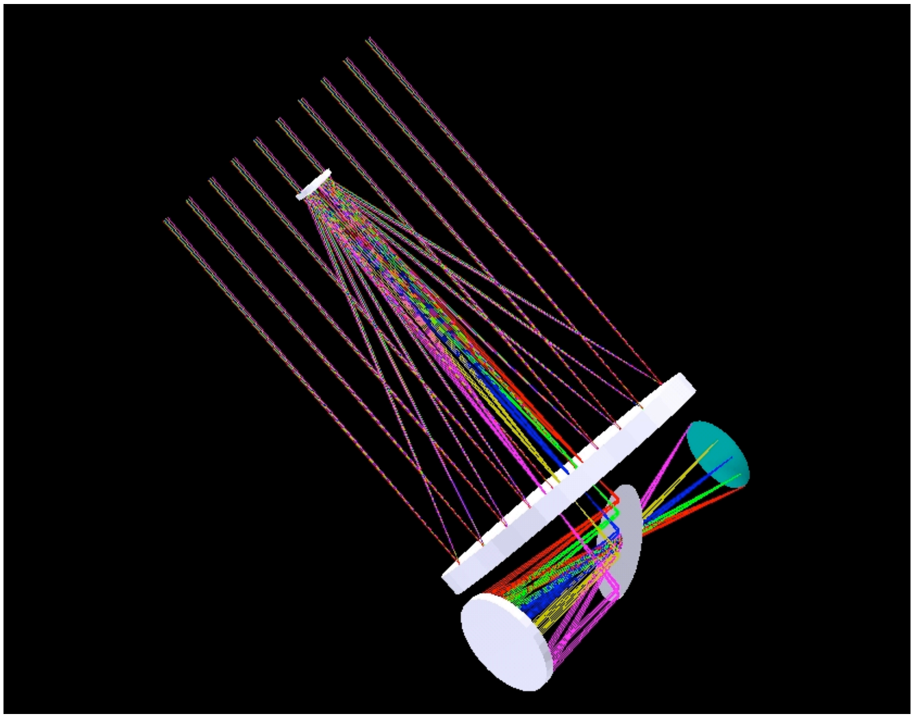

Final Report of the CSA Discipline Working Group on Wide-Field Imaging from Space

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1 Executive Summary

From 2007 to 2009, a DWG with representation from academia, government and industry examined the scientific motivations and technical requirements for possible CSA participation in a mission to carry out wide-field, UV-optical-IR imaging from space. The DWG considered a variety of options — from scenarios in which the CSA would lead the mission design, development, fabrication and operation, to a possible collaboration in one of several missions now under development at NASA, ESA and JAXA. The conclusions of the DWG are as follows:

There is an overwhelming scientific need for a high-resolution, wide-field imaging space telescope with an aperture of roughly $\sim$ 1m. Some of the key science drivers for such a facility include characterizing the nature of dark energy (DE) and measuring the equation of state of the universe; mapping the growth of dark matter (DM) structures as a function of cosmic time; observing directly the "gastrophysical" evolution of galaxies from "first light" to the present day; decoding the fossil record of the assembly of baryons within merging DM halos in nearby galaxies; and characterizing the evolution of star formation over cosmic time.

Not surprisingly, the precise choice of wavelength region for any such facility is driven by the highest priority science goals: investigations into the nature of DE and the equation of state of the universe are most efficacious at IR wavelengths, while studies of galaxy evolution since "first light" (i.e., the formation of baryonic structures inside merging DM halos) are best carried out at optical and UV wavelengths. These are among the most pressing open questions in astrophysics, and future progress in both areas will require an imaging space telescope since only in a space environment will it be possible to obtain high angular resolution images with a stable PSF over wide fields (and observe astrophysical sources in the UV spectral region).

Future space missions such as JWST and JDEM have focused almost entirely on the IR region. With the inevitable demise of the Hubble Space Telescope (HST), astronomers across the world will soon loose the high-resolution UV/optical imaging capabilities that have been so instrumental in transforming the astronomical landscape, as no replacement mission is currently planned by any international space agency. The wavelength region below $\sim 0.7\mu$m, where the response of both JWST and JDEM fall to zero, is not only critically important in the study of how galaxies and their constituent stars evolve over cosmic time, but will also prove indispensable in interpreting the observations from DE studies at longer wavelengths.

The DWG believes that there is a compelling opportunity for CSA to seize an international leadership role in space astronomy by capitalizing on the need for high-resolution, wide-field, UV/optical space imaging capabilities. This could take the form of either:

(1) a dedicated, diffraction-limited, UV-optical (≈ 0.2–0.8μm) telescope with aperture $\sim$1m (i.e., a Canadian Space Telescope = CST), that would offer HST-like resolution but with a $\sim$100$\times$ increase in field of view (baseline diameter $\approx 45'$); or

(2) a UV/optical channel for a targeted IR imager such as JDEM, which is currently planned to operate in the ≈ 0.7–1.7μm range only.

The DWG advocates a two-tiered strategy to further explore these options. First, given the the rapid pace of development for JDEM, which is presently *not* envisioned as an open user facility, *it is recommended that CSA immediately begins a dialog with NASA to explore possible terms for Canadian involvement in JDEM*. NASA's initial technical analysis of the JDEM mission requirements identified technical capabilities (including guider systems) developed through the Canadian roles in JWST and FUSE that may be valuable for JDEM; CSA should investigate the possibility of contributing hardware of this kind in exchange for guaranteed Canadian observing time on JDEM, and/or early access to JDEM data, that could be used for both DE, and non-DE, science. Second, a preliminary investigation by the DWG of the technical requirements for a dedicated mission suggests that this is an ambitious but feasible option for CSA — comparable in scope to Radarsat, and thus offering many excellent opportunities for Canadian industries to capitalize on their expertise in optical design and fabrication, guider systems, detector systems, spacecraft attitude control and deployable systems. Therefore, *it is recommended that a comprehensive feasibility study for a dedicated 1m-class facility, including a detailed cost and risk analysis, be undertaken immediately.*

Either route forward — leading a dedicated mission (CST) or participating in JDEM — would fulfill the overarching goals of the Long Range Plan (LRP) for Canadian astronomy released in 2000. As a dedicated 1m-class telescope, CST would be a "flagship" Canadian astronomy mission — likely supplanting *Canadarm* as the most visible project ever undertaken by CSA — and a prime candidate for inclusion in the national community's next LRP for astronomy. Nearly all aspects of such a mission have long and distinguished histories in the Canadian astronomical community: i.e., wide-field and high-resolution imaging, optical and UV astronomy, structure formation, cosmology and fundamental physics. Such a mission would also have broad appeal to the *entire* Canadian astronomical community, as it would provide a formidable research tool for virtually all other fields of astrophysics including the outer solar system and Kuiper Belt, near Earth objects, extrasolar planets and brown dwarfs, star formation, Galactic structure, active galaxies, supermassive black holes, and "first light" objects. Finally, by powerfully combining the wide-field and high-resolution features of the HST and CFHT imaging that has been so effective in public outreach programs, such a mission would be an unprecedented opportunity for CSA to play a leading role in communicating the importance of science, technology and research to the public at large.

