Cosmic Evolution Through UV Spectroscopy (CETUS)
Probe-Class Mission Concept

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Thematic Activity: Space Based Activity

1 Executive Summary

CETUS is a concept for an affordable, Probe-Class (circa $1B) mission based on a 1.5-m-aperture space telescope with a wide (~1.0 degree by ~0.3 degree) FOV covering UV wavelengths from ~100 to ~400 nm. The carefully chosen complementary set of science instruments consists of a wide-field camera (CAM), a wide-field Multi-Object Spectrograph (MOS), and a Point/slit Source echelle Spectrograph (PSS) with high spectral resolution. CETUS is designed to operate for 5 years (but with enough propellant and other consumables to operate for ~10 years) in an SEL2 orbit that provides constant sunlight, thermal stability, constant contact with Earth, plus the ability to view 2π steradians of the sky at any time and 4π steradians of the sky over 6 months. This orbit enables efficient surveys and a high probability of being able to quickly observe any transient event. These features will allow CETUS to: 1) maintain equivalent or better observational access to the ultraviolet (UV) after Hubble is gone; 2) be a companion to multi-wavelength survey telescopes starting operations in the late 2020's; 3) be a scout for the extremely large ground-based telescopes that will operational beginning in the mid-to-late 2020s and beyond and; 4) provide discoveries that can be pursued by other space telescope concepts, such as HabEx or LUVOIR. The starting point for the CETUS mission concept was the Astro2010 panel's recommendation for a more capable UV-optical telescope to follow Hubble. However, new technologies and features were also incorporated, such as lithium-fluoride mirror coatings effective at shorter wavelengths, a Micro-Shutter Array (MSA)-based MOS, and the ability to slew quickly for observing transient events. With these capabilities, CETUS will not only make revolutionary progress toward answering existing questions, but it will also make discoveries that cannot be anticipated at this time.[1]

2 Key Science Goals and Objectives

CETUS directly responds to the 2010 Astrophysics Decadal Survey panel (Astro-2010) recommendation for a "more capable UV-optical telescope to follow the Hubble" (NWNH Panel Reports, p. 296). This section summarizes the science investigations that CETUS can undertake, which will answer many (**Table 1)** of the key science questions formulated by Astro2010 panel (NWNH, p. 247). Where applicable the section titles identify (in italic blue font) what Astro-2010 key science questions are addressed by a given investigation.

Table 1: CETUS addresses nearly half of ASTRO2010's Key Scientific Questions.

Cosmology and Fundamental Physics (CFP) *✓CFP 3 What is dark matter?* **Galactic Neighborhood (GAN)** *✓GAN 1 What are the flows of matter and energy in the circumgalactic medium?* *✓GAN 2 What controls the mass-energy-chemical cycles within galaxies?* *✓GAN 3 What is the fossil record of galaxy assembly from the first stars to present?*	**Galaxies Across Cosmic Time (GCT)** *✓GCT 1 How do cosmic structures form and evolve?* *✓GCT 2 How do baryons cycle in and out of galaxies, what do they do while they are there?* *✓GCT 3 How do black holes grow, radiate, and influence their surroundings?* **Stars and Stellar Evolution (SSE)** *✓SSE 3 How do the lives of massive stars end?* **Planetary Systems and Star Formation (PSF)** *✓PSF 4 Do habitable worlds exist around other stars?*

[1] This white paper summarizes the CETUS Final Report that was submitted on March 4, 2019 and is located at: https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/CETUS_Study_Rpt.pdf.

Table 2 summarizes the capabilities of each CETUS instrument and identifies which instruments support each of the wide range of CETUS science investigations described in this section.

Table 2. CETUS Instrument Capabilities and Applications to Science Investigations

	Objectives	2.1 Understanding the evolution of galaxies, stars, planets			2.2 The Modern Universe		2.3 Transients; 2.4 Surveys: CETUS prime, Multi-Telescope		
Scienc	Principal Targets	z~1 galaxies	Primitive stars	M-star Flares	Galaxies & Outskirts	The CGM	UV Surveys	Rapid Transients	Multi-λ surveys
	Measurement Types	Spectral lines	Spectral lines	Emission lines, continuum	Spectral lines, continuum	Spectral lines	Spectral lines	UV light curves	UV SED
	Observations by Prime Science Instrument	NUV MOS	NUV SPEC	NUV, FUV SPEC	FUV SPEC, FUV CAM	FUV SPEC	FUV SPEC	VARIOUS	NUV. FUV CAM
OTA/Obs	Aperture diameter 1.5 m	✓	✓	✓	✓	✓	✓	✓	✓
	Mirror coatings Al/LiF/MgF_2				✓	✓			
	λλ 100-1000 nm (>400 nm for guider only)				✓	✓			
	FoR > anti-solar hemisphere							✓	
	Pointing stability 64 mas 1σ							✓	
	Slew time < 15 min for 180 deg							✓	
	Parallel Operation of SI's	✓	✓	✓	✓	✓	✓	✓	✓
NUV MOS	λλ 180-350 nm; RP ~ 1000@300 nm; MSA ~ 190x380 shutters; Shutter = 100 x 200 micron (2.75" x 5.50"); FOV=17.4' x 17.4'	✓							
FUV SPEC	λλ 100-180 nm; Slit 0.2" x 3"; RP~20,000			✓	✓	✓	✓	✓	
	Slit-LS 2" x 360"; RP~2000 (ext. sources)				✓	✓	✓	✓	
NUV SPEC	λλ 180-350 nm; Slit 0.2"x3"; RP 40000 @ 300 nm		✓	✓	✓			✓	
FUV CAM	λλ 115-180 nm; 5 long-pass filters; FOV 17.4' x 17.4'; Res 0.55" (22 mm); Sub-pix sampling	✓			✓			✓	✓
NUV CAM	λλ 180-400 nm; 5 filters; FOV 17.4' x 17.4'; Res 0.33" (12 mm); Sub-pix sampling	✓						✓	✓

