Science Drivers for a Wide-Field, High-Resolution Imaging Space Telescope Operating at UV/Blue Optical Wavelengths[1]

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I. Summary

A wide-field (0.5-1 deg^2), ~1m-class space telescope that provides nearly diffraction-limited imaging (FWHM ~ 0.15″) at UV/blue optical wavelengths (0.15–0.55 μm) has the potential to make a unique, powerful, and lasting contribution to modern astrophysics. Such a mission would be a natural successor to both the Hubble Space Telescope (HST) and the Galaxy Evolution Explorer (GALEX), and would far surpass any ground-based optical telescope in terms of angular resolution. It would also provide crucial "UV/blue" imaging to supplement longer-wavelength data from future dark energy space missions (Euclid, WFIRST) as well as from the ground-based Large Synoptic Survey Telescope (LSST). For maximum scientific impact and complementarity with Euclid/WFIRST, the facility should allow the implementation of GO/PI programs, but concentrate initially on a small number of "legacy" surveys — including a "wide survey" that would cover an area of at least ≈5000 deg^2, in three filters, to depths of ≈ 25.8 mag (UV), 27.1 (u) and 27.8 (g). We review the rich and diverse science investigations that such a wield-field imaging facility would enable, which include (but are not limited to) dark energy, galaxy evolution, near-field cosmology, stellar astrophysics, the outer solar system, and time-domain astronomy.

II. Scientific Context

Perhaps no astronomical facility in history has had a greater impact than the Hubble Space Telescope (HST), which is widely regarded by scientists and the public alike as an unconditional success. However, HST will almost certainly cease operations before the end of this decade, either due to orbit decay or failure of a critical subsystem, and astronomers worldwide will then lose access to the high-resolution, UV/optical/IR imaging capabilities that they have come to rely on for more than two decades. Those capabilities have so profoundly changed the scientific landscape that much of our current understanding of astrophysics can be traced directly to HST. Meanwhile, GALEX — the highly successful SMEX mission that was launched in 2003 and went on to pioneer the field of panoramic UV imaging — is also likely to cease operations soon. It is expected that the launch of Astrosat in ~2014 will provide wide-field UV imaging capabilities, for a five-year period, but not at high resolution (i.e., FWHM ~ 1.8″).

Future (i.e., post ~2020) space imaging missions are instead concentrating on the IR/red-optical spectral region (i.e., ~0.55 to 2μm) driven by the desire to better understand dark energy: i.e., both Euclid and WFIRST aim to perform IR/red-optical imaging surveys of 15,000-20,000 deg^2. However, optical data remains essential for the success of these missions. For instance, according to current plans, IR/red-optical data from the first of these missions (Euclid, which is scheduled for launch in 2019) will be combined with ground-based (optical) imaging from the Large Synoptic Survey Telescope (LSST) to measure the dark energy equation of state.

Beyond this critical contribution to dark energy studies, LSST is expected to be a powerful research tool with many scientific applications. Nevertheless, some of the most pressing questions in astrophysics and cosmology can be addressed only through short-wavelength (i.e., ≈0.15

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to 0.55μm) imaging from space, which offers a number of key advantages over ground-based observations: i.e., much better image quality and stability, higher observing efficiency, lower sky backgrounds, superior photometric precision, and access to critical spectral regions, such the UV, that are unobservable from the ground.

In our view, a wide-field, high-resolution imaging capability at UV/blue-optical wavelengths represents the single most important "unfilled niche" among the international suite of astronomical facilities that are expected to be in operation near the end of this decade. The science drivers for a for such a facility have recently been examined as part of a concept study sponsored by the Canadian Space Agency for a wide-field, high-resolution imaging space telescope, as recommended in the recent *Long Range Plan for Canadian Astronomy* (Pritchet et al. 2011). The present document is based largely on lessons learned during the CSA concept study (Côté al. 2012).

