 TB
Typical lossless compression	Factor of 2-3.5
Imaging Broadband Sensitivity	m_V ~ 29 in 2000 seconds
Imaging Narrowband Sensitivity	10^{-16} ergs/cm²/s/arcsec² in 2000 seconds