2 Scientific Rationale for Wide-Field UV/Optical Imaging from Space

2.1 Objectives and Priorities

The discovery in the late 1990s (Riess et al. 1998; Perlmutter et al. 1999) that the expansion of the universe is accelerating due to an unknown dark energy (DE) component that makes up $\sim$70% of the mass-energy budget of the universe highlights our incomplete understanding of cosmology. This startling discovery, along with the earlier realization that the overall mass budget of the universe is dominated by dark matter

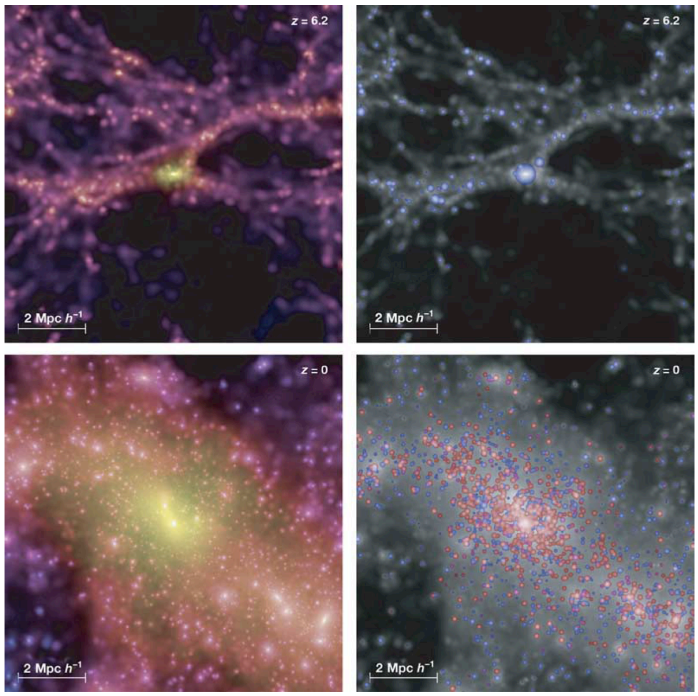

Figure 1: Figures illustrating ΛCDM predictions for the growth of structure from the Millenium Simulation of Springel et al. (2005). The left panels show the projected dark matter (DM) distribution, at $z = 6.2$ and $z = 0$, in a cube of co-moving side-length $10h^{-1}$ Mpc. The colour-coding reflects the DM density. The panels on the right show the galaxies predicted by a semi-analytic formation model overlaid on a greyscale image of the DM. The volume of the sphere representing each galaxy is proportional to its stellar mass, and the chosen colours encode the rest-frame optical stellar colour. At z = 6.2 (corresponding to an age of the universe of 0.9 Gyr), all galaxies appear blue because of ongoing star formation. At z = 0, many of the galaxies that have fallen into the rich cluster have turned red (i.e., are passively evolving), while star formation is occurring mainly in the less spatially concentrated galaxies. Understanding, in detail, the complicated physical processes underlying gas accumulation and star formation within merging DM halos is among the most active areas in modern astrophysics. A wide-field UV/optical imaging space telescope, such as CST, would make it possible to observe this processes *directly*, over cosmic timescales. Such a facility would be the natural successor to HST.

(DM), set the stage for research in astrophysics at the start of the 21st century. The nature of these dark components — and their role in the formation of the luminous, baryonic structures (i.e., stars and gas) that we observe directly as galaxies, clusters and superclusters — are among the most important open questions in modern science.

Ten years after the discovery of DE, it is clear that if we are to make progress in understanding these fundamental issues in cosmology, then *wide-field, high-resolution imaging at UV-optical-IR wavelengths (where the stars that make up galaxies emit most of their light) will be absolutely essential.* To meet the simultaneous requirements on image quality (i.e., angular resolutions of $\sim$0.1$''$–0.3$''$, or 1–0.3$\times$ that of HST) and field of view (i.e., a FOV $\sim$ 0.5-1 deg^2, comparable to those available with the largest CCD mosaic cameras on ground-based telescopes), an *imaging space telescope is required*. That is to say, only in a space environment will it be possible to obtain high resolution images, with a stable and well-characterized PSF, over wide fields. Several missions that are intended to address the key questions mentioned above are under active development, including NASA's Joint Dark Energy Mission (JDEM) and ESA's Euclid mission. In both cases, the primary science driver is a characterization of DE and a measurement of the universe's "equation of state" (which relates pressure, P, to energy density, ρ, of the DE: $w = P/\rho$), including its possible evolution with redshift.

Because they will be optimized for DE studies, such missions focus almost exclusively on the IR wavelength region (i.e., $0.7 \lesssim \lambda \lesssim 1.7\mu$m) which is well suited to probing the geometry of the universe and the growth of DM structures at low to moderate redshifts. Unfortunately, relying *exclusively* on IR observations not only limits the effectiveness of DE studies (see §2.1.1), but it makes it impossible to address another, equally important, issue in cosmology: i.e., understanding how baryonic matter evolved within merging DM halos to produce the galaxies we observe today. Although ΛCDM simulations designed to tackle this problem can now make testable predictions about the small-scale distribution of mass and light within galaxies (see Figure 1 and §2.1.3) significant uncertainties remain as these predictions depend critically on physical processes that are poorly understood at the present time, including gas dynamics, radiative cooling, star formation, and stellar/AGN feedback (considered collectively, the evolution in the visible components of DM-dominated galaxies as a result of these complex processes is sometimes referred to as "gastrophysical evolution"; §2.1.2).

Much of the credit for our current understanding of galaxy evolution, however incomplete, is due to the Hubble Space Telescope (HST). Arguably, this facility has had a greater impact on astrophysics than any other telescope in history. However, with no servicing missions for HST planned after SM4 in May 2009, astronomers will soon loose the high-resolution UV/optical imaging capabilities that have so profoundly changed the astronomical landscape. Moreover, future space missions, most notably JWST and JDEM, are heavily focused on the IR region, with essentially no response at UV or optical wavelengths — regions that are critically important in the study of galaxies (and their constituent stars) over cosmic time. Indeed, no major *high-resolution* UV-optical mission is currently planned by any international space agency for the pre-2020 period. While significant capabilities in the optical have been added by wide-field cameras on ground-based telescopes, these facilities fall far short of the angular resolution requirements needed to address many of the most fundamental questions in astrophysics.

