Astro2020 Science White Paper

Understanding Cosmic Evolution: The Role of UV Spectroscopic and Imaging Surveys

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☒Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☒Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments
☒Galaxy Evolution ☒Multi-Messenger Astronomy and Astrophysics

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Abstract (optional):

A Probe-class ultraviolet (UV) telescope having capabilities not available to Hubble can help answer many outstanding Key Science Questions posed by Astro2010. Measurements of the processed UV data will increase the scientific yield and impact of this telescope.

Introduction

This paper is in response to a request to identify scientific opportunities and compelling scientific themes in astrophysics in the 2020's, and to identify the key advances needed to realize these scientific opportunities. We believe the compelling themes of the 2020's can be found if the words, "Understanding the astrophysics of" are inserted in front of each thematic area: understanding the astrophysics of galaxy and stellar evolution; understanding the astrophysics of formation and evolution of compact objects; etc. In this white paper, we focus on the role that UV observations could play in developing such understanding.

The Need for a New UV Telescope in the 2020's

The Hubble Space Telescope is the only U.S. telescope currently obtaining UV observations. Thanks to a series of servicing missions, Hubble now comprises 2 cameras and 2 spectrographs, all having UV capabilities. These UV-sensitive instruments are finely tuned to get the most benefit from the telescope as possible. Hubble now is inarguably the best it's ever been.

Largely due to Hubble's great successes, today's interesting astrophysics problems are not the same as those when Hubble was being developed. We have new questions such as those posed by Astro2010 (*New Worlds New Horizons*, p. 247). Many of these questions are best answered by large survey observations and therefore await survey telescopes of the 2020's for answers. Indeed, the 2020's will be a golden era of wide-deep telescopes surveying the sky at wavelengths ranging from gamma rays to radio waves. E-ROSITA will perform an all-sky X-ray survey with unprecedented sensitivity and resolution; Subaru's Prime Focus Spectrograph and ESO's MOONS spectrograph will focus on studies of dark energy, galactic archeology, and understanding the evolution of galaxies at redshifts z=1-2 using optical-IR spectra; the Large Synoptic Survey Telescope will map the southern sky discovering billions of new galaxies and stars and detecting transient objects; the Wide-Field Infrared Survey Telescope will make an imaging and slitless spectroscopic survey of the sky at near-IR wavelengths; and the Square Kilometer Array and other radio telescopes will map a billion galaxies using the 21-cm hydrogen line. These surveys will be highly synergistic leading to new, important discoveries.

But there is a glaring hole in this vision: it lacks a wide-field, UV-sensitive telescope. This will hinder all astronomy – not just wide-deep surveys – because the UV spectral region is so rich in diagnostics that it has become a natural and necessary companion to space and ground-based telescopes observing at all wavelengths. Rest-frame, far-UV spectra (1,000-1,800 Å) promise to reveal the underlying physics because:

- The far-UV is exceptionally rich in spectral-line diagnostics (c.f. *Cosmic Baryons to Living Earths*, figure on p. 56);
- The far-UV lays bare stellar and AGN feedback processes such as stellar and AGN winds, supernovae ejecta, photo-ionization and heating – all important drivers of galaxy evolution;
- The far-UV (and near-UV) is extraordinarily sensitive to recent star formation.

The table (next page) shows that 9 out of the 20 Key Questions posed by Astro2010 could be addressed by a 1.5-m wide-field UV telescope with capabilities not on Hubble.