2.1 Understanding cosmic evolution – galaxies, stars, and planets *(GCT 1, GCT 2)*

2.1.1 Galaxies - Understanding the star-formation history

The era corresponding to z ~ 1-2 is particularly important, because it corresponds to the time when the rate of star formation in the universe was at its peak. We know the star-formation history of the universe, but we don't understand it (Madau and Dickinson 2014). CETUS will make a massive UV spectroscopic and imaging survey of galaxies at z~1 aimed at deriving information about the physics of the ISM, self-regulated accretion and star formation, stellar and AGN feedback. NUV spectra of z~1 galaxies, corresponding to rest FUV spectra promise to lead to an understanding of the evolution of galaxies because:

- The FUV is exceptionally rich in spectral-line diagnostics, which yield "direct, quantitative measures of many astrophysically important elements in the majority of their ionization states" (HDST figure, p. 56);

- The FUV lays bare stellar and AGN feedback processes e.g., stellar and AGN winds, supernovae, photo-ionization and heating – all thought to be important drivers of galaxy evolution;
- The FUV gives an effectively instantaneous snapshot of physical processes at work; if quenching has started, we will see symptoms of it in UV spectra and images.

CETUS spectra will be combined with optical spectra of the same galaxies as obtained by ground-based observatories to obtain a full picture of the properties of z~1galaxies.

2.1.2 Astro2010 Area of Unusual Discovery Potential: The Epoch of Reionization

CETUS/MOS will extend further into the rest Lyman-UV (912-1216 Å) than does the Keck spectrum of cB58. In fact, CETUS will probe below the Lyman limit in the rest-frame of large samples of star-forming galaxies at z > 1 with the near-UV MOS. The ability to probe the Lyman continuum is directly relevant to the reionization of the universe at "cosmic dawn." Only a small sample of galaxies exists with detected Lyman continuum escaping and no clear understanding how/why these galaxies are "leaky". The current observational picture is captured in the conference, "Escape of Lyman Radiation from Galactic Labyrinths", and in Gazagnes et al. (2018), Izotov et al. (2018a, b), and Steidel et al. (2018). Using rest FUV spectra, CETUS will study the physics of the ISM, self-regulated accretion and star formation, stellar and black-hole feedback, and supernovae and black-hole accretion disk-driven galactic winds. CETUS spectra will be combined with optical spectra of the same galaxies as obtained by Subaru Prime Focus Spectrograph and VLT MOONS, and other ground-based observatories to obtain a full picture of the properties of z~1 galaxies. Comparison of CETUS UV images with those from X-ray telescopes such as Swift or E-ROSITA will give a more complete census of the stellar and black-hole content of a galaxy. Similarly, combining CETUS UV images with longer-wavelength data from telescopes like LSST, Subaru HSC, WFIRST, and radio telescopes will also be fruitful.

2.1.3 The First Stars *(GAN3)*

The nucleosynthetic signatures of the first stars and supernovae are imprinted in the elements observed in second-generation stars, which are likely found among the most metal-poor stars. These ancient stars have less than 1/3000 of the solar iron abundance ([Fe/H] ≤ 3.5). About 80 such stars are known today, and hundreds more are expected to be found among ongoing and future surveys (e.g., LAMOST, SkyMapper, Pristine, 4MOST, WEAVE, LSST). Only a few tens of absorption lines are commonly found in the optical and near-IR (λ > 310 nm) spectra of these stars, so only ~5-10 elements are regularly detected. This limits the utility of these stars for understanding the nature of the first stars and first supernovae. Many other elements are expected to be present, but they remain undetected. The strongest transitions of these elements are in the UV, below the atmospheric cutoff, requiring space facilities for detection. The Hubble Space Telescope (HST) is limited to studies of only the brightest stars, and only one star with V < 10 and [Fe/H] < —3.5 is known at present (BD+44 493; Roederer et al. 2016). Many of the most metal-poor (or iron poor) stars are too faint for HST.