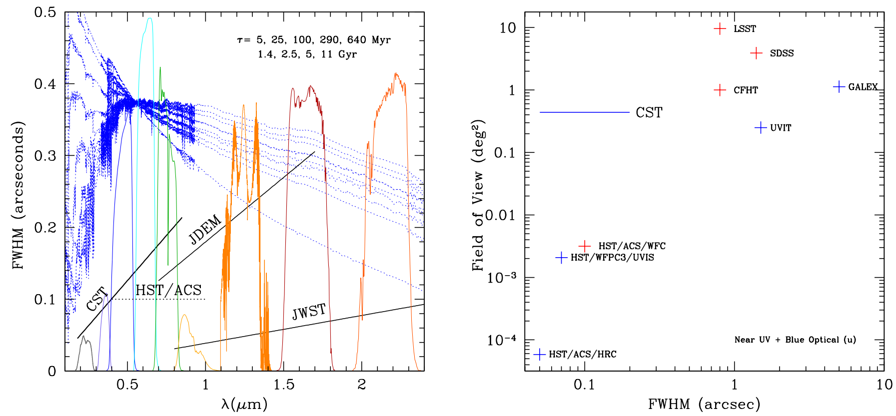

Figure 2: *(Left)* Angular resolution as a function of wavelength for a 1m CST compared to several other existing (HST), planned (JWST) or proposed (JDEM) space telescopes. Note that neither JWST or JDEM will operate in the blue/visible or UV spectral regions. The dotted blue curves in this figure show SEDs for simple stellar populations (from Bruzual & Charlot 2003) having solar metallicity and ages as indicated in the upper right corner. This illustrates the critical role the UV/optical region plays in measuring the star formation histories of galaxies. *(Right)* Field of view plotted against image quality for the CST and existing/planned imagers on ground- and space-based telescopes. The comparison is limited to those facilities that have good performance in the range 0.3–0.4μm from the ground, or 0.2–0.4μm from space. The line for CST indicates the diffraction limit in the range 0.2–0.8μm. With a 45$'$-diameter field and diffraction-limited optics, CST would have $\approx 10\times$ the angular resolution of the best ground-based telescopes, and cover a field $\approx 100\times$ that of HST.

The DWG believes that there is an exciting opportunity for CSA to seize an international leadership role in astronomy by capitalizing on the need for a high-resolution, wide-field UV/optical imaging facility in space (see Figure 2). This could conceivably take the form of either a dedicated standalone, 1m-class facility (i.e., a Canadian Space Telescope, or CST) and/or a UV/optical channel for a planned IR imaging mission led by NASA or ESA (JDEM, Euclid, or an eventual merger of these missions).

While this conclusion rests primarily the need to study fundamental cosmology and the evolution of galaxies over the age of the universe, wide-field space imaging capabilities would be broadly appealing to the *entire* Canadian astronomical community as it touches upon virtually all fields of modern astrophysics. We now briefly highlight some of the key science drivers for a wide-field, high-resolution imaging space telescope, with particular emphasis on the impact of a standalone mission in the areas of cosmology and galaxy evolution.

2.1.1 Dark Energy and the Equation of State of the Universe

An improved understanding of DE has emerged as a top priority for the US and European astronomical communities, as evidenced by the rapid development of the JDEM (NASA) and Euclid (ESA) missions. These missions will rely on three principal methods of determining the expansion history of the universe, and thus the nature of DE: (1) the "Hubble diagram" of distant supernovae (SNIa); (2) the weak gravitational lensing of galaxies or "cosmic shear"; and (3) variations in the large-scale distribution of matter (baryon acoustic oscillations, or BAO). It is likely that these missions will also use a number of secondary methods, such as galaxy cluster counts and the integrated Sachs-Wolfe effect, to further improve upon the final DE constraints.

The SNIa and BAO methods are geometric probes of the universe, relying on measuring luminosity and angular diameter distances, respectively. Weak lensing, by contrast, yields both angular diameter distances *and* the evolution of structure growth by measuring slight distortions in the images of distant galaxies caused by the way their light is deflected by the intervening mass. The degree of distortion depends on the distance the light has to travel, and on how the expansion of the universe has affected the distribution of the mass along the line of sight (which is dominated by DM). It is important to note that each method on its own provides only weak constraints on DE and the equation of state of the universe. It is only by combining the results from the different methods (and observations of the cosmic microwave background from WMAP, Planck, etc) that useful information on the nature of DE, and the possible redshift evolution of its equation of the state, can be obtained. In all cases, high-resolution imaging with low levels of systematic errors and covering a large field is necessary to perform the measurements; this is the primary motivation for the wide-field, nearly-diffraction-limited designs of the JDEM and Euclid satellites.

Because the fractional contribution of DE to the total density of the universe rises steeply from $z \sim 3$ to $z \sim 0$, these DE missions are being optimized for observations of galaxies in the "low-z" universe. To obtain high-quality lensing measurements for galaxies in the range $0.5 \lesssim z \lesssim 1.5$, accurate distances — derived using photometric redshift methods — are crucial. (This is equally true of the BAO technique, as well as for several secondary DE probes.) At present, however, JDEM's sensitivity is being optimized for the near IR region (with significant response only over the range ≈ 0.7–1.7μm). This lower limit excludes the short-wavelength bandpasses that are essential in improving the overall accuracy of photometric redshift measurements and reducing the number of so-called "catastrophic" failures. While it may be possible to perform the optical measurements with ground-based telescopes, the much lower photometric precision obtained in this way will lead to larger errors on the photometric redshifts, and *much* larger errors on the equation of state. For instance, one comprehensive study recently showed how a $\sim 1\%$ error in the mean redshift of a $photoz$ bin translates into an error of $\sim 100\%$ in the equation of state parameter, w (Huterer et al. 2006).

For these reasons, there is considerable discussion within the NASA and ESA communities about the feasibility of extending the capabilities of the DE missions into the blue-optical regime. Thus, DE studies offer an immediate and important example of the need for wide-field, high-resolution space imaging capabilities at "short-wavelengths" ($\lambda \lesssim 0.7\mu$m). Given the importance of DE research and the expertise of Canadian researchers in the relevant fields (i.e., in the SNIa, BAO and weak-lensing techniques), this represents an exciting opportunity for either direct Canadian participation in JDEM/Euclid, or leadership in a dedicated mission that could leverage the IR observations from these missions.

2.1.2 Gastrophysical Evolution over Cosmic Timescales

Significant observational progress has been made during the past decade in tracing the the hierarchical assembly of galaxies over cosmic time. As a result, a general picture of how galaxies form and evolve is beginning to take shape. At high redshifts ($z \gtrsim 2$), massive galaxy formation appears to have occurred via intense merging activity and rapid starbursts, approximately tracing the hierarchical buildup of DM mass. By $z \sim 1$, most massive galaxies were already in place and had largely ceased forming stars. At $z \lesssim 1$, star formation in galaxies had begun to be strongly quenched at a rate and time that depended sensitively on their mass and environment, while clusters and superclusters of galaxies continued to grow. The challenge is now to understand, *in detail*, the physical processes that bring this about. Because of the complex gas-dynamical processes involved in the formation of baryonic structures within merging DM halos (including gravity, magnetohydrodynamics and nucleosynthesis), this "gastrophysical evolution" is perhaps the most poorly understood stage of structure formation in a ΛCDM universe.

