Deep Survey Telescope: Exploring the First Billion Years
Probe-Class Astrophysics Mission Concept

Frederick R. Hearty, PhD   Pennsylvania State University   frh10@psu.edu
H. Philip Stahl, PhD   NASA MSFC

Deep near infrared and time domain discovery space remains largely unexplored in the era of time domain astrophysics, even though the technology exists to do so now. This white paper presents a mission concept for exploring the origin and evolution of large scale structure during the Universe's first billion years by direct observation of the entire sky within that discovery space. Though optimized for this primary science driver, this all-sky NIR and time domain survey will raise the entire astronomical community's data foundation to unprecedented levels. This work draws heavily on the approach and scientific success of the Sloan Digital Sky Survey (its primary science driver was one million galaxy redshifts) and is fully complementary to all operational and planned observatories as well as all completed, in-progress, and planned sky surveys.

Science Drivers

The early Universe is largely known through models and isolated deep observations, neither of which well-predict the assembly of baryons into the earliest structures. The birth epoch of the first super-massive black holes and activation of the first QSOs are unknown observationally, though predicted by existing models to be accessible by existing technology (e.g., large ground-based observatories, JWST). Assembling baryons into the first massive galaxies and clusters, as evidenced by isolated deep observations, appears to have started earlier and progressed much more rapidly than predicted by existing models. Onset of the first Type 1a supernovae (SNe-1a) is a definitive milepost at the end of the first billion years that can be used to empirically establish the end of this early era, yet it has not been observed. *No existing or planned experiment will fully conduct this science.* JWST has the light collecting ability to observe such events as the first QSOs and clusters, and the onset of SNe-1a, but not the field-of-view to routinely discover them and characterize their environments. LSST will successfully explore subsequent generations of such phenomena, but is ultimately limited to moderate redshift by its cutoff at optical NIR wavelengths and the NIR-bright and variable sky. Wavelength limitations also exist for WFIRST-AFTA now that it is baselined on a warm observatory; it will search another micron further into the NIR in a single pass (several filter bands) over 5% of the sky. Only a large-grasp, cold telescope can discover the range of events during the rapidly evolving first billion years and characterize the environments within which they originated.

Therefore, the primary science driver for the Deep Survey Telescope (DST) is, ***"How was large-scale baryonic structure assembled in the early Universe?"*** This is an empirical study -- direct observation in great depth and breadth is used to illuminate our cosmic origins and substantiate existing models. The secondary but not lesser science driver is, ***"Provide a deep, high photometric and astrometric precision, time-domain survey of the entire sky at near infrared wavelengths to enable scientific investigations from planetary science to cosmology."*** In short, DST will chart the observable Universe to discover and understand both its earliest and its rarest phenomena. A few examples of the range of enabled science are provided below.

DST will identify at high redshift:
- The first QSOs
- The earliest massive galaxies and galaxy clusters
- High redshift supernovae of all varieties

DST will identify at low redshift:
- Host galaxy type and redshift for each supernova discovered by LSST
- Progenitor star for many future supernovae from Local Group to Virgo cluster
- Tidal streams and halo structures for Local Group galaxies

DST will identify in our Solar System
- Potentially hazardous asteroids
- Near-Earth asteroids down to 30m
- Planet (and dwarf planet) resident in Kuiper Belt, Inner Oort Cloud, and possibly Oort Cloud itself

Technical capabilities

In order for a simple imaging survey to accomplish such ambitious goals, a combination of technology and operational strategy is needed. A deep NIR survey will detect hundreds of billions of individual objects – notable discoveries can only be isolated from these vast numbers by producing sufficient information to characterize each object… no small task. Spectroscopic follow-on, even when available, would only characterize 1% or so of the objects imaged. A single-epoch of observation using a broadband filters, such as u, g, r, i, and z in the SDSS imaging survey, will enable separation of objects by type and limited-

accuracy photometric redhsifts (z_{phot}). Morphology also can be used to separate point and extended sources. Proper motion and parallax measurements can be used to separate near and distant targets.