The CETUS R~40,000 NUV echelle spectrograph offers a new opportunity to expand our capability to observe the sample of the most metal-poor stars known by orders of magnitude, revealing the true diversity of the first stars and supernovae. High spectral resolving power (R ~ 40,000) and high S/N ratios (S/N ~ 50/1 or greater) are ideal to detect and accurately measure the relatively weak absorption lines produced by these elements in FGK-type stellar photospheres. CETUS enables long, *uninterrupted* exposures of these fainter stars for the first time, revolutionizing our understanding of the first stars, supernovae, and metals in the Universe.

2.1.4 Planets - Effect of stellar flares on the habitability of exoplanets *(PSF 4)*

Kepler scientists have found that, on average, every star in the Milky Way hosts a planetary system. Some of these systems contain one or more planets in the "habitable zone" (HZ). M-dwarfs, the most common stars in the galaxy and solar neighborhood, are expected to host most HZ planets that will be found by TESS (Sullivan et al. 2015). The HZ is where the surface temperature is such that liquid water may exist for some portion of the "year." However, the effective surface temperature alone is insufficient to establish habitability or to interpret spectral features in terms of biosignatures (e.g. Meadows et al. 2018). Other information is needed, particularly the EUV-NUV stellar energy distribution because it drives the atmospheric heating and chemistry of terrestrial planets. The stellar spectrum is also critical to the long-term stability of terrestrial atmospheres. Stellar flares can alter the UV luminosity by factors of 10 on timescales of seconds, and even non-flaring states are characterized by stochastic fluctuations of ~30% on minute timescales (Loyd & France 2014).

CETUS will monitor the UV spectrum of selected M-type stars in order to get better statistics on flares, (frequency, intensity, duration, ionization level, etc.). Spectrally resolved monitors are critical for properly modeling M-stars atmospheres including the thermal structure of the transition region (from O VI 1032Å, 1038Å), which gives rise to much of the EUV emission, and the corona (from [Fe XXI] 1354Å, [Fe XIX] 1118Å, and [Fe XII] 1242Å). CETUS data will provide the necessary observational constraints to predict the physical processes involved in atmospheric heating and chemistry of their exoplanets. Spectral features of O_2, O_3, CH_4, and CO_2, are expected to be the most important signatures of biological activity on planets with Earth-like atmospheres (Des Marais et al. 2002). The chemistry of these molecules in the atmosphere of an Earth-like planet depends sensitively on the strength and shape of the UV spectrum of the host star. H_2O, CH_4, and CO_2 are sensitive to LUV+FUV radiation (100 – 175 nm), while the atmospheric oxygen chemistry is driven by a combination of FUV and NUV (175 – 320 nm) radiation.

2.2 Understanding the Galactic neighborhood: What it's made of; How it works or "the Modern Universe"

CETUS can study nearby galaxies and surrounding gas and dust in detail in the galactic neighborhood. For these science objectives there is no need for a telescope aperture as large as that of LUVOIR or HDST that can resolve 100 pc anywhere in the universe. It is enough that CETUS can resolve 100 pc up to 40 Mpc away. A sphere of radius 40 Mpc contains an abundance and variety of galaxies and circumgalactic media (CGM). Since nearby galaxies appear brighter than more distant ones, they are more likely to have been observed by telescopes at wavelengths from X-rays to radio waves, providing excellent test cases to learn what the local universe is made of, how it works, and how it got that way.

2.2.1 Galaxies and their outskirts *(GAN 2)*

2.2.1.1 Understanding low-z starburst galaxies. Galactic winds driven by the energy and momentum supplied by massive stars and supernovae play a crucial role in the evolution of galaxies and the intergalactic medium. Most of the current data on these outflows measure the properties of interstellar absorption-lines in the rest-UV. While highly useful in measuring outflow velocities, these data provide no direct information on the spatial extent or structure of the outflow. Without this, we cannot reliably measure the outflow rates of mass, metals, momentum, and kinetic energy nor can we test competing models for the acceleration of the outflowing gas. This can be best addressed by imaging spectroscopy of these same UV resonance lines in emission. Therefore, CETUS would be a game-changer for understanding low-z starburst galaxies that are driving winds.

These can serve as local laboratories for better understanding the winds seen in high-redshift galaxies.

2.2.1.2 Quasar and AGN Winds. Galactic winds in gas-rich mergers are an essential element of galaxy and supermassive black hole evolution (e.g., Hopkins et al. 2006; Cicone et al. 2014; Rupke et al. 2017). The most powerful of these outflows are driven by quasars and likely feed the circumgalactic medium. The outflow energetics are often dominated by the outer (> kpc) and cooler dusty molecular and neutral atomic gas phase, but the driving mechanism is best probed by the inner (sub-kpc) highly ionized gas phase. While current X-ray observatories are not sensitive enough to carry out a systematic survey of these inner winds, results from recent and on-going FUV studies with COS on HST indicate that CETUS will be ideally suited for this task. Prominent, highly blue-shifted (1000 km/s) Lyα emission has been detected in most ultra-luminous infrared galaxies (ULIRGs), often accompanied by blue-shifted absorption features from N V and O VI (Martin et al. 2015). The internal kinematics of ULIRGs seem to be the single most important factor determining the profile and escape fraction of the Lyα emission. However, the trends so far are entirely driven by the few AGN-ULIRGs in the current sample and are therefore highly uncertain. CETUS will study the gaseous environments of nearby gas-rich mergers as a function of host properties and age across the merger sequence, ULIRG --> QSO (e.g., Veilleux et al. 2009) with unprecedented statistics.