A major impediment to a deeper understanding of the formation of stars and galaxies within the "cosmic web" is that most observations are limited to the gross properties of galaxies: e.g., total stellar mass, star formation rate, luminosity–weighted age, etc. However, galaxies are remarkably complex entities, comprised of dynamically-hot spheroids, cold disks, bars, star clusters, nuclei, black holes, and other distinct components, all of which likely form through different processes. Yet there is mounting evidence that they all coevolve in an interdependent way; for example, bars can form rapidly once a massive rotationally-supported disk is present, and afterwards exert a strong influence on the dynamical evolution of the host galaxy. More dramatically, stellar nuclei and supermassive black holes in bulges are likely sources of the energetic "feedback" that must play a key role in suppressing star formation in massive halos. Moreover, the hierarchical nature of structure formation itself implies that galaxy evolution will be influenced by interactions with neighbouring galaxies and large-scale structure. We know, for example, that galaxy properties are sensitive to the local density on scales of several Mpc. The abundance of massive disk galaxies with little sign of recent star formation, such as S0 galaxies and passive spirals, depends strongly on both redshift and environment. This suggests they may be key tracers of the transformation processes driving the shutdown of star formation since $z \approx 1$.

Disentangling these myriad gastrophysical effects will require multi-wavelength, high-resolution imaging of galaxies over wide fields. High-resolution imaging is absolutely essential to distinguish the various galaxy components. For example, stellar nuclei have sizes of ~ 10 pc, which corresponds to $0.1''$ or less at the distance of the Virgo custer (Figure 3). At $z \approx 0.5$, whole galaxies subtend only a few arcseconds and HST-like resolution is absolutely essential to study disks, bulges, bars, or tidal features. Deep optical imaging is especially important for measuring key spectral features and

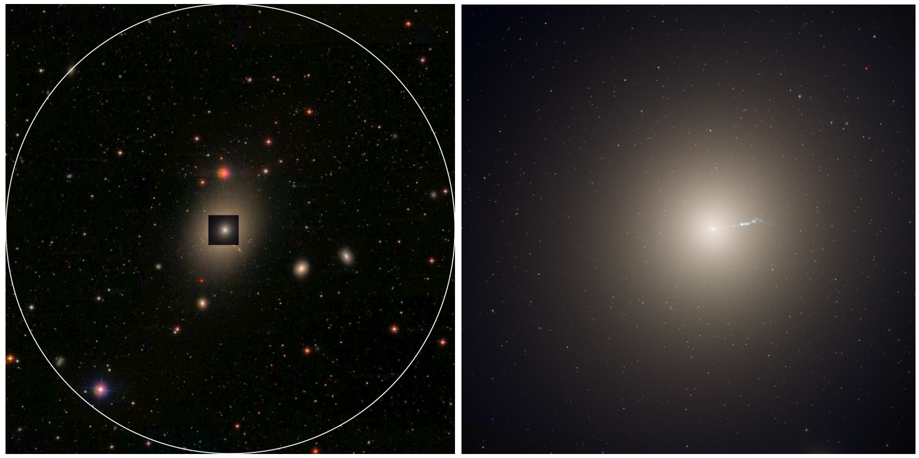

Figure 3: *(Left)* The core of the Virgo cluster of galaxies, the rich cluster nearest to the Milky Way, as seen with the SDSS — the most ambitious optical sky survey ever undertaken (York et al. 2000). The $45'$-diameter FOV of CST is shown by the circle, while the inset shows an HST image of M87 taken with the *Advanced Camera for Surveys* (ACS). A 3-hour blue-optical (g) exposure with CST would reach sources $\approx 250\times$ fainter than SDSS, with HST-like angular resolution. *(Right)* Magnified view of this HST/ACS image. Note the optical synchrotron jet from the central supermassive black hole, and the thousands of star clusters and faint galaxies visible in this HST image. CST would deliver HST-quality images over fields comparable to those available with the largest mosaic cameras on ground-based telescopes.

photometric redshifts for these galaxies.

While HST has taught us much about the morphological evolution of galaxies, most of what we know is restricted to one or two filters, and/or small areas. Even at $z \approx 1$, the HST/ACS field corresponds to only ~ 1.6 Mpc, or the size of a single galaxy cluster. Dedicated surveys such COSMOS (2 deg^2) and GEMS (0.2 deg^2) cover larger areas but, despite their extreme expense (i.e., COSMOS used 590 orbits, or 10% of all time available in a given HST cycle), have imaging in only one or two filters, making it impossible to connect star formation history to the different structural components. The largest multicolor HST survey conducted to date — GOODS — used four filters but covered less than 0.1 deg^2 making it extremely difficult to gauge cosmic variance and environmental effects. Indeed, all of these relatively shallow surveys detected at most about 1% of the number of galaxies in SDSS (which is itself severely limited for such studies given its poor angular resolution). In short, *a wide-field space telescope with HST-like resolution would completely revolutionize this field by providing the first data needed to uncover definitely the gastrophysical processes shaping galaxy evolution over cosmic time.*

2.1.3 The Archaeology of Structure Formation: Baryons and Dark Matter at Low Redshift

An inevitable consequence of galaxy formation in the ΛCDM paradigm is that a galaxy like the Milky Way will accrete hundreds of small, dark-matter-dominated subhalos. Many of these low-mass halos will contain stars and gas, and will be shredded by the gravitational tidal forces of the large galaxy. Thus, the outer regions of galaxies are expected to contain many luminous substructures that are the "fossil records" of the host's formation. By identifying and studying these substructures, it is possible to reconstruct the detailed merger history of the host galaxy, and determine how and when it formed. Equally important, by characterizing the stellar populations of these protogalactic building blocks, it is possible to connect the properties of their visible (=baryonic) components to those of their DM halos.

The majority of the baryonic substructures in massive galaxies are much too faint to be detected through unresolved light and can only be identified by resolving their constituent stars — which, for old, metal-poor halo populations, have $M_V \gtrsim -2.5$. Thus, this science is technically challenging as it requires both high-resolution imaging capabilities and a wide FOV in order to map the stellar populations of $z \approx 0$ galaxies efficiently. Currently, this work can only be done for the Milky Way galaxy and its two nearest neighbours, the Andromeda (M31) and Triangulum (M33) galaxies. Canada is already leading the most ambitious imaging survey to date of these two galaxies by exploiting the unique capabilities of the MegaPrime mosaic camera on CFHT. However, this outstanding instrument, which boasts a large (1 deg^2) FOV, is still limited by its angular resolution, which is about ten times worse than HST. By contrast, HST is able to resolve galaxy halos in the Local Group with spectacular success, but it covers a field only 0.3% that of MegaPrime and is thus incapable of mapping the nearby halos in their entirety. Note that, at the distance of M31 and M33, the brightest halo stars have apparent magnitudes of $m_V \sim 22$; although faint, this is easily within the reach of CCD mosaic cameras on 4-10m-class ground-based telescopes. For more distant systems, however, the poor seeing available from the ground, excessive image crowding, and the high sky brightness means that such observations quickly become impossible with existing (or planned) ground-based telescopes: i.e., $m_V \sim 26$ and 28.5 at 5 Mpc and at the distance of the Virgo cluster (16.5 Mpc), respectively.