III. Technical Requirements and Implementation Strategy

Wide-field imaging is the backbone of astrophysics. While many ground-based optical telescopes are equipped with mosaic CCD cameras, a vast array science drivers (see §IV) require the combination of *wide field of view* with *exceptional imaging quality* in the UV/blue-optical region — requirements that cannot be achieved from the ground. Although it is not the purpose of this document to advocate a specific mission concept, the technical requirements needed to address the science questions listed below have already been examined as part of our CSA study. We therefore briefly summarize the "baseline" technical requirements that are needed to achieve the key science goals, as well as possible strategies for mission operations.

The baseline specifications adopted in the discussion of science drivers (§IV) is a 1m, unobscured aperture telescope that carries out imaging over a 0.67 deg^2 field in three broad filters in the UV/blue-optical region: (1) 0.15-0.32μm (the 'UV' filter); (2) 0.32-0.41μm (u); and (3) 0.41-0.55μm (g). Imaging quality is nearly diffraction limited in each band, with FWHM ~ 0.15″. Baselined to a five-year mission lifetime, the facility would focus on 3-4 "Legacy" surveys during its first 2-3 years of operation, and then move on to the implementation of routine GO/PI programs. The largest of the Legacy surveys — denoted below as the Wide Survey — would perform UV-, u- and g-band imaging to depths of ~25.8, 27.1, 27.8 mag, respectively, over a minimum area of 5000 deg^2 that overlaps with the Euclid and LSST survey footprints.

IV. Science Drivers

We describe briefly a number of scientific investigations that would be enabled by a facility of the sort described above. While this list is far from complete, the programs are representative in that they illustrate the breadth of science that can be addressed using wide-field, high-resolution imaging in the UV/blue-optical spectral region. We include several examples of how high-resolution, UV/blue-optical imaging could leverage the longer-wavelength data from forthcoming dark energy missions, thereby enabling science that would not be possible with either mission alone. While the discussion in such cases focuses mainly on Euclid, given its somewhat more mature status compared to WFIRST, many of the same arguments apply to the latter mission.

1. Cosmology and Dark Energy

Photometric Redshift Measurements: ESA's Euclid mission aims to measure of the geometry of the universe through baryon acoustic oscillations (BAO) and weak lensing (WL). For the WL analysis, shape measurements for galaxies — carried out in a broad red-optical (RIZ) filter — will be combined with distances estimated from photometric redshifts ("photozs") to measure the dark energy equation of state. However, Euclid alone lacks the spectral energy distribution (SED) coverage needed to derive accurate photozs, so its long-wavelength (RIZ,Y,J,H) photometry will need to be combined with ugrizy data from LSST and other ground-based telescopes. The left panel of Figure 1 shows how adding UV-, u- and g-band imaging Euclid and LSST data improves the photoz measurements and allows a definitive characterization of dark energy. In particular, the short-wavelength data improves the photoz accuracy (particularly in the $0 < z < 1$ range) and reduces the number of catastrophic errors. The final redshift precision meets all requirements for an unbiased measurement of the dark energy equation of state based on gravitational lensing data

(Albrecht et al. 2006; Huterer et al. 2006), and should ultimately result in sub-percent accuracy in the equation of state parameters w_0 and w_1.