2.2.1.3 UV Dust Halos. A significant fraction of dust in the Universe resides in the circumgalactic medium (Ménard et al. 2010), and this dust contains information about the feedback history of galaxies and the metal content of extragalactic gas. One of the few ways to observe this dust around individual galaxies is through reflection nebulae, which are visible around highly inclined, star-forming galaxies. The combination of high resolution, low sky brightness, and large extinction cross-sections make the ultraviolet band the best place to detect them as diffuse halos around galaxies within about 10-20 kpc of the disk (Hoopes et al. 2005; Hodges-Kluck & Bregman 2014; Seon et al. 2014; Shinn & Seon 2015; Hodges-Kluck et al. 2016; Baes & Viaene 2016). The luminosities and FUV-NUV colors of these halos are sensitive probes of the amount of dust in the halo and its composition, which constrain the mass and character of galactic outflows. In many cases, UV halos are the only feasible probes of individual galaxies because emission is faint (halo dust is cool), while reddening can only be studied by stacking large samples of background sources (Ménard et al. 2010).

2.2.2 What are the flows of matter and energy in the circumgalactic medium? *(GAN1)*

2.2.2.1 The Warm-Hot Circum-galactic Medium (CGM): The circum-galactic medium (CGM) is the gas and dust surrounding a galaxy. It contains more baryonic (normal) matter than does the galaxy itself. Whether it contains all the matter needed to account for the "missing baryons" at low-red- shift is still open to debate. Most matter in the CGM is "hidden" in a warm-hot phase (100,000 – 500,000 K) or in a hot phase. The only observable signature of the warm-hot interstellar medium (WHIM) is the O VI doublet at 1032 Å, 1038 Å, which cannot be observed by the HST COS spectrograph for most targets with redshifts, $z<0.16$. COS observations of O VI and other FUV resonance lines arising in the CGM of galaxies at $z>0.16$ have yielded important statistics on the frequency, column density, velocity, and velocity dispersion of O VI in the CGM of galaxies (e.g. Tumlinson et al. 2017, Keeney et al. 2017). However, they have not led to definitive conclusions about the missing baryons problem, their location and phase, or relation to the host galaxy.

2.2.2.2 The Hot Circumgalactic Medium. In 2018, Anderson and Sunyaev discovered [Fe XXI] λ1354-emission in a filament of M87. This emission line is indicative of a 1 keV ($T\sim10^7$ K) plasma. The discovery suggests that CETUS may be used to study not only gas in the warm-hot phase (O VI doublet) but also gas in the hot phase of plasma in galaxy clusters and very massive galaxies. CETUS can explore nearby galaxy clusters such as Perseus, Virgo, or the Coma cluster utilizing the spectrograph's long slit to obtain imaging spectra over 6' to map the [Fe XXI] λ1354 Å line emission arising in the warm-hot or hot medium.

2.2.2.3 Role of the CGM in galaxy evolution: Recent results from cosmological models (EAGLE, Illustris, IllustrisTNG, GalICS, and L-Galaxies) indicate that feedback from stars and black holes determines how effectively CGM gas cools as it is falling back onto the galaxy, thereby providing fuel for star formation. The CGM needs to be continually prevented from cooling to prevent star formation from occurring in the galaxy (Terrazas et al. 2016, 2017, 2019). How cooling is prevented is not observationally constrained well enough to inform models, so this physical process differs in all models. Illustris-TNG uses mechanical energy, EAGLE uses thermal energy, and other models use a combination of these. None of the models does an adequate job at matching observations, so better observational constraints are needed. CETUS will help constrain feedback from black holes and stellar winds and supernovae in two ways: (1) It will extend observations by COS to understand the properties of winds from supermassive black holes; and (2) Comparison of the properties of the CGM and host galaxy will show how the feedback affects the CGM.

2.3 Understanding Transient Events

2.3.1 Direct Observations of Electromagnetic Counterparts of Gravitational Wave Events *(GCT 3)*

The joint discovery of gravitational waves (GWs) and electromagnetic (EM) radiation from the binary neutron star (BNS) merger GW170817 was an exciting moment for astrophysics (Abbott et al. 2017). The detection two seconds later of a short gamma-ray burst established BNS mergers as the progenitors of these systems. With a luminosity distance from GWs and a redshift from the host galaxy NGC4993, the Hubble constant can be measured in a manner independent of the local distance ladder. The light curves and spectra of the associated UV/optical/NIR counterpart revealed the presence of heavy element r-process nucleosynthesis in the merger ejecta (a "kilonova"), with a total mass sufficient for BNS mergers to serve as the dominant production sites of heavy elements in the Universe. The prompt-response capabilities and UV sensitivity of CETUS make it a unique facility to probe the origin of the rapidly fading UV component. CETUS will work well with future more sensitive LIGO detectors, as the UV camera should be able to detect a GW170817-like object (at maximum) at a distance of 750 Mpc, or equivalently, to follow the light curve of a similar object at 200 Mpc for 10 hours after the merger.