A 1m-class, UV/optical space telescope with a ≈ 0.5 deg^2 FOV and operating at the diffraction limit could obtain, in just a few tens of hours, images for a galaxy at 5 Mpc deep enough to resolve stars within the top few magnitudes of the red giant branch. With the resolution of HST and a FOV comparable to MegaPrime, a CST would be able to extend the sample of galaxies for which this science can be conducted from *three* galaxies within ~ 1 Mpc to many tens of galaxies within 5 Mpc that span a wide range of mass and morphology. Rather than relying on a mere handful of Local Group galaxies to test the detailed predictions of ΛCDM models, we could obtain equivalent data for all high-mass galaxies in a complete sample of nearby groups —- Maffei, IC342, Sculptor, M81, M83, Cen A and Canes Venatici I — as well as for *hundreds* of lower-mass dwarfs. Moreover, such a facility would bring the vast reservoir of galaxies in the Virgo (Figure 3) and Fornax clusters within range, enabling the study of resolved substructures in literally hundreds of galaxies within a common environment. Taken together, the observations from such surveys would constitute an *unprecedented test of models for the growth of baryonic components in DM halos, integrated over the age of the universe*. Indeed, these observations represent an essential pre-requisite for constraining the precise mechanisms of structure formation on galactic and sub-galactic scales.

2.2 Synergy with the Long Range Plan for Canadian Astronomy

Either of the space facilities considered here — a standalone mission (CST) or participation in JDEM through the contribution of a UV/optical imaging channel — would fulfill the overarching goals of the Long Range Plan (LRP) for Canadian astronomy, released in 2000, by: (1) providing unique capabilities that would advance our understanding of the fundamental scientific questions identified by the LRP; (2) complementing and enhancing Canada's investment in the missions already implemented as part of the LRP; and (3) providing outstanding opportunities for public outreach and science education within the broader community.

Many of the core science drivers for a wide-field UV/optical imager in space — including the formation of stars and galaxies, their evolution over cosmic time, a detailed exploration of the early Universe, and the nature of DM and DE — either figure prominently as key science goals in the LRP or represent questions arising naturally from the scientific initiatives underway at that time. The complexity of these issues is such that they cannot be addressed by any single facility, but rather, require a carefully chosen set of complementary facilities. It will be the role of a wide-field space-based imaging telescope to map out the distribution of mass and constrain the physical conditions in the early Universe through large-scale weak-lensing studies; to follow the detailed evolution of galaxy properties from "first light" to the present day; to decode the fossil record of galaxy assembly within merging DM halos by mapping the distribution of stars within nearby galaxies; and to characterize the evolution of star formation over cosmic time.

Although there was no specific provision in the LRP for either participating in a wide-field imaging mission like JDEM or leading a dedicated mission like CST, the plan did strongly endorse Canadian involvement in the construction of a new 8m-class wide-field optical/IR telescope; either JDEM or CST would be a natural extension of this recommendation. *Wide-field science is greatly enhanced by both high angular resolution and a stable PSF, neither of which can be achieved from the ground over the FOV considered here.* Furthermore, the opportunity to add unique UV capabilities provides additional justification for a space mission. The priority facilities outlined in the LRP — most notably TMT, JWST and ALMA — will soon provide Canada with high-resolution imaging capabilities from the optical to the mm, but over comparatively small field of views. CST would extend such capabilities to the UV and, by so doing, would be both a logical followup to FUSE, the highly successful CSA/NASA UV spectroscopic mission, and a spectacular advance in image quality (a roughly $\sim 25\times$ improvement in FWHM) relative to what will soon be the world's leading UV imager: i.e., the CSA/ISRO UVIT instrument on board *Astrosat*. In the optical, its unique ability to survey large areas of the sky will generate the follow-up opportunities that are critical to exploit the full discovery power of the Canadian community's other, more targeted, facilities.

Finally, a wide-field imaging space telescope would be perfectly suited to fulfilling the cultural and educational goals outlined in the LRP. Wide-field, high-resolution images would combine the two characteristics that have made HST and CFHT so effective and popular in public outreach programs. Canada would therefore be posed to play a leading role in communicating the importance of science and research to the public. In short, a CST would represent both the obvious next step in the scientific process laid out in the last LRP, and a facility with the community-wide appeal needed for a Canadian "flagship" space mission to be included in the forthcoming LRP.

2.3 Alignment with International Long Range Plans

The US astronomical community is currently in the process of identifying priorities for the most urgent scientific and technical activities in the period 2010–2020 (i.e., the 2010 "Decadal Survey"). However, the need for high resolution and/or wide-field imaging facilities, either on the ground or in space, has consistently emerged as a priority in past Decadal Surveys (e.g., most notably in the form of HST, JWST, LSST) and there is no reason to believe that this strategy will be abandoned in the coming decade. Indeed, there is a tremendous momentum within the US community to "fast track" the JDEM satellite, as illustrated by the recent agreement signed between NASA and DOE to develop this mission on a rapid timescale (with launch around 2015). Thus, a wide-field UV/optical imaging facility would not only complement JDEM by strengthening the DE science capabilities but, by virtue of the extended wavelength coverage and ability to conduct pointed observations, would align closely with the likely priorities of US astronomical community on the eve of their 2010 Decadal Plan.

The same is true for the European and Japanese communities. Wide-field imaging missions to study DE and the early universe are being actively developed, including Euclid (ESA) and WISH (JAXA). The former mission has been selected as one of four M-class mission concept studies under *ESA Cosmic Visions (2)* and has a target launch date of 2017. *Indeed, ESA and NASA are currently discussing a possible merger of the JDEM and Euclid missions.* Meanwhile, the WISH mission, although not yet approved by JAXA, aims to carry out wide-field, diffraction-limited imaging at IR wavelengths to explore the early universe and probe the epoch of reionization. Thus, the development of a wide-field UV/optical imaging capability by CSA would be fully complementary to the plans of all the international leaders in space astronomy. It would allow the Canadian community to leverage the observations taken at longer wavelengths to strengthen the core science of the JDEM, Euclid and WISH missions, and enable dramatic scientific progress in key areas (including galaxy evolution and star formation within merging DM halos) that will be impossible with these facilities alone.

Finally, the expected demise of HST in the next few years — combined with the strong emphasis placed on the IR spectral region for the space missions currently under development — has led to significant building interest in a very large UV/optical telescope (8-16m aperture) that would be launched in the 2020-2030 time frame (the Advanced Technology Large-Aperture Space Telescope = ATLAST). There is, however, currently no identified funding mechanism for this extraordinarily complex telescope. The DWG feels that a significant number of the science questions motivating this very ambitious facility can be addressed in a more timely and cost effective way by focusing on the opportunities for wide-field UV/optical imaging at angular resolutions comparable to that of HST.