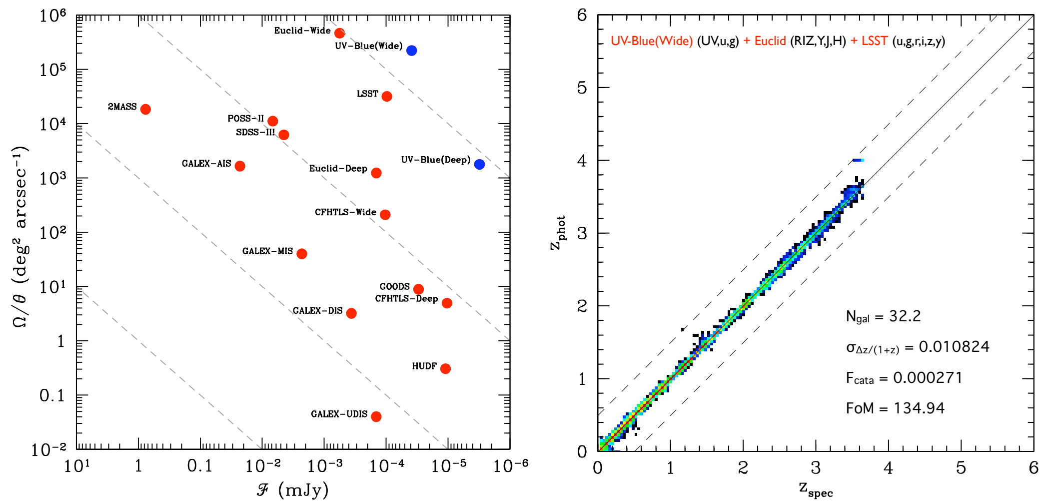

Figure 1. *(Left Panel) One representation of the "information content" of wide-field imaging surveys in the UV, optical and IR spectral regions. The abscissa gives the depth of each survey in mJy while the ordinate shows between Ω, the survey area in deg², and θ, the FWHM in arcseconds. Information content increases diagonally toward the upper right corner: i.e., dashed lines are separated by factors of a thousand in Ω/θF . (Right Panel) Comparison between photometric, z_{phot}, and spectroscopic redshifts, z_{spec}, based on simulated galaxy catalogs computed as described in Sorba & Sawicki (2011). The comparison assumes that RIZ,Y,J,H data from Euclid are combined with the end-of-survey data from LSST (u,g,r,i,z,y) and UV,u,g data from a ~1m space telescope that surveys an area of 5000 deg² to a depth of u=27.1 mag.*

The Structure of Dark Matter Halos from Lensing Magnification: Structure growth can be probed by looking at the abundance of massive, gravitationally-bound objects as function of redshift — a well known technique that can be used to set constraints on dark energy. The accurate photozs obtained by combining the UV/blue-optical imaging with data from Euclid and LSST (Figure 1) can be used to identify clusters from a few 10^{13} to 10^{15} $M_\odot$ using matched filter, red sequence, or max BCG methods. The 0.15 to 2 μm region is ideal for the matched filter approach which offers the advantage of being only weakly dependent on precisely how clusters are defined. Tight constraints on dark energy will then come from the large number of high-z clusters identified with this technique, which can be combined with magnification measurements to place independent limits on the dark energy equation of state over the range $0 \leq z \leq 2$.

Cosmic Shear and Galaxy Shapes: Although Euclid will provide excellent space-based imaging for galaxy shape measurements, there remains some concern that complications could arise from the use of a single, broad, visible filter for the shape measurements. Technically, this complication comes from the fact that stars (which are used to correct the effects of the PSF) do not have the same SEDs as galaxies. In other words, one cannot directly use stellar PSFs to correct galaxy shapes, as it is necessary to account for possible "gradient color" effects. While this problem can in principle be addressed via extensive SED simulations, the use of narrower u and g filters provide a unique way to explore the gradient color effect directly — on real data — without relying on simulated SEDs. Moreover, galaxy shapes measured directly from the u and g images could be used to characterize possible systematic errors in the shape measurements carried out at longer wavelengths with Euclid.