2.3.2 Witnessing tidal disruption events *(GCT 3)*

CETUS will witness the rebirth of accretion disks around the nuclei of galaxies thought to be inactive by observing a tidal disruption event (TDE) and viewing its effect on its surroundings. As a star comes close to an inactive black hole it is tidally distorted and then shredded. Some of the debris escapes the black hole; the remainder orbits the black hole to form an accretion disk, which is then viewed as an active galactic nucleus (AGN). Hubble's STIS instrument has obtained low-resolution UV spectra (115-320 nm) of TDE's (Cenko et al. 2016, Brown, Kochanek 2017). The spectra, at least in these two cases, bear a resemblance to those of WN stars, meaning a He- and N-rich Wolf-Rayet star with a strong, high-velocity wind with strong emission. Monitoring of the tidal disruption flare reveals strong spectral evolution in the velocity, Doppler width, and strength of the emission lines. With the many transient-search telescopes coming on line, there should be ample TDE's for the CETUS FUV spectrograph to follow and to derive the physical processes involved.

2.3.3 Identifying the Progenitors of Core Collapse Supernovae *(SSE 3)*

In most cases, the progenitors of core-collapse supernovae are not known. A massive star near the end of its life may be a red supergiant (RSG), a blue supergiant (BSG) or a Wolf-Rayet (WR) star. Nakar & Sari (2010) have found that the FUV light curve of a supernova can be used to determine its progenitor. The CETUS FUV camera is well suited for this task as it can respond rapidly to reports of a newly discovered supernovae and it can follow the FUV light curve down to m_{AB}~27.

2.4 Surveys *(CFP 3, GCT 1)*

2.4.1 UV Surveys. The Dwarf Galaxy Problem: Cold dark matter (CDM) has long been the leading candidate for the missing mass in the nearby universe. However, CDM has problems on small scales. One of the problems, called the "missing satellite problem" or "dwarf galaxy problem" is an apparent lack of satellite galaxies around massive galaxies like the Milky Way that are predicted by CDM theory. CETUS will search for dwarf galaxies in NUV and FUV pass-bands very efficiently since CETUS will more than cover the LUVOIR search region in only 9 telescope pointings compared to LUVOIR's 156 pointings. The CETUS camera is very sensitive to faint, extended objects, because CETUS' f/5 optics are 23 times more sensitive to faint, diffuse objects than is LUVOIR (f/24).

2.4.2 The Lyα Sky at Low Redshift: H I Lyman-α at 1216 Å is probably the most important spectral line in its own right. In emission, it may also be the best indicator of Lyman continuum radiation that has escaped a galaxy and ionized hydrogen gas in its surroundings (Verhamme 2018). Wisotzky et al. (2018) found that Lyα emitters (LAE's) were plentiful at high redshifts, z~3-6. How has the Lyα sky evolved? CETUS will answer this question through both imaging and spectroscopy at low redshifts and at z~1, completing the picture of the evolution of Lyα emission.

2.4.3 Multi-wavelength Surveys: In the 2020's and beyond, current and future wide-deep telescopes will survey 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 PFS and the VLT's MOONS spectrograph will concentrate on understanding the evolution of galaxies at redshifts z=1-2, using optical-IR spectra; the LSST will map the southern sky discovering billions of new galaxies & stars and detecting transient objects; WFIRST and Euclid will make an imaging and slitless spectroscopic surveys of the sky at near-IR wavelengths; the Large Millimeter Telescope (LMT) will map the mm sky; and the Square Kilometer Array (SKA; 2021+) and other radio telescopes will map a billion galaxies using the 21-cm hydrogen line. CETUS will provide the critical UV portion of these multi-wavelength surveys to help piece together a more complete picture.

3 Technical Overview

3.1 Science PL

The science objectives drive the design and configuration of the CETUS architecture resulting in a broadly capable 1.5-m aperture UV WFOV telescope and complement of three instruments. Thus, CETUS is optimized for both a comprehensive UV spectral survey of as many as 100,000 galaxies with redshifts with z ~1 - 2, and for specific spectroscopic goals, some requiring agile response to different sectors of the sky, with different solar view factors. Its 1.5-meter aperture wide field-of-view telescope with three science instruments allow long exposure, efficient, wide-field surveys of stellar objects by both a NUV MOS spectrograph and a FUV/NUV Camera. The third SI, the