3 Technology

3.1 Technology Description

Here we provide a brief description of the technology requirements for a wide-field imaging telescope that would address the scientific issues described in §2. We focus on the case of a standalone mission (i.e., a CST). The science performance requirements outlined above lead to the following specific technical requirements for the instrument and spacecraft:

- Primary optics of order 1m aperture with diffraction-limited performance over a ~ 0.5 deg^2 FOV for wavelengths $\lambda \approx 0.18$–0.8μm.
- Structures and mechanisms to house and focus the optics, including appropriate sunshading and baffling.
- A spacecraft that can provide the pointing and drift rates required to deliver diffraction-limited imaging (i.e., 20 mas or better).
- 2D detectors for the UV/optical region that cover the FOV and sample the images adequately; CCDs or CMOS devices are the likely choice, perhaps with two coating designs for the UV and optical.
- Filters, beamsplitters, gratings and associated mechanisms.
- An integration and test facility.
- Ground links and on-board storage to support continuous observations.
- A ground station, data pipeline, archive and mission planning center.
- A launch vehicle for an appropriate orbit. The choice of orbit will be a tradeoff between minimizing cost (low altitude) and achieving the lowest possible background in order to maximize sensitivity to faint astrophysical sources.

A more detailed description for two of these key technologies follows:

Optical Design versus Mirror Mass and Performance

For a 1m-aperture telescope having wide spectral coverage and a large FOV, a Korsch system is a good all-reflective baseline design (see Appendix E), although we emphasize that a thorough study of optical designs must be carried out. For good performance in the UV, it will be necessary to polish and test the optical components to high accuracy and this would be an important part of a trade study. Because the Korsch can deliver a much wider FOV than is nominally required, giving diffraction limited performance over a full degree or more, it is possible to consider both circular and rectangular fields. Paving this FOV might eliminate the need for a beamsplitter configuration.

A weakness of the Korsch design is the tight alignment requirements for the three elements, so we might consider the tradeoff between an actuator solution to maintaining WFE versus the raw structural mass for the primary mirror. For example, the mass

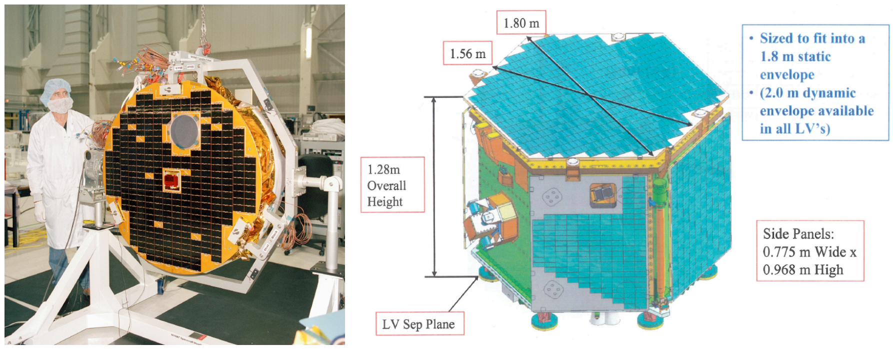

Figure 4: *(Left)* The CSA small satellite SciSat-1 undergoing integration. *(Right)* The CASSIOPE (CASade, Smallsat and IOnospheric Polar Explorer) spacecraft model.

surface density of the HST primary mirror is 150 kg m^{-2} while that of JWST is 15 kg m^{-2} (including the actuators needed to tune the telescope). It should also be investigated whether an approach similar to ground-based AO is worthwhile: i.e., fixing the WFE from a floppy primary by using a deformable mirror downstream. For an overall spacecraft mass target of $\sim$ 500 kg (i.e., a small satellite class mission, see below), then accommodating a $\sim$1m-diameter telescope, instruments and spacecraft within this mass target should be feasible using an extension of current technologies.

Spacecraft, Launcher and Deployables

While payload mass is always a system driver, especially for a small satellite, the telescope volume ($\sim$ 10 m^3) required by a design similar to that shown in Figure 5 is too large for many of the available smaller class launchers. To fit in typical small satellite volumes (e.g., a Pegasus launch), a deployable secondary and baffle system are likely required; this will certainly be true if a shared launch is planned. However, the basic $\sim$1m telescope primary mirror is fully compatible with current Canadian small satellites, as shown in Figure 4.

Note that the total mass of SciSat-1 was $\approx$150 kg and was intended to be launched as a partial Pegasus payload, while the predicted mass of CASSIOPE is $\sim$500 kg. The CST could therefore target a CASSIOPE-class spacecraft.

4 Anticipated Benefits and Applications

4.1 Technology Development in Canada

A standalone mission of this sort would offer countless opportunities for Canadian industries to capitalize on their expertise in key areas, including optical design and fabrication, guider systems, detector systems, spacecraft attitude control and deployable systems. We now examine the technological requirements and challenges for these various subsystems and highlight, on a case-by-case basis, possible synergies with Canadian industrial partners.

4.2 Technology Readiness Levels and Sources of Risk

None of the hardware mentioned above is new, although these systems have not been combined in a single mission by Canadian organizations. Significant technology development will be required to enable a standalone mission, and some technologies are worth demonstrating before full-blown mission development is undertaken. There are also some areas that will require significant additional study before a detailed design analysis could proceed, including:

Mission Architecture

A mission design study should be carried out to optimize the selection of orbit, spacecraft mass, launcher availability, and, of course, cost. MDA has significant expertise that might be applicable to this mission, having recently developed a mission centered around an ultra-high resolution, earth-observation imaging system. This work — which leverages the RapidEye earth observation constellation of five medium-resolution optical imaging spacecraft that are now in full commercial operations — is led out of MDAs Richmond, B.C. office and includes significant collaboration from its other space divisions in Brampton and Montreal.

Optical Design

A study of the optical design tradeoffs, mentioned briefly above, will be critical in optimizing the design for the available mass and volume. COM DEV (Cambridge, Ottawa) has extensive opto-mechanical design capability for space systems, having developed and successfully flown 15 optical payloads for a variety of different science and operational missions. For the JWST FGS project, a number of early opto-mechanical tradeoffs were done that are broadly similar to the ones required here: i.e., reflective vs refractive, or hybrid beryllium vs aluminum structures, etc.

Deployable Systems

Deployable space systems much larger than those required for the CST baffle and secondary mirror have been successfully implemented on many previous missions. For example, the Radarsat-1 & 2 antenna panels were large deployed systems, as, of course, are the Space Shuttle and ISS Canadarm systems. For CST, the secondary mirror deployment system requires a careful study and, ideally, some prototyping. While the deployment systems mentioned above can position objects to within a millimeter, the secondary mirror in typical telescope designs must be placed within microns of its ideal position. A multistage mechanism is certainly required and would be best done as a ground-based prototype/demonstration.