2. Galaxy Evolution

Evolution of Cosmic Star Formation and Stellar Mass: A survey of 5000 deg² in the LSST and Euclid survey regions would provide data spanning the UV to IR region for billions of galaxies. Photozs for galaxies in this sample (Figure 1) could be measured to a precision of $\Delta z < 0.02(1 + z)$, and the observed SEDs fitted with theoretical models to constrain their physical parameters. The long-wavelength data are critical for establishing the stellar mass and constraining the dust reddening and metallicity, while the instantaneous star formation rate (on timescales of $\tau \sim 10^8$ yr) can be measured from the flux from the massive stars that dominate the SED at $\lambda \leq 0.4\mu m$. UV imaging would be ideal for measuring this flux for galaxies out to z~1, while u-band data will serve the same purpose at $1 < z \leq 1.5$. Because the (UV-u) color index is a good indicator of dust extinction, it would allow, together with the LSST/Euclid data, robust measurements of the intrinsic star formation rate (SFR) and the stellar mass function and clustering of galaxies with different SFRs. The clustering analysis would also provide a measurement of the halo masses, and this technique could be used to trace how the connection between halo and stellar mass evolves and to link the growth of stellar mass to the mass assembly history of dark halos.

Dark Matter and Strong Lensing: Strong lenses are important cosmological probes of both galaxy dynamics and the structure of dark matter halos. Despite their importance, relatively few systems have been identified to date; mostt come from the SDSS spectroscopic database or wide-field imaging surveys with ground-based telescopes. In nearly all cases, high-resolution imaging from HST is needed to confirm their nature and to give reliable constraints on the gravitational potential of the lensing galaxy. An imaging survey of 5000 deg^2 at HST-like resolution has the potential to uncover >1000 strong lenses — roughly an order of magnitude increase over current samples. Thanks to the depth and resolution of the UV/blue optical imaging, it will be possible to establish quickly the morphology of the lenses, constrain the properties of the source galaxies, and explore the structure of galaxy-scale dark matter halos and their evolution with redshift.

QSOs and Active Galactic Nuclei: UV imaging allows QSOs to be selected efficiently in a variety of redshift ranges. For example, UV-, u- and g-band imaging allows high-purity QSO samples to be assembled in the ranges $1 \leq z \leq 2$ and $2 \leq z \leq 4$, with flux alone limiting the selection. Moreover, the high resolution of the imaging will make it possible to carry out morphological studies of these QSOs and their nearby companions. At the depth of the Wide Survey, it will be possible to identify QSOs with absolute g-band magnitudes $M_g \approx -22$ at $z = 4$, and several magnitudes fainter than this at the lowest redshifts, thus reaching deep into the regime of low-luminosity "Seyfert-type" galaxies. This would be the largest and most complete sample of QSOs and AGN at these redshifts, providing uniquely powerful constraints on QSO evolution. Monitoring observations would provide important information on the innermost regions of QSO accretion disks, which are probed directly by their UV- and u-band emission.

3. Near-Field Cosmology

The Halo Structure, Stellar Populations, and Accretion Histories of Nearby Galaxies: The history of mergers and accretions in luminous galaxies — which are powerful constraints on models of hierarchical galaxy formation — can be examined directly using the resolved stellar populations that make up their extended halos. Numerical simulations carried out in the framework of ΛCDM models make clear predictions for the number and morphology of satellites, shells, and streams within the halos of $z \sim 0$ galaxies. With a relatively shallow survey that focuses exclusively on long-wavelength observations, Euclid will be limited in its ability to probe the stellar populations in nearby galaxies. At the same time, severe crowding makes studying their resolved stellar populations with ground-based telescopes (e.g., LSST, Pan-STARRs) virtually impossible for all but the nearest systems (nor can ground-based facilities probe the UV region, where the emission from young/hot stars is largest). A wide-field, UV/blue-optical imaging facility with HST-like resolution would revolutionize our understanding of the nearest galaxies.

Compact Stellar Systems: One of the most exciting questions to have emerged from the study of nearby galaxy clusters during the past decade is the origin of the faintest and most compact stellar systems. The relationship between these so-called "ultra-compact dwarf" galaxies (UCDs) and massive star clusters remains obscure, largely because there exists no comprehensive (i.e., complete and unbiased) catalog of star clusters and UCDs within even a single environment. By combining wide field with its excellent sensitivity and superb image quality, it would be possible to carry out the first complete, and unbiased, survey of compact, low-luminosity objects in the local volume. For instance, a two-week survey of the Virgo cluster would allow a complete census of all compact stellar systems down to g ≈ 28 (equivalent to a limiting stellar mass of roughly $5000M_\odot$) and resolve individual UCDs, star clusters and dwarf galaxies with sizes as small as $R_e \approx 3$ pc. Such observations would provide a wealth of information (such as luminosities, stellar masses, concentration indices, mean surface densities and spatial distributions) that can be used to test models for their formation and evolution.