PSS, has two high resolving power spectroscopy modes: LUV/FUV/NUV, long slit, imaging spectrograph that extends the CETUS spectral capability to beyond HST cutoff into the LUV (100 nm) and a NUV point source echelle spectrograph. The detailed optical design, recently published in Woodruff et al. (2019), is summarized here. CETUS is designed to study galaxy evolution providing long exposure observations of a large number of objects. Cataloging a large sample of objects is provided by high-pixel-count detectors and parallel observing. A typical observation with the MOS and the Camera will be ~ 10 hours long with detector read-out every 30 minutes to

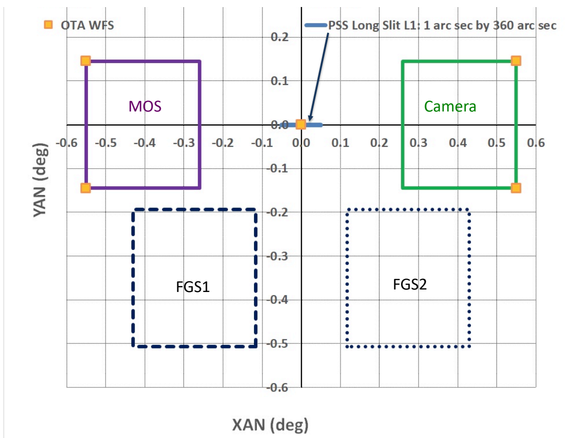

Figure 1: Shared-splitting of CETUS OTA FOV provides simultaneous observing with all science instruments for highly time efficient data collection.

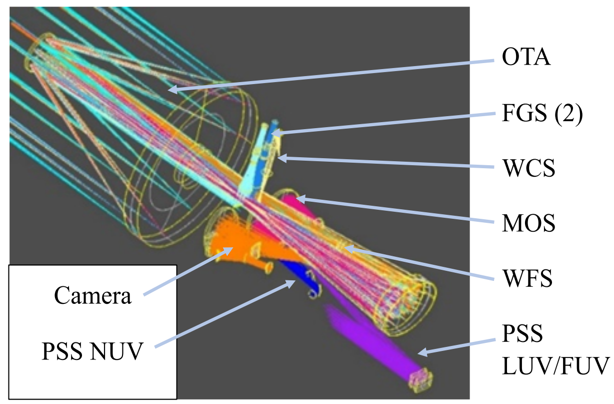

Figure 2: The CETUS Telescope feeds the 3 UV instruments which have been laid-out and packaged to fit within the allowable volume. The number of reflections has been minimized.

minimize cosmic ray/charged particle pixel detections.

CETUS detects spectrally filtered images, as well as low and high resolving power spectroscopy of galaxies in the vacuum ultraviolet spectral region. The highly efficient photon detection design is enabled by 1) an all-reflective optical design of OTA and instruments, 2) using Lyα optimized (or as an option, LUV optimized) reflective mirror coatings, 3) minimizing the number of reflections in each optical path, 4) field sharing that permits simultaneous observing by science instruments, and 5) using detectors with minimum number of windows and with high quantum efficiency. As illustrated in **Figs. 1** and **2,** the large FOV of Three Mirror Anastigmatic (TMA) Optical Telescope Assembly (OTA) simultaneously feeds the three separate scientific instruments. That is, the instruments view separate portions of the TMA image plane enabling parallel operation by the three instruments, as well as numerous programmatic and program schedule risk benefits (instruments procurable separately, AI&T of aligned assembly can

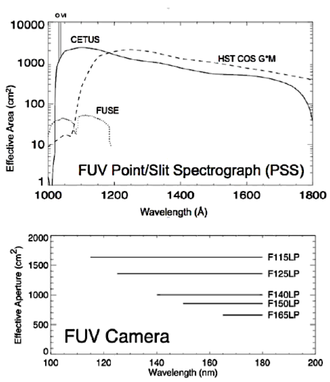

Figure 3: (Top) Comparison of CETUS effective area with COS and FUSE. (Bottom) Effective areas of FUV camera filters.

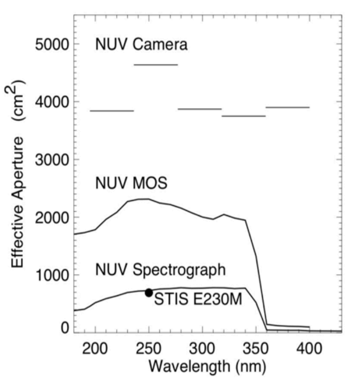

Figure 4: Effective apertures for CETUS NUV Camera, MOS, and Spectrograph compared to STIS.

proceed with no interference if problems in any one instrument arise). This implementation allows for a very substantial increase in effective area compared to COS/FUSE/HST (**Figs. 3 & 4**).