For DST, the following strategy will be use to fully characterize the majority of identified objects:
1) Precision photometry using 12-16 broadband filters from 0.5-5microns provides spectral energy distribution for object identification and better than 1% accurate redshift (z_{SED}) determination;
2) Precision astrometry and parallax measurements (building on the GAIA catalog) to separate near and distant objects;
3) High spatial resolution to differentiate extended objects from point sources; and
4) Time domain observations to detect and characterize photometric (e.g., QSOs, SNe-1a) and astrometric variability.

This set of observables produced by imaging alone is sufficient to identify and characterize the vast majority of objects detected. Data volume handling and the tools to reduce the data are similar challenges to those being met by the LSST team.

The observatory itself is based on a 4m-class monolithic primary mirror telescope, passively cooled to around 70K. A major 'breaking' of the cost curve is needed to meet Probe-Class guidelines of approximately $1B. Design approaches that have great potential for cost savings and/or minimizing risk:
1) Single imaging instrument with fixed filters as used in the SDSS design (single operating mode)
2) Moderately light-weighted Zerodur substrate mirrors (available in 6-12mo) with integrated CTE-matched carbon fiber telescope structure to allow warm figuring, alignment, and testing (Note: Moderate light-weighting halves the cost compared to ultra-light-weighting). Cast borosilicate mirror is also low cost option.
3) Mirrors figured for infrared imaging observations (Note: $\lambda/8$ figuring halves the cost compared to UV/Optical)
4) Liberal mass budget generally used to limit ultra-light-weighting costs
5) Commercially available electronics with fault-tolerant design
6) Near zero on-board software for data processing
7) Commercially available spacecraft SEP buses such as Boeing's 702SP/MP
8) Heavy launch for direct-to-GSO insertion (engineering flight on SLS, or commercially available heavy launcher)
9) Continuous data downlink from GSO instead of Deep Space Network from L2 (laser downlink is baseline)
10) Spacecraft ground control from established facility and team (Swift mission) at Penn State University
11) Science collaboration structure for experiment design, operations planning, and data processing and release derived from SDSS and LSST collaboration models

Based on discussions with AST Division at MSFC, and recent NASA investigations that compared internal development costs with the private sector, substantial reductions in the cost for a large aperture observatory are attainable. The implications of reduced cost for this aperture favorably impact planned observatories (e.g., HabEx) and open the door to significantly more capable experiments.

Technical capabilities of DST will include:
1) Spectral coverage (continuous) 0.5-5 microns; 12-16 filter bands with fixed filters
2) Pixel scale 0.18-0.20 arcsec/pixel, 10 or 15 micron pixels (dithering/Drizzling to improve spatial resolution)
3) Pointing accuracy <5mas
4) Field of View nominally 1.6 degrees on a side, 2.5 sq. degrees
5) Sensitivity ~27mag in 60 s integration
6) Single operational mode – imaging survey; sample-up-the-ramp non-destructive reads
7) Design reference mission (nominal year of survey)
   a. Galactic Caps (~20,000 deg^2) 1 visit @60s (~7.5 mo.), 27.0 ABmag each filter
   b. Galaxy Plane (~20,000 deg^2) 1 visit @20s (~2.5 mo.), 26.4 ABmag each filter
   c. Deep Field (~2x100 deg^2) 13.5 visits (~1.0 mo.), ~800s + above, 28.5 ABmag
   d. Ultra Deep Field (~2x10 deg^2) 135 visits (~1.0 mo.), ~8,000s + above, 29.5 ABmag
8) Mission lifetime: ten years with a substantial guest investigator program; five years minimum without

New technologies
No new detector technologies, beyond those being developed for WFIRST-AFTA, are required. Fine steering mirror for large field is needed; available at smaller scale, but not yet confirmed for this application. Rapidly developing commercial applications for laser downlink, technology demonstrations NASA (OPALS, LLDC), and ESA (EDRS) can be leveraged.

Probe-Class Mission Needed?
The large-aperture observatory required to exploit the NIR, time domain discovery space dictates a Probe-Class mission. Such an observatory would fall under flagship status without extreme effort to simplify experiment design, followed by building to cost. Smaller aperture designs have insufficient grasp to accomplish this science.