The Central Structure of Nearby Galaxies: Another surprising discovery from HST surveys undertaken during the past 10–15 years has been detection of compact, structurally-distinct stellar components at the centers of most intermediate- and low-mass galaxies. Since these compact stellar nuclei are found in galaxies spanning the entire Hubble sequence, it is clear that a rather generic formation mechanism is needed to explain this ubiquity. A UV/blue-optical imager with a wide field of view and a resolution comparable to HST would allow the definitive study of the core vs. global structure for many thousands of galaxies in field, group and cluster environments. Given the low luminosities of these nuclei (typically less than ~1% of the host galaxy luminosity) and their small sizes ($R_e \leq 0.1''$ at the distance of the Virgo cluster), such a facility offers the only hope of identifying and studying these nuclei in a systematic and unbiased way.

4. Stellar Astrophysics

High-resolution imaging from the Wide Survey (as well as from deep, pointed observations of nearby galaxies) would allow comprehensive studies of the young stellar populations in the local universe, including ***hot massive stars***. For instance, in exposures of just 30 minutes, it would be possible to detect $9M_\odot$ main-sequence (B0) stars in the Virgo Cluster, and $2M_\odot$ (A0) stars in M31. Crowding in these fields will pose a severe problem for all other facilities, including ground-based telescopes like LSST. ***Pulsating variable stars*** (including Cepheids and RR Lyraes) could be detected and studied in nearby galaxies with unprecedented samples and precision. For example, RR Lyraes in Local Group galaxies could be detected with nearly 100% completeness in just ~30 minute exposures. ***Symbiotic binaries***, in which the components have similar luminosity but very different temperatures, have traditionally been discovered serendipitously but they could be detected large numbers in the legacy surveys and GO programs. This would allow a global study of this important stage of evolution in nearby galaxies and, for the first time, a detailed comparison between observations and the predictions of stellar evolution models. ***X-ray binaries and transients,*** which have not been studied fully in Local Group galaxies despite their significance in understanding both star formation and the fundamental physics of extreme objects, could also be readily identified. Other types of "stellar exotica" could also be detected and studied, such as ***post-AGB stars*** (which are of interest both for stellar evolution theory and for understanding the nature of the emission from LINER galaxies) and ***planetary nebulae***, which can be detected via their characteristic emission-line properties. Finally, a facility of this sort would be an ideal instrument for dedicated, wide-area searches for hot and/or ***extremely metal-poor stars*** in the Galactic halo (relying on selection in the color-color diagram). In the Wide Survey, each pointing would contain ~7000 halo stars brighter than g = 27.8, so there is an almost limitless potential for studying the stellar populations in the Galactic halo.

5. The Outer Solar System

Mapping the Outer Solar System. The outer solar system (OSS) represents the most accessible laboratory for understanding the details of planet formation and evolution. Yet we are remarkably ignorant of its structure and composition, with only two objects known to have pericenter distances > 47 AU. Surveys with even the best ground-based telescopes are fundamentally limited in two distinct ways: (1) Deep surveys, like the CFHTLS, do not cover sufficient area to be sensitive to rare and distant (> 60 AU) solar system objects; while (2) surveys that cover sufficient area do not have the image quality or cadence needed to detect very distant objects. However, nearly diffraction-limited g-band images from a 1m-class telescope can reach very deep levels in short exposure times, allowing faint OSS objects to be detected in successive exposures. For instance, in the 5000 deg^2 Wide Survey region, observations to an equivalent depth of r ~ 26 with a cadence of three exposures per hour should detect ~50 OSS objects at distances > 400 AU. The total number of OSS objects that would be detected in such a survey is estimated to be ~20000, compared to the ~1500 OSS objects known at the present time.

Stellar Occultations and the Size-Frequency Distribution. The size-frequency distribution (SFD) of Kuiper Belt objects is an excellent probe of the processes of planetesimal formation. The ~20000 OSS objects that would likely be detected in a Wide Survey would allow an excellent measurement of the SFD for OSS objects, although the SFD transition that is expected to have arisen from *collisional processing* probably occurs in objects that are so small and faint (r ~ 33) that it is beyond the reach of any facility that relies on reflected sunlight. An alternative is to rely on serendipitous occultations of stars by passing Kuiper Belt and Inner Oort Cloud objects. This is the only technique that is sensitive to sub-km objects in the OSS, and it clearly requires a space-based observing platform. With a detector focal plane that is capable of reading 300 sampling regions (ROIs) at 10-20 Hz sample speed, it should be possible to detect multiple occultations by small (sub-km) OSS objects, and hence provide a first characterization of the SFD.

Surface Chemistry of OSS Objects. Spectroscopic studies for small bodies in the asteroid belt, including broadband measurements of SEDs, have played a key role in piecing together the formation history of the solar system. While one would like to extend these successes to OSS objects, they clearly exhibit ice as a dominant component — something which is obviously not true for asteroids. Characterization of these ices remains elusive, and even their identification is possible only for water-ice and methane which happen to exhibit deep absorption features at near-IR wavelengths. Broadband colors for OSS objects reveal a curvature of their reflectance slope (or color) in the u-band to more neutral colors than is seen in the optical. This has been interpreted as evidence for organic ice, which exhibits a similar behavior. The shape of this flattening into the UV region is not only a diagnostic of the what surfaces ices may exist, but also of the amount of radiation-induced chemistry the ices have undergone. The coarseness of available data (primarily broadband colors) prevents quantitative interpretation of the observations. Depending on the adopted observing strategy and cadence, the Wide Survey could detect up to ~20000 OSS objects, including ~800 with high-quality u- and g-band data (compared to only ~10 for which u-band fluxes are currently available). Such data would allow the first robust characterization of the SEDs of OSS objects, and would make it possible to not only constrain the types of ice that exist in the OSS, but also to explore both the nature of the primordial ices from which that these bodies originated and the chemical pathways that gave rise to them.

VI. Education and Public Outreach

Panoramic, high-resolution UV/optical imaging would not only transform astronomical research, but it would likely capture the public imagination in a way that few, if any, previous missions have managed. While HST remains the “gold standard” in terms of public visibility for astronomical facilities, a UV/optical imaging mission with a ~ two order-of-magnitude increase in field of view relative to HST, combined with an operations model that places high priority on wide-field legacy surveys, has the potential to rival, or even exceed, HST in its ability to convey the beauty and importance of science, technology and research to the public. It would also be an extraordinary teaching tool, offering many opportunities for students of all ages to experience the joys of scientific discovery first-hand through outreach programs like *Galaxy Zoo*.

References

1. Albrecht, A., et al. 2006, e-print arXiv:astro-ph/0609591.
2. Blandford, R.D., et al. 2010, New Worlds, New Horizons in Astronomy and Astrophysics, The Astronomy and Astrophysics Decadal Survey.
3. Côté, P, et al. 2012, *CASTOR: The Cosmological Advanced Survey Telescope for Optical and UV Research*, Report on CSA Contract No. 9F052-101461-001-MTB.[2]
4. Huterer, D., et al. 2006, MNRAS, 366, 101.
5. Pritchet, C.P., et al. 20111, *Unveiling the Cosmos: A Vision for Canadian Astronomy 2010-2020*, Report of the Long Range Plan 2010 Panel.
6. Sorba, R., & Sawicki, M. 2011, PASP, 123, 777.

[2] http://orca.phys.uvic.ca/~pcote/castor