Astro2010 Key Science Questions (green font)	Hubble	Required Observational Capability
Cosmology and Fundamental Physics (CFP)		
✓CFP3 **What is dark matter?**		
Search for missing satellite galaxies predicted by CDM	X	Wide field of view (FOV)
Mapping the cosmic web at z~1 and z~0 in Lyman-a	X	Wide-field multi-object slit spectrograph (slit MOS)
Galactic Neighborhood (GAN)		
✓GAN 1 **What are the flows of matter and energy in the circumgalactic medium?**		
LUV/FUV spectroscopy of the CGM backlit by QSO	X	Sensitivity over 1000-1800 Å
Lyman-α imaging survey of the low-z universe	X	Wide FOV
✓GAN 2 **What controls the mass-energy-chemical cycles within galaxies?**		
LUV/FUV spectroscopy of low-z starburst galaxies	X	Sensitivity over 1000-1800 Å
LUV/FUV imaging spectroscopy of galaxy outskirts	X	"
LUV/FUV spectroscopy of quasar/AGN winds	X	"
FUV/NUV neutron-star binary light curves	X	Rapid response
UV imaging spectroscopic survey of UV dust halos	X	Long slits ≥17' in NUV, ≥6' in FUV
✓GAN 3 **What is the fossil record of galaxy assembly from the first stars to present?**		
Near-UV spectroscopy of extremely metal-poor stars	(✓)	Sensitivity over 1800-3200 Å
Galaxies Across Cosmic Time (GCT)		
✓GCT 1 **How do cosmic structures form and evolve?**		
Survey of rest far-UV spectra of z~0.5-1.5 galaxies	X	Wide-field slit MOS
FUV/NUV imaging survey of galaxies at z~0-2	(✓)	Small FOV limits efficiency
Lyman-α spectroscopic survey at z~0.5-1.1	X	Wide-field slit MOS
Probe of Lyman continuum survey at z>1.0	X	Wide-field slit MOS
✓GCT 2 **How do baryons cycle in and out of galaxies, what do they do while they are there?**		
Rest far-UV spectroscopy of z~1 galaxies/ISM/CGM	X	Wide-field slit MOS
✓GCT 3 **How do black holes grow, radiate, and influence their surroundings?**		
FUV/NUV spectroscopy of tidal disruption events	✓	
LUV/FUV spectroscopy of z~1-2 galaxies	X	Sensitivity over 1000-1800 Å
Stars and Stellar Evolution (SSE)		
✓SSE 3 **How do the lives of massive stars end?**		
Far-UV light curves of core-collapse supernovae	X	Rapid response
Planetary Systems and Star Formation (PSF)		
✓PSF 4 **Do habitable worlds exist around other stars?**		
Far-UV/near-UV spectroscopy of flares of M-type stars	✓	

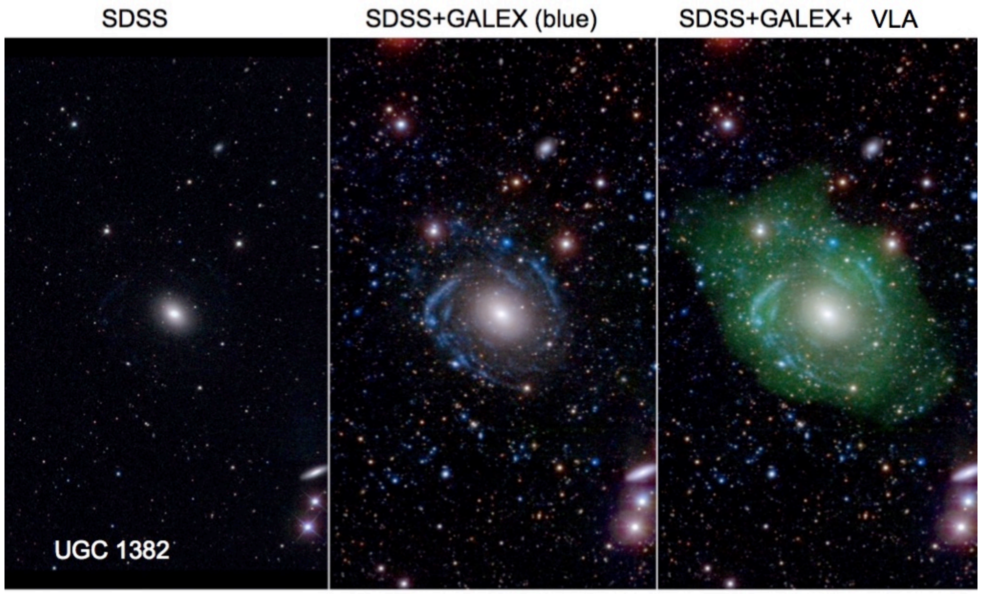

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Figure 1. Benefits of Multi-Wavelength Surveys Including the UV. At left: an optical image of UGC 1382, classified as an elliptical or S0 galaxy; center: detection of low-surface brightness spiral arms by the UV telescope, GALEX; at right: a VLA image in 21 cm reveals H I halo, making UGC 1382 one of the largest, isolated galaxies known. Reproduced from Hagen, Seibert et al. (2016)