3.2 Mission

Overall Mission design for a space telescope such as CETUS focuses on developing the most cost-effective means for the Science PL (**Fig. 5**) to carry out its intended observations. Accomplishing this objective requires careful design of four separate but interrelated mission elements: orbit, operations, SC Bus, and launch vehicle (LV). The starting point for CETUS is to define the "accommodation requirements" of the Science PL, summarized as follows:

- Instrument Envelope: ~5-m long and ~2-m diameter
- Instrument Mass and Power: ~1,084 kg and ~1,200 W
- Operating Temperature Environment: ~293 K
- Science Data Downlink: ~27 Gbit/day
- Command Uplink: Anytime to initiate a slew and quickly begin observation of a transient event
- Instrument Slew Speed: <=180 degrees in less than 15 minutes after commanded
- Instrument pointing accuracy: ~0.1 arcsec
- Instrument Field of Regard (FoR): ~2 π steradians of sky centered on anti-Sun direction at any time and all 4 π steradians of sky over a period of ~6 months.
- Duration of observations: 5-year design life with 10-year goal

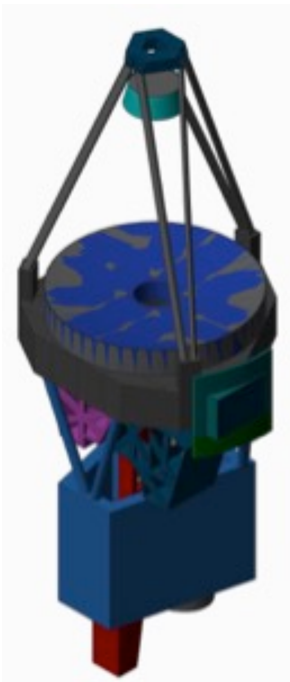

Figure 5. CETUS Science PL.

The orbit selected for CETUS (**Fig. 6**) is approximately centered on the Sun-Earth Second Lagrange Point (SEL2), providing an unobstructed view of about 2 π steradians of the sky at any point in time, and 4 π steradians over 6 months. This orbit has been used by multiple space telescopes (e.g., WMAP, Planck, Herschel, Gaia) and is the planned orbit for multiple observatories in development (JWST, WFIRST, PLATO).

The combination of the relative proximity of a SEL2 orbit and non-extreme downlink requirements (~27 Gb per day) allows CETUS to use the Near-Earth Network (NEN) as opposed to the more expensive Deep Space Network (DSN). Also, the larger number of NEN ground stations relative to the just-three DSN stations will facilitate having a ground station available to transmit an immediate command sequence for CETUS to monitor a transient event.

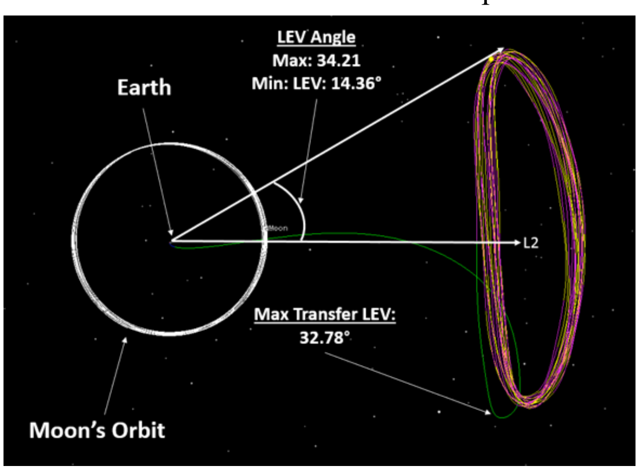

Figure 6. CETUS SEL2 Orbit.

The SC Bus designed to support, and meet all performance requirements of, the CETUS Science PL in its SEL2 orbit is shown in **Fig. 7** in its on-obit deployed configuration (left) and stowed in the fairing of a Falcon 9 LV (right). The Falcon 9 is a desirable LV choice for CETUS due to its well-established reputation for low cost and reliability. It has also successfully launched a spacecraft (DSCOVR) into a SEL1 orbit, which from a LV perspective requires the same kind of trajectory capability as a SEL2 orbit.

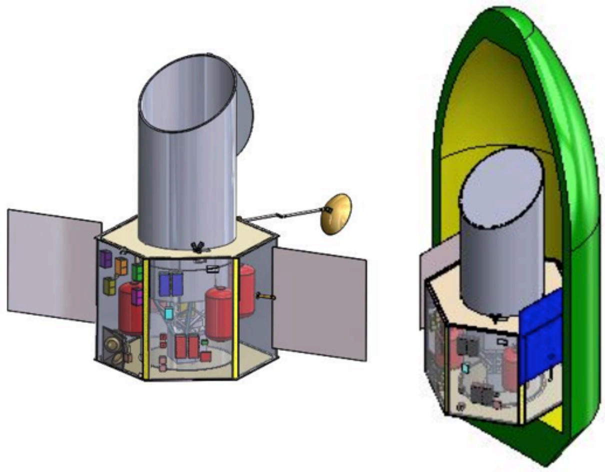

Figure 7: CETUS SC-Bus Deployed on-Orbit (left) and Stowed in Falcon 9 Fairing 9 (right)

The Maximum Expected Value (MEV) of the total wet mass of the CETUS observatory (Science PL and SC Bus with propellants) is ~2,970 kg. This mass is comfortably below the ~3,370 mass capacity of Falcon 9 to a SEL2 orbit. As shown on the Right of **Fig. 7**, the stowed configuration of CETUS Observatory fits easily within the standard 5-m fairing of the Falcon 9.