Tracking and Guiding

The choices of guider design and tracking strategy are important given the need to maintain high angular resolution. Drift scanning with strips of filters, or pointed full-field observations, are two obvious options. In both cases, a combination of gyro drift rates and fine guidance imaging would be used. There is very considerable Canadian industrial experience in this area, particularly with COM DEV who built the FES for the highly successful FUSE mission and are currently developing the JWST FGS.

Detector Arrays and Electronics

For a 1m telescope, the diffraction limit between 0.18 to 0.8 μm varies from $\approx$ 45 to 200 mas. To fully cover a $45'$-diameter field with 100 mas pixels requires 600

Megapixels (i.e., about a factor of two increase relative to MegaCam on CFHT), or 75 $2{\times}4$k CCDs. For comparison, covering a $15'$-diameter field with 40 mas pixels would require a total of 50 CCDs of this size. Thus, it is worth exploring the possibility of including a beamsplitter to target a subset of the full field with optimal sampling for the shortest wavelengths (e.g., 0.18–0.30μm). While the electronics may be challenging, many ground-based mosaic cameras are currently under development that greatly exceed the above requirements in terms of overall pixel numbers (e.g., Pan-STARRS, Hyper-Suprime Cam).

Attitude Control System

In addition to the sensors providing pointing knowledge (star tracker and/or focal plane guider), precise attitude control actuators are required for such a mission. While such systems certainly exist at a TRL of 9, they have not yet been incorporated into a Canadian small satellite. Bristol Aerospace (Winnipeg, Ottawa) has developed the attitude control systems of SciSat-1 and CASSIOPE, including a novel gyro-wheel system that combines the features of gyroscopes used for rate sensing and momentum wheels used for active attitude control.

Data Handling

A system is required that is capable of storing and handling large amounts of data with low noise. Telemetry and data compression will also require further study given the very large numbers of pixels involved. Canadian companies such as MDA have studied data compression systems for other data-intensive missions (such as hyperspectral earth imaging systems). The Cascade portion of the CASSIOPE mission is a state-of-the-art data handling system that stores and forwards large quantities of data.

A feasibility study should be undertaken to examine all of these issues in detail. Other areas to be addressed in such a study include the mechanical and thermal design, optical alignment, test strategies, mass estimates, power requirements, and optical error budgets. Only when the results of this feasibility study are available will it be possible to provide a reliable cost estimate and mission timetable.

5 Summary and Recommendations

The DWG concludes that there is an overwhelming scientific need for a high-resolution, wide-field imaging space telescope, operating in the UV-optical-IR region, with an aperture of roughly $\sim$ 1m. Some of the key science drivers for such a facility include characterizing the nature of DE and measuring the equation of state of the universe; mapping the growth of DM structures as a function of cosmic time; observing directly the "gastrophysical" evolution of galaxies from "first light" to the present day; decoding the fossil record of the assembly of baryons within merging DM halos in nearby galaxies; and characterizing the evolution of star formation over cosmic time. Two high-profile space missions which target the IR wavelength region, and focus heavily on the issue of DE, are under active development at NASA (JDEM) and ESA (Euclid).

The DWG believes that there is a compelling opportunity for CSA to seize an international leadership role in space astronomy by capitalizing on the need for wide-field, UV/optical space imaging capabilities. This could take the form of either:

(1) a dedicated, diffraction-limited, UV-optical ($\approx$ 0.2–0.8μm) telescope with an aperture of $\sim$1m that would offer HST-like resolution but with a $\sim$100$\times$ increase in field of view (i.e., a Canadian Space Telescope); or

(2) a UV/optical channel for a targeted IR imager such as JDEM, which is currently planned to operate in the $\approx$ 0.7–1.7μm range only.

Either option would present outstanding opportunities for Canadian industries to capitalize on their expertise in key technology areas, including optical design and fabrication, guider systems, detector systems, spacecraft attitude control and deployable systems. The DWG therefore suggests that CSA immediately undertakes a two-fold strategy to further explore these options:

(1) Given the the rapid pace of development for JDEM, which is presently *not* envisioned as an open user facility, *it is recommended that CSA immediately begin a dialog with NASA to explore possible terms for Canadian involvement in JDEM*. NASA's initial technical analysis of the JDEM mission requirements identified technical capabilities (including guider systems) developed through the Canadian roles in JWST and FUSE that may be valuable for JDEM; CSA should investigate the possibility of contributing hardware of this kind in exchange for guaranteed Canadian observing time on JDEM, and/or early access to JDEM data, that could be used for both DE, and non-DE, science.

(2) A preliminary investigation by the DWG of the technical requirements for a dedicated mission suggests that this is an ambitious but feasible option for CSA — comparable in scope to Radasat. Therefore, *it is recommended that a comprehensive feasibility study for a dedicated 1m-class facility, including a detailed cost and risk analysis, be undertaken immediately. CSA should issue an AO that is suitable for such a concept study as soon as possible, and preferably no later than the fall of 2009.*

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C Discipline Working Group Meetings and Events

The DWG on wide-field imaging from space was formed in December 2006. A proposal was submitted to CSA and approved in early 2007, at which time the DWG consisted of 13 researchers. It has since expanded to 34 researchers from coast to coast, with representation from academia, government and industry. During the past two years, seven "face to face" meetings have been held either as dedicated DWG workshops, or during meetings of the broader Canadian astronomical community (e.g., CASCA, Astro-Ski). A summary of these meetings may be found in table below.

Table 1: Meetings of the DWG on Wide-Field Imaging from Space: 2007–2009

Event	Date	Location	DWG Attendees	Expenses Claimed?
38th mtg. of CASCA	07/06/2007	Kingston, ON	5	No
Astro-Ski 2008	21/02/2008	Mt. Washington, BC	10	Yes
39th mtg. of CASCA	22/05/2008	Victoria, BC	5	No
Team meeting	15/10/2008	Toronto, ON	6	Yes
Team meeting	04/11/2008	Victoria, BC	8	Yes
Team meeting	04/28/2008	Victoria, BC	7	No
Astro-Ski 2009	19/02/2009	Mt. Washington, BC	10	Yes

D Acronyms

ACS	Advanced Camera for Surveys
ALMA	Atacama large Millimetre Array
AO	Adaptive Optics
ATLAST	Advanced Technology Large-Aperture Space Telescope
BAO	Baryon Acoustic Oscillations
CASCA	Canadian Astronomical Society, Société Canadienne d'Astronomie
CASSIOPE	CASade, Smallsat and IOnospheric Polar Explorer
CCD	Charge Coupled Device
CDM	Cold Dark Matter
CFHT	Canada France Hawaii Telescope
CMD	Color Magnitude Diagram
CMOS	Complementary Metal Oxide Semiconductor
COM DEV	COM DEV International Ltd.
COSMOS	Cosmological Evolution Survey
CST	Canadian Space Telescope
DE	Dark Energy
DM	Dark Matter
DOE	Department of Energy
DWG	Discipline Working Group
ESA	European Space Agency
FES	Fine Error Sensor
FGS	Fine Guidance Sensor
FOV	Field of View
FUSE	Far Ultraviolet Spectroscopic Explorer
FWHM	Full Width Half Maximum
GALEX	Galaxy Evolution Explorer
GEMS	Galaxy Evolution From Morphology And SEDs
GOODS	Great Observatories Origins Deep Survey
HST	Hubble Space Telescope
IR	Infrared
ISRO	Indian Space Research Organization
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JDEM	Joint Dark Energy Mission
JWST	James Webb Space Telescope
ΛCDM	Λ Cold Dark Matter
LRP	Long Range Plan (for Canadian Astronomy)
LSST	Large Synoptic Survey Telescope