Metrics for an Affordable UV Telescope Having Capabilities Beyond Hubble

Given NASA budget realities, a next-generation UV telescope needs to stay below the Probe mission budget cap ($1.0B), and to have maximum impact, it should be developed in due haste so as to have at least partial overlap with major surveys of the 2020's. Both cost and schedule constraints imply that little to no technology development should be needed. The UV telescope should be strong in areas where Hubble is weak (indicated by the "x"s in the Table). This UV telescope would have 3 scientific instruments: a wide-field far-UV/near-UV camera, a wide-field near-UV multi-object spectrograph (MOS) with a micro-shutter array (MSA), and a far-UV/near-UV point/slit spectrograph. An affordable next-generation UV telescope would have the following capabilities:

- *Light-gathering power of a 1.5-m telescope*
- *Wide field of view: 300 sq. arcmin*, which is 1000 times the area of Hubble's far-UV cameras and nearly 40 times the area of Hubble's near-UV camera. This wide FOV enables full participation in multi-wavelength deep, wide surveys;
- *Spatial resolution: <0.5"*, which is10 times finer than the resolution of GALEX, and as good or better than the resolution of large ground-based survey telescopes.
- *Telescope focal-ratio: 5*. The detectability of a faint, extended object scales with the inverse of the f-ratio (e.g. Abraham et al., 2016). The UV telescope is much faster than

Hubble (f/24) and much slower than LSST (f/1.2). but with the sensitivity of the UV to recent star formation (Fig. 1.2), this UV telescope makes a useful complement to LSST.

- *Spectral coverage*: *1800-3500 Å in the near-UV; 1000-1800 Å in the far-UV*. The UV telescope has 2 orders of magnitude higher sensitivity than does Hubble in the far-UV below 1150 Å, which enables observation of the O VI doublet in nearby galaxies. It also has better sensitivity than Hubble's spectrographs below ~2400 Å, which enables searches for Lyman continuum radiation escaping from z>1 galaxies.

- *Wide-field multi-object slit spectrograph (MOS) with a single JWST-size micro-shutter array (MSA).* This instrument has no counterpart on Hubble. It enables simultaneous spectroscopy of 50-100 sources; or in long-slit mode, enables searches of the cosmic web in Lyman-α. The MSA works to block unwanted background such as zodiacal light and to eliminate confusion of spectra from nearby sources.

- *Superior spectroscopic performance in the far-UV.* Modern techniques of polishing telescope mirrors have the means of suppressing mid-spatial frequency wavefront errors (*aka* quilting or tool-path errors) that plague Hubble's far-UV spectra (Ghavamian 2009) leading to possible systematic underestimates of absorption line strengths. The UV telescope will provide accurate line profiles of important far-UV diagnostic absorption lines.

- *Long-slit imaging spectroscopy over ≥6' in far-UV, ≥17' in near-U*V - to trace variations in diagnostic spectral features of extended sources.

- *Rapid response to transients* – to enable monitors of core-collapse supernovae where the far-UV light curve can be used to identify the progenitor (Nakar & Sari 2010), or the aftermath of mergers of neutron-star binaries where the UV light curve can be used to estimate the fraction of free neutrons *not* involved in the creation of heavy elements (Metzger et al. 2015). The UV telescope's rapid response derives from a field of regard slightly larger than the hemisphere opposite the sun; readiness to receive transient alerts from the ground; and slew time to the transient of 15 minutes or less.

- *State-of-the-art detectors* in the far-UV (microchannel plate detectors from Berkeley Space Science Lab, the makers of Hubble's COS detectors) and in the near-UV (Teledyne-e2v's CCD 272, a variant of the 4k X 4k CCD's made for ESA's Euclid mission but with window coatings for UV sensitivity).

Required Advances in Measurements to Produce Science-Ready Data

NASA typically requires processing of observed data from space telescopes through removal of the instrument signature and conversion of the data to physical units. NASA typically does not require making measurements on the processed data. However, such measurements are essential to maximize the *scientific* yield and impact of the observations.

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