Overall, the CETUS mission implementation consists of high-heritage, high-TRL, conventional components for not only the SC-Bus, but also for the orbit parameters, LV and NEN-based ground system. The SC-Bus has a "donut-hole" configuration, which has been used on other missions such as IUE, that reduces the overall observatory length, the moment of inertia in the transverse axes (allowing faster slews) and the Cp-Cg offset (reducing the rate of momentum build-up). The science operations include a) planning for the nominal surveys along with pre-planning for targets of opportunity, b) scheduling, and c) data processing, data storage, and dissemination of results

4 Management Budget and Schedule

4.1 Management: The CETUS Probe Study Team consisted of scientists and engineers from a range of institutions. A comparable NASA/University/Industry team will be formed for the successful execution of the CETUS Mission. We have also engaged prospective foreign partners in discussions for potential contributions including major portions of some of the instruments (e.g., CNES has an interest in offering to provide the PSS.) With its modular design of the Science PL and each individual science instrument, CETUS's implementation may be accomplished in several ways, including having diverse laboratories or companies, and even foreign partners, produce assemblies and instruments.

4.2 Schedule: The planned CETUS Mission development schedule for CETUS assumes a Phase A start in October 2023 and a launch in October 2030, assuming continued technology development of Next Generation Micro-shutters (NGMSA), high-QE MCP detectors, and ALD protected LiF/Al coatings prior to phase A start. The 7-year duration minimizes cost by providing sufficient but not excessive time for developing a mission of this size. Operations are planned for a 5-year mission, but consumables will allow for 10 years of operations.

4.3 Cost Estimates: Different cost estimating methodologies have given total mission cost estimates ranging from ~\$1B to ~\$2B, resulting in a first-cut cost estimate of ~ \$1.5 B in FY18 dollars.

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ACRONYMS

Acronym	Definition
4MOST	4-meter Multi-Object Spectrograph Telescope
AGN	Active Galactic Nucleus
AI&T	Assembly Integration & Test
ALD	Atomic Layer Deposition
BNS	Binary Neutron Star
BSG	Blue Supergiant
CETUS	Cosmic Evolution Through UV Spectroscopy
CDM	Cold Dark Matter
CGM	Circumgalactic Medium
CNES	Centre national d'etudes spatiales
COS	Cosmic Origins Spectrograph
DSN	Deep Space Network
EUV	Extreme Ultraviolet
FOR	Field of Regard
FOV	Field of View
FUSE	Far UV Spectroscopic Explorer
FUV	Far Ultraviolet
GSFC	Goddard Space Flight Center
GW	Gravitational Wave
HDST	High-Definition Space Telescope
HSC	Hyper Suprime Camera
HST	Hubble Space Telescope
HZ	Habitable Zone
IR	Infrared
ISM	Inter-Stellar Medium
IUE	International Ultraviolet Explorer
km	Kilometer
JWST	James Webb Space Telescope
LAE	Lyman alpha emitting
LAMOST	Large Sky Area Multi-Object Fibre Spectroscopic
LEV	L2-Earth-Vehicle
LIGO	Laser Interferometer Gravity Observatory
LMT	Large Millimeter Telescope
LSST	Large Synoptic Survey Telescope
LUV	Lyman Ultraviolet
LUVOIR	Large UV/Optical/IR Surveyor

Acronym	Definition
mas	milli-arcsecond
MCP	Micro-Channel Plates
MDL	Mission Design Lab
mm	millimeter
MOS	Multi-object Spectrograph
MSA	Micro Shutter Array
NASA	National Aeronautics and Space Administration
NEN	Near Earth Network
nm	nanometers
NGIS	Northrop Grumman Innovation Systems
NGMSA	Next Generation Micro Shutter Array
NIR	Near Infrared
NUV	Near Ultraviolet
NWNH	New Worlds New Horizons
OTA	Optical Telescope Assembly
PL	Payload
PSS	Point/Slit Spectrometer
QSO	Quasi-stellar Object
RSG	Red Supergiant
SC	Spacecraft
SED	Spectral Energy Distribution
SEL2	Sun-Earth Lagrange Point 2
SI	Science Instrument
STIS	Space Telescope Imaging Spectrograph
TDE	Tidal Disruption Event
TESS	Transiting Exoplanet Survey Satellite
TMA	Three Mirror Anastigmat
ULIRG	Ultra-Luminous Infrared Galaxy
UV	Ultraviolet
UVIT	Ultraviolet Imaging Telescope
VLT	Very Large Telescope
WCS	Wavelength Calibration System
WFIRST	Wide-Field Infrared Survey Telescope
WFOV	Wide Field of View
WFS	Wavefront Sensor
WHIM	Warm Hot Interstellar Medium
WMAP	Wilkinson Microwave Anisotropy Probe
WR	Wolf-Rayet