MDA	MacDonald, Dettwiler and Associates Ltd.
NASA	National Aeronautics and Space Administration
Pan-STARRS	Panoramic Survey Telescope & Rapid Response System
PSF	Point-Spread Function
SDSS	Sloan Digital Sky Survey
SED	Spectral Energy Distribution
SM4	Servicing Mission 4
SNIa	Supernova (Type Ia)
TMT	Thirty Meter Telescope
TRL	Technology Readiness Level
UV	Ultraviolet
UVIT	Ultraviolet Imaging Telescope
WFE	Wavefront Error
WISH	Wide-field Imaging Surveyor for High-Redshift
WMAP	Wilkinson Microwave Anisotropy Probe

E A Preliminary Korsch Concept for the CST

The essential elements of CST are wide-field coverage and excellent image quality at UV/optical wavelengths. We have developed a preliminary Korsh concept that meets these requirements. Note that this concept is intended to demonstrate mission feasibility and is *not* an optimal design. The telescope specifications are summarized in Table 2.

Table 2: CST Concept Design

Primary Aperture	1m
Spectral Coverage	0.2μm to 0.7μm
Field of View	0.44 deg^2 (anular, $\pm$0.39 degrees with a $\pm$0.1 degree blind spot)
F#	20.6
Plate Scale	0.1 mm/arcsec (0.1$''$ per 10 micron pixel)
Image Performance	diffraction limited

An examination of telescope speed versus FOV for different optical layouts leads us to consider a Korsch design as our baseline because it combines a wide FOV with a compact structure, leading to a cost-effective implementation. Note that a feature of a Korsh design is its curved focal surface. The suggested imaging method is to pave the surface with 2k$\times$2k flat detectors, arranged along the curved focal surface. With the F/20.6 focal ratio, the image quality will be diffraction limited for wavelengths greater than 0.25μm on each of the flat detector segments as shown Figure 5 (for detectors near the center of the field). Paving the curved focal surface with flat detector segments eliminates the need for an additional field flattener optical element.

The FWHM of a diffraction limited image at 0.2μm is 4.2μm. With diffraction limited images, the 10μm pixels undersample the image so there is margin to reduce the image quality requirement and the violation of the diffraction limit at wavelengths less than 0.25μm and at field locations where the telescope image quality is less than at the center. Using flat detectors to image the curved focal surface is likely to be acceptable. Other options are to curve the detectors to the image surface curvature, or to put field correctors in front of the detectors. These options should be considered in a formal feasibility study.

A challenge with this design is the choice of detector. In consultation with Tim Hardy (HIA), we have identified the Teledyne H4RG-10 with the HyViSI detector layer as a promising candidate. It is a CMOS hybrid detector with high UV quantum efficiency and small pixels. There is a limited availability of scientific grade, UV-sensitive detectors with pixels 10μm or smaller; if a detector with larger pixels were chosen, the plate scale would need to be larger in proportion. The current detector array size is 320 mm in diameter, so there is considerable motivation to keep the pixels as small as possible. Unfortunately, this detector pixel size is presently only available as a production item with a 4k$\times$4k device. Given the large number of detectors required for the project, it is highly likely that a custom run of this detector with a smaller array size could be arranged.

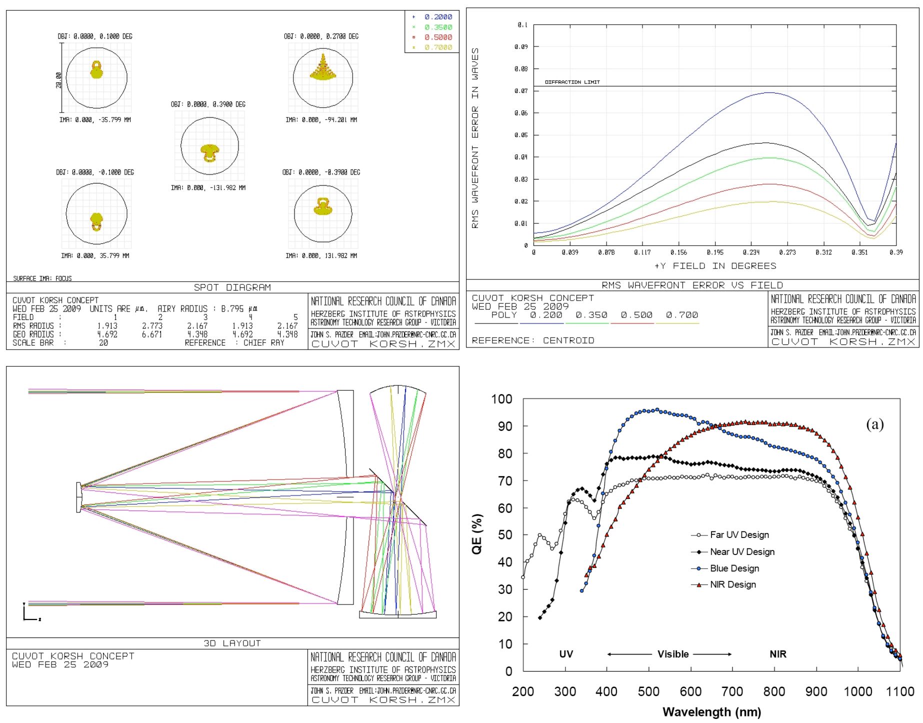

Figure 5: *(Upper Left)* Spot diagram of the preliminary Korsch design for the CST. *(Upper Right)* Radial variation in image quality over the full FOV. The smooth curves show the performance at 0.2, 0.35, 0.5, 0.7μm, and averaged over all wavelengths (polychromatic), while the horizontal line indicates the telescope diffraction limit. *(Lower Left)* Optical layout for this CST design which utilizes a folded, four-element optical arrangement and all reflective optics to meet the FOV requirement. Note the curved focal surface. *(Lower Right)* HyViSI spectral response with various anti-reflective coating options.

There is space in the design for filters to be placed just after the annular mirror. The beam size is less than 100 mm, and the beam angle of incidences are less than 15 deg. Interference filers of modest size would work well in this area.

Further study is necessary to refine this optical design and to explore other configurations; in particular, careful attention must be given to alignment sensitivities. Alternative optical configurations should also be investigated to find other detector options and designs that are insensitive to